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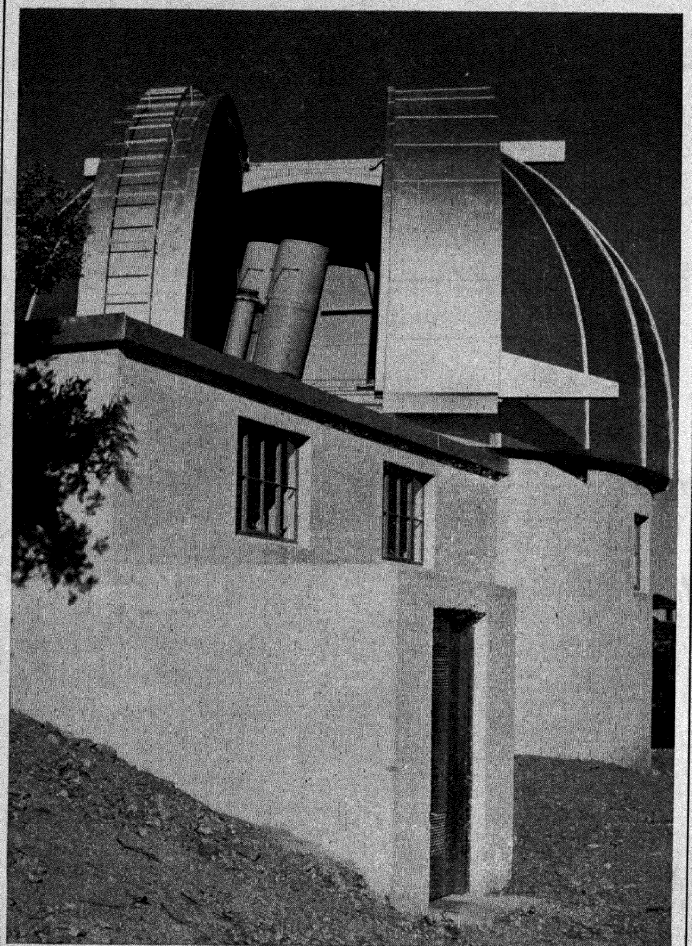
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TELESCOPES AND ACCESSORIES



A view of the new 20-inch Ross photographic telescope of the Lick Observatory.

THE HARVARD BOOKS ON ASTRONOMY

Edited by

HARLOW SHAPLEY AND BART J. BOK

TELESCOPES AND ACCESSORIES

BY

GEORGE Z. DIMITROFF

AND

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1

LIGHT AS A TOOL

NATURE ENDOWED MANKIND LONG AGO THROUGH AGES OF evolution with the ability to examine his environment with the aid of light. The eye of man is no better than that accorded many a high type of animal, but man's maturing intelligence has enabled him to interpret the light patterns falling on his retina to the enrichment of his experience.

Practical economic problems occupied early man's time to the exclusion of aesthetic and moral values. During these times normal human vision proved more than adequate. With the appearance of the early philosophers, who lived beyond their surroundings in a still more beautiful intellectual world, there grew a need for supplementary aids to human observation.

This book describes how modern man has learned through procedures and instruments of great power to analyze the universe in which he lives. Giant telescopes sweep the sky nightly, gathering information that would otherwise never be revealed. Men are busy, even as you read, translating their photographs of the sky into scientific language correlated with previous observations and theories. These scientists are studying light beams. You will see how they proceed.

Our volume presents a description of the principal instruments and procedures of use in astronomical observations. It is intended for the reader who would like to learn how the astronomers investigate the universe beyond the earth. Although telescopes are discussed at length in all their intriguing detail,

the book devotes a large amount of space to the auxiliary instruments that make a telescope highly effective. Before going into the nature of astronomical instruments, we invite you to dwell

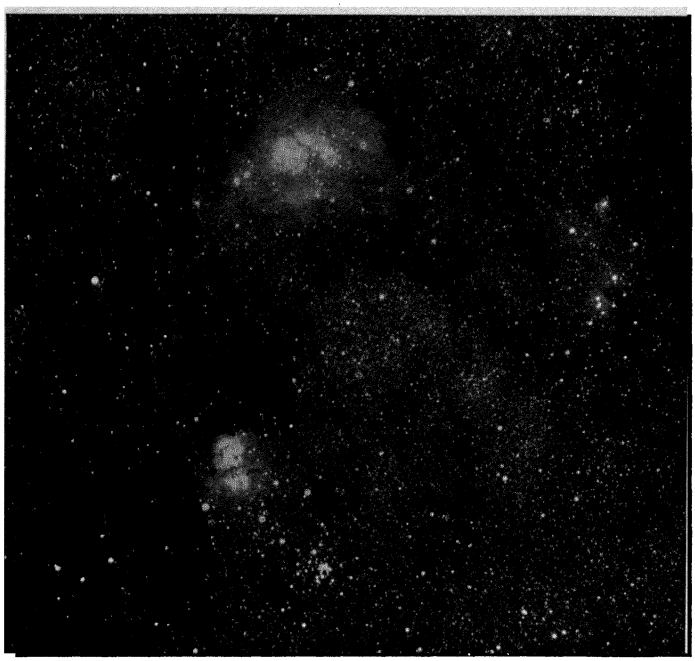


Fig. 1.—Messier 8 and the Trifid Nebula.

The diffuse nebula Messier 8 (top) and the Trifid Nebula, photographed with the 24-inch Bruce camera in South Africa.

with us for a short time on the important subject of the nature of light.

Light Waves

During the seventeenth century Christiaan Huygens (1629–95) worked extensively on the question of the nature of light. By careful study of the phenomena of reflection and refraction, Huygens was led to the conclusion that light is energy flowing

in wave motion, and that light travels away from its source along lines perpendicular to a common surface of vibration called the *wave-front.* All points on the wave-front are in exactly the same phase of vibration.

Let us draw an analogy to surface waves on a pond (as in Figure 2) set up by some disturbance like the fall of a stone. The ripples spread outward from the source. The moving crest of each wave defines clearly what we have called above a wave-

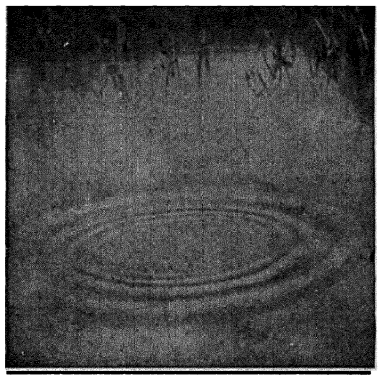


Fig. 2.—Water waves on the surface of a pond.
(*Foley "College Physics."*)

front and each ripple is traveling along a line at right angles to it. The distance between corresponding points of successive waves is called the *wave-length* of the wave.

The waves on the surface of a pond are three-dimensional in character. First, the water particles are moving up and down with respect to the surface of the pond. Second, any point on the wave-front is moving outward from the source. And third, the wave-front, as a whole, is moving outward in ever-widening circles, always centered at the source of the disturbance. The radial cross-section of a surface wave resembles the two-dimensional wave of a vibrating string.

Light from a small source moves outward in spherical wave-fronts. The wave-front of a vibrating string, we may note is but

a moving point, and that of a water-wave, an expanding circle. A spherical wave-front is simply an expanding sphere centered at the source of light. A perfect spherical wave-front has a mathematical point as the source of light. In practice the source is never as small. For all practical purposes, however, a *point-source* of light may be taken as one subtending a very small angle as seen from the particular wave-front studied. Stars are such point-sources. Although huge in diameter, stars, as seen from the earth, subtend angles smaller than 0.07 seconds of arc, smaller than the angle subtended by a printed period seen from a distance of one kilometer.

Light coming to us from a distant source like a star is part of a spherical wave-front of such tremendous radius that the portion we see travels effectively in a plane rather than in a spherically curved surface, and is called a *plane* wave. The perpendiculars to the plane wave-front are essentially parallel to one another; their direction, after corrections caused by the earth's motion, is considered to be the direction of the star. A beam of light from such a distant point-source is often called *parallel* light.

When light passes through an extremely narrow opening, it no longer continues along the original wave-front. Instead, a new one is formed with its apparent source at the narrow opening. Imagine a room completely light-tight with the exception of somewhere in one wall a small lens of such focal-length that sunlight transmitted through it is focused into an image of the sun on the opposite wall of the room. If this lens is of the order of several inches in diameter, it will form a sharp image of the sun on the wall. More than 99% of the sunlight entering the room lies in the image of the sun. Now let us decrease the size of the lens and observe the effect on the sun's image. We shall see that the image of the sun becomes less and less distinct. Finally, with a lens of inappreciable aperture, the small amount of light still coming through the lens will be distributed throughout the room. The light intensity in the room will still be a maximum where the sun's image had been centered, and will fall off with

increasing angle from the original direction of the sunlight. At 90 degrees to the direction of the sunlight the intensity has fallen to zero. The distribution of the light within the room now reveals almost no trace of the original image of the sun.

The spreading of light from the edges of an aperture is called *diffraction.* Such studies of the phenomenon as we have described

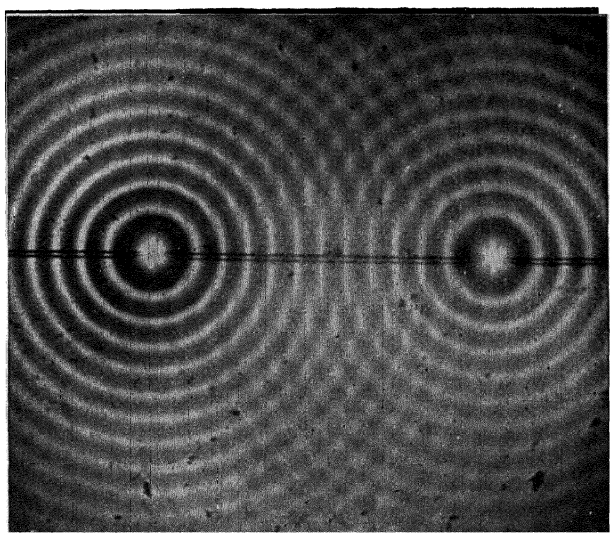


Fig. 3.—Interference of water waves.

The sources of disturbance are two small beads vibrating in a vertical plane in contact with the surface of the water. (*From Lemon and Ference's "Analytical Experimental Physics," Courtesy of University of Chicago Press.*)

prove that *any* point on the wave-front can be regarded as a source of light, from which light spreads outward in spherical wave-fronts. Our discussion of the last paragraph establishes this fact only for very small apertures. How are we to apply the principle to the motion of light in space?

We can return to our analogy with water-waves on the surface of a pond. If two separated sources of vibration are in motion at once (for example, two stones dropped into the water simulta-

neously and several feet apart), the wave-fronts from one source move through the wave-fronts of the other source. Although the identity of each wave-front is fully preserved long after the two

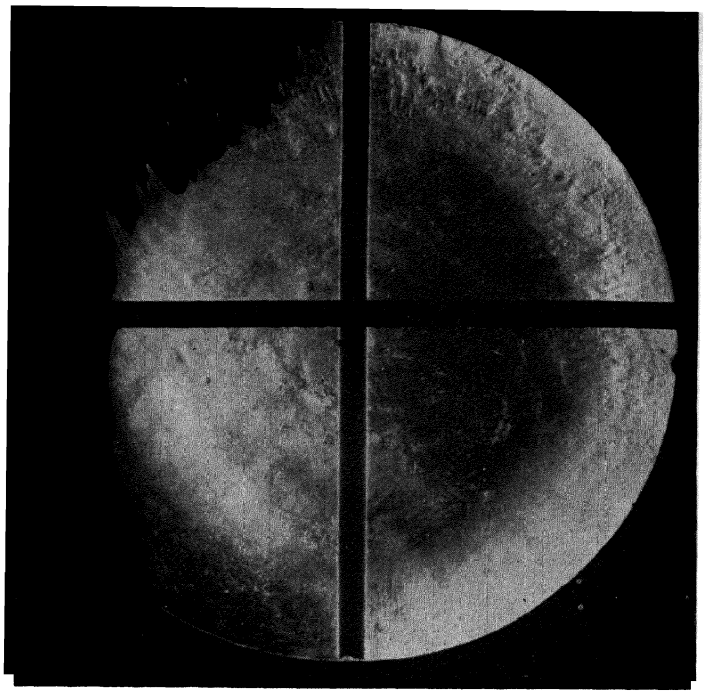


Fig. 4.—Focogram made of an old astronomical telescope mirror by means of a camera placed behind the knife-edge, focused on the mirror.

Of the two opaque strips at right angles on the surface of the mirror the one parallel to the knife-edge is bordered by diffracted light, the other is sharply defined. It is evident that much light has entered the poorly defined strip by diffraction; the sharply defined strip is black Note the detail shown by the focogram of defects in the aluminum film and glass surface.

waves have passed through one another, there takes place at the intersection of any two wave-fronts a phenomenon called *interference.* Wherever two wave-crests intersect, the up and down motion of the water is increased; but where the crest of one wave-

front lies in the trough of another of equal agitation, the water is undisturbed and no wave-motion exists. (Cf. Figure 3.)

In a traveling wave-front of light each point on the wave-front may be considered to emit a series of *secondary* waves. These waves so interfere with one another that the energy is transmitted along the perpendiculars to the original wave-front, but is completely annulled in every other direction in the "forward" hemisphere. The secondary wavelets do not exist in the "backward" hemisphere for it may be shown that they do not even get started.

The phenomenon of diffraction involves the incomplete interference of secondary wavelets at the edge of a light beam. (Figure 4.) The percentage of light energy lost from the original direction of a light beam is unimportant when the cross-section of the beam is large. When the cross-section is small, diffraction predominates, and there no longer is a sense of direction to the light beam, beyond that of a forward or a backward hemisphere.

Color

In 1666 Sir Isaac Newton in a classical observation demonstrated that white light is made up of component colors of what we now call the *pure spectrum.* Newton placed a glass prism in the path of sunlight coming through a small hole in his windowshade. Newton found that the beam of sunlight emerging from the prism resolved itself on the wall into a series of continuous colors ranging from deep red through orange, yellow, green, and blue, into deep violet. In order to ascertain whether these colors were properties of the light beam or of the prism, he sent the light through a second prism, inverted relative to the first. After so doing, he found that the light recombined into a white beam.

A century later Sir William Herschel found that a thermometer reads high relative to the surrounding air when placed beyond the deep red in the spectrum of sunlight; he concluded properly that the spectrum must continue into invisible regions of energy. Photographic observations show that the spectrum extends much farther on either side of the visual limits of red and

violet; indeed, further investigations indicate that the visual spectrum is but a single octave in a far greater compass of radiation phenomena.

The wave-length of a light-wave, where the pure spectrum is considered, bears a direct relation to the psychological phenomenon of color. Visible light has a wave-length quite small by ordinary standards of measurement. For example, green light has a wave-length of about 0.0005 millimeters. Visible light comprises the range of wave-lengths between 0.0008 (deep red) and 0.0004 millimeters (deep violet).*

The complete spectrum of radiation begins on the long wave-length side with radio waves. From the *long-wave* radio waves (10,000,000 millimeters) we pass through *short-wave* to deep infra-red; then to infra-red, red, orange, yellow, green (0.0005 millimeters), blue, violet, ultra-violet (0.0001 millimeters), into the X-ray and gamma ray regions (0.0000000001 millimeters). Astronomical observation, because of the lack of transparency of our atmosphere to shorter wave-lengths, is confined mostly to wave-lengths longer than 0.0003 mm.

For many purposes the "Angstrom unit" (A.) is a more convenient unit of length than the millimeter. One angstrom is 0.0000001 millimeters. Green light, therefore, has a wave-length in the neighborhood of 5,000 A. Likewise, the micron, or 0.001 millimeter, is often a convenient unit of length.

Interference and diffraction depend directly on the wave-length of the light. For example, a pinhole forty wave-lengths in diameter will diffuse transmitted light of corresponding wave-length by diffraction; but for ultra-violet light a pinhole forty waves in diameter would measure only 0.013 mm across; for long radio waves, it would measure several kilometers. Conversely, if we use a pinhole 0.030 millimeters in diameter, there will be considerable diffraction in visual light, practically no diffraction in far ultra-violet light, and total diffraction in the far infra-red.

* 25.4 millimeters to an inch.

X-rays are so short in wave-length that pinholes 0.010 mm in diameter cause no appreciable diffraction; consequently pinhole X-ray pictures reveal clearly details of the size of the pinhole.

Polarized Light

Let us return to the subject of water-waves on the surface of a pond. A cork floating on the water will bob up and down as the waves pass beneath it. The motion of the cork is at right angles to the direction of motion of the expanding wave. In the case of a vibrating string, a knot in the string moves up and down in a direction at right angles to the string. Such up and down motion is called a *transverse* vibration.

Sound waves in gases, liquids, and solids are of a different character. A particle taking part in the wave-motion vibrates back and forth in the line of motion of the wave. Such a medium as a whole contains compression regions between rarefactions, and the wave-motion is associated with pressure. Such a wave-motion is called a *longitudinal* vibration.

The particles partaking of a longitudinal vibration oscillate along a single line in the direction of motion of the wave; particles partaking of a transverse vibration move at right angles to the wave-motion, yet the plane of vibration requires still another quantity to define its orientation (that is, up or down, or sideways, etc.). In the case of surface waves on a pond the motion is definitely up and down. The plane of vibration is therefore perpendicular to the surface of the pond.

Early in the nineteenth century Fresnel proved that light vibrates transversely, and that it can be made to vibrate in a plane of any given orientation. A light beam vibrating transversely in a single plane is said to be *polarized*. Ordinary light from an electric lamp is composed of mixed wave-fronts and wave-lengths, vibrating in a mixture of planes. Polarized light consists of a light beam vibrating in one plane, although in this plane there may be a variety of wave-lengths.

The most familiar source of polarized light in modern life is the *polaroid* light filter, now generally available. Ordinary light of mixed polarization becomes polarized on passing through a sheet of polaroid; apart from inefficiency, 50% of the light is absorbed by the polaroid, and 50% is transmitted. The transmitted portion vibrates in a single plane which we may call the plane of vibration of the polaroid. If this transmitted beam is sent through another polaroid sheet, we encounter a striking phenomenon. As the second polaroid is rotated with respect to the first, the beam passing through both varies from nearly zero intensity to nearly full transparency (that is, to the 50% of the original light transmitted by the first polaroid). The beam that succeeds in getting through the pair of polaroids at any orientation is polarized in the plane of vibration of the second polaroid, but the intensity of this beam depends entirely on the orientation of the polaroids with respect to each other.

Observations of this kind show clearly that light must travel in transverse wave-fronts, inasmuch as a longitudinal vibration does not possess properties of polarization. Many natural crystals possess the property of polarization. The polaroid itself is merely an assembly of minute polarizing crystals (for example, herapathite or quinine iodosulphate) brought by ingenious chemical methods into a common plane of polarization.

According to the electromagnetic theory of light developed by Clerk Maxwell in the last century, the transverse vibrations we have so far discussed are related to the variation of electric and magnetic fields, which vary at right angles to one another. The concept of a plane of polarization requires one to specify the plane containing the magnetic field or the electric field. The plane of the other is thereby determined.

Reflection and Refraction

Many historical observations show that light in a vacuum travels in straight lines at a constant speed *independent* of color

and polarization. The velocity of light in vacuo has been found by Anderson to be 299,776 ± 14 kilometers per second. From distant celestial objects, red and violet light traveling through the near vacuum of interstellar space probably arrive in the same wave-crest in which the energy was emitted thousands of

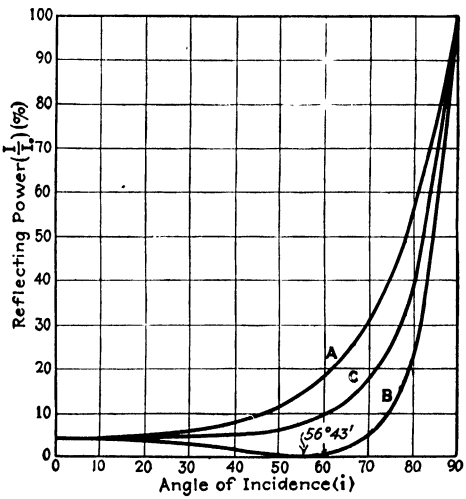


Fig. 5.—Variation of intensity of reflected light.

The variation of intensity of reflected light with angle of incidence for *A*-light polarized in the plane of incidence, *B*-light polarized perpendicular to the plane of incidence, and *C*-unpolarized light. (*From Hardy & Perrin, "The Principles of Optics," McGraw-Hill Book Company, Inc.*)

years ago. On the other hand, in material media not only does the speed of light change to a much smaller value, or values, depending on the particular medium, but it depends on color as well. The index of refraction (n) of a medium for laboratory purposes is a convenient way of expressing the retarding effect of a medium on the speed of light. Indeed,

$$n = \frac{\text{speed of light in air}}{\text{speed of light in medium}}.$$

When a beam of light passes from one medium into another at a smooth boundary, the light beam in general divides into two parts, one reflected, the other refracted. By means of the wave theory it is possible to derive the relative intensities of the two beams, and the result is found to agree well with observation. The reflected beam arises from the appearance of *back* secondary wavelets, non-existent except in the region of the disturbance at

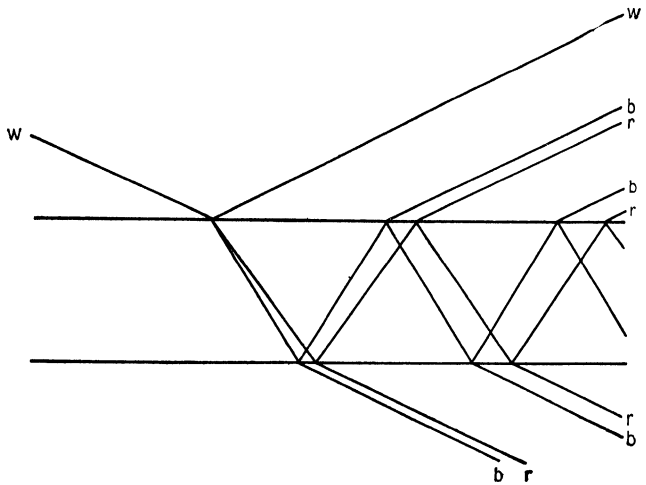


Fig. 6.—The refraction and reflection of a ray of white light by a thick glass plate.

The incident beam labelled W is on the top left.

an interface. Figure 5 contains a plot of the intensity of light reflected from a clean glass surface according to the angle between the perpendicular and the incident ray, known as the angle of incidence.

Figure 5 shows that at an angle of incidence of about 57 degrees for ordinary glass, (Brewster's angle), the reflectivity in one kind of polarization (where the plane of incidence contains the electric field) drops to zero. The reflected beam is therefore all of the other kind of polarization (where the plane of incidence con-

tains the magnetic field). Thus, a 57 degree reflection of mixed light from glass will produce polarized light. In practice, the presence of even slight traces of grease or of contamination with ordinary air prevents complete polarization in the reflected beam. In a vacuum, or from a glass surface for a minute or so after it has been chemically cleaned, the polarization is strikingly observable.

When a ray of light is reflected from a polished surface, the angle of reflection equals the angle of incidence. In the refracted beam the angle of refraction is related to the angle of incidence by Snell's law:

$$\sin i = n \sin r.$$

The index of refraction n is dependent on the wave-length or color of the light beam. Figure 6 shows what happens when a ray of white light strikes a thick plane-parallel glass plate. The beam is broken up into a series of refracted and reflected rays.

Quanta

By electrical methods it is observed that the impact of a light-wave on the sensitive surface of a photoelectric cell ejects a stream of electrons that can be attracted to a positively charged electrode, amplified, and made to perform a variety of tasks. Observations show clearly that the velocity of an ejected electron is quite independent of the intensity of the incident light beam.

If we cause a light beam of a single color, blue (monochromatic light), to fall on a photoelectric cell, the electrons will be ejected with but one specific velocity. As the light beam becomes more and more violet, the electrons leave with greater and greater velocity, but the entire group at the same velocity. If we let a beam of X-rays strike the photoelectric cell, the electrons leave with an extremely high but definite velocity. If we use the beam of monochromatic blue light again, but this time vary the intensity of the beam, we shall observe no change in velocity

of the ejected electrons, but only a variation in the numbers leaving.

The conclusions are that the number of ejected electrons depends solely on the light intensity, but that the velocity of the ejected electrons depends only on the wave-length of the incident light. When a beam of white light, comprising therefore a mixture of wave-lengths or heterochromatic light, strikes the photoelectric cell, we have a mixture of electron velocities, and the number of electrons leaving will depend on the distribution of energy with wave-length of the incident light.

The most important result derived from the photoelectric effect is that the energy in a light beam comes in individual packages or *quanta*. Except for a correction due to the work done in tearing the electron away from the surface of the photoelectric cell, an ejected electron has kinetic energy equal to the energy absorbed from the incident light quantum. Since a monochromatic beam of light produces a single velocity in the ejected electrons, it must be that the energy in the light beam depends on the wave-length; moreover, since each electron has exactly the same energy, the quanta must also have exactly the same energy, which is found to be inversely proportional to the wave-length.

The wave-theory of light provides no suitable explanation of the photoelectric effect. Therefore, we conclude that light is not made up alone of simple wave-motion, but must be of a more elaborate construction. Still another type of phenomenon that cannot be explained by the wave-theory is the ordinary photographic effect. Although this effect is less clearly understood than the photoelectric effect, it is nevertheless established that the nature of the blackening of a photographic grain can best be interpreted as arising from the absorption of energy packets or quanta from the incident light beam.

What Is Light?

No one has yet given a completely satisfactory picture of the nature of light. We have only a very precise description of its

behavior. Perhaps we should regard a light beam as composed of wavicles of energy called quanta, or photons. With each of these quanta is associated a definite amount of energy. Each photon is quite independent of every other photon in the wave-front as far as loss of energy is concerned; however, from phenomena of diffraction and interference we are forced to conclude that the

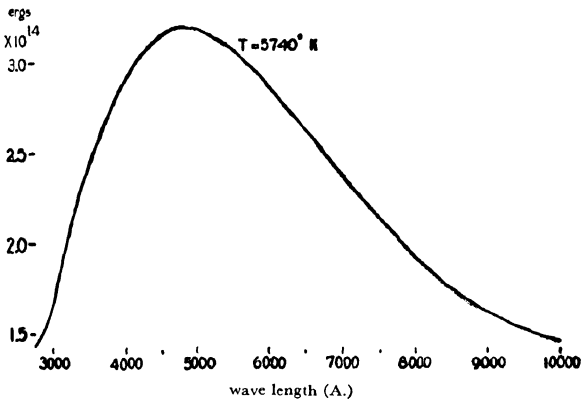


Fig. 7.—The curve above shows the distribution of light energy with wave-length emitted by any glowing solid, liquid, or gas under pressure, at the temperature specified.

The curve is derived by theoretical means to represent the radiation emitted by the sun. For a lower temperature, the maximum of the curve shifts toward the right and assumes a proportionately smaller value. Some stars are so hot that the maximum of the curve lies far off the left of the diagram.

photons vibrate transversely and therefore possess polarization, and that the photons are quite capable of interfering with one another constructively or destructively, although no energy is lost in the process.

It is not the purpose of this book to deal with the details of the emission and absorption of light by atoms or molecules.*

* Another book of this series, L. Goldberg and L. H. Aller, *Atoms, Stars and Nebulae*, deals with this subject.

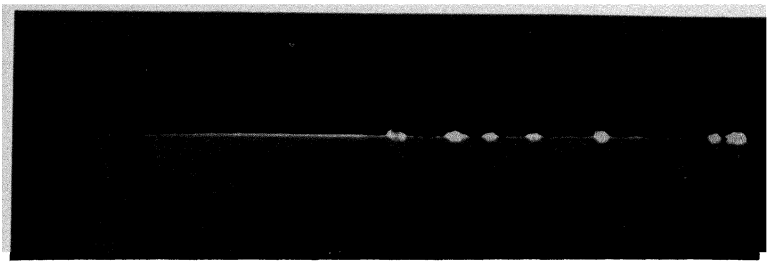


Fig. 8.—The spectrum of a planetary nebula. (N.G.C. 6543.)

The two overlapping nebulous discs at the right end are in the green. The last large broken disc to the left is ultra-violet and invisible to the eye. The horizontal narrow streak is the continuous spectrum of a star in the very center of the gaseous cloud comprising the nebula.

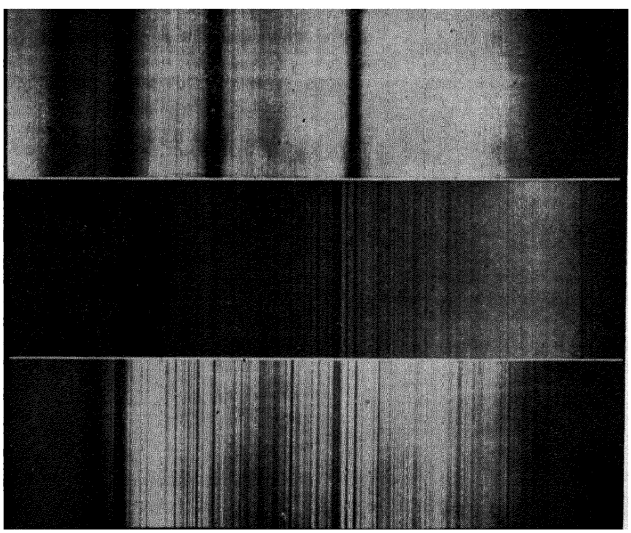


Fig. 9.—The absorption spectra of three kinds of stars.

The heavy lines in the top spectrum arise from cool hydrogen in the stellar atmosphere. Second of pair still obscure.

Suffice it to say, the light quantum remains a light quantum, unvaried in energy content, until it is absorbed or disturbed within or near an atom.

Light from radiating atoms would not provide much information unless the quality of light emitted depended on the nature of the source. The ordinary electric light, for example, produces a spectral range of colors with no gap at any point. The distribution of light intensity with wave-length is quite the same whether tungsten, copper, or some other metal is used at a specific temperature for a lamp filament.

A spectrum like that given by an electric light is said to be *continuous*. All glowing solids and liquids, as well as gases under high pressure, emit a continuous spectrum. The distribution of light intensity with wave-length as in Figure 7 depends almost entirely on the temperature and not on the nature of the substance.

In contrast to a continuous spectrum, a glowing gas under *low* pressure emits a large number of monochromatic lines with no intermediate radiation. The pattern along the spectrum formed by these lines is uniquely characteristic of the atomic constitution of the gas itself. Such a spectrum as shown in Figure 8 is called an *emission* or *bright-line* spectrum.

When a gas lies between the observer and a continuous light source hotter than the gas, the continuous spectrum of the light source is crossed by many dark lines. The line pattern is identical with the bright-line spectrum of the intervening gas, proving that the gas has absorbed the light energy in those wave-lengths. Such a spectrum, shown in Figure 9, is called an *absorption* or *dark-line* spectrum.

The spectrum is a key to the nature of the atom and of the celestial object of which the atom is a part. Indeed, all of the properties of light—diffraction, interference, direction, energy content, polarization, and quality—comprised within the spectrum lead us along the road to a detailed knowledge of the universe.

2

VISUAL TELESCOPES

ONE OF THE MOST IMPORTANT INVENTIONS OF ALL TIME IS THE telescope. Centuries have elapsed since the first crude instrument showed Galileo the moons of Jupiter, centuries that have seen much progress. The fundamental significance of the telescope, however, has not changed. The human eye, feeble in itself, by means of the telescope becomes powerful.

Until the discovery of photography astronomical telescopes were designed entirely for visual observation. Even today outside of professional use the telescope remains primarily a visual instrument, one that still enthralls the star-gazer. Many amateur astronomers use visual telescopes of their own making.

The visual telescope performs two fundamental functions. First, it must gather in starlight and convey this light to the retina of the eye. Secondly, it must form on the retina a sharp image of the celestial object under surveillance, an image greatly magnified relative to that formed by the unaided eye. The visual telescope customarily has three parts: the light-gathering objective; the eyepiece; and finally, the human eye. Since the human eye is the structure to which the telescope must be adapted, it is well that we consider the physical nature of the eye before we discuss the telescope.

VISION

The human eye is a complex optical instrument from a physiological point of view, but physically it is relatively simple.

Figure 10 is a diagram of the normal human eye. The six muscles on the outside of the eye are firmly attached to a tough outer layer; these muscles not only hold the eye in its socket, but also rotate the eye to any desired position over nearly a hemisphere. At the front of the eye the white outer layer merges into a transparent layer called the *cornea.* The cornea provides the greater part of the lens action of the eye. If the cornea departs from the spherical curvature needed for focusing sharp images on the retina, various defects in vision arise, many of which can be corrected by spectacles.

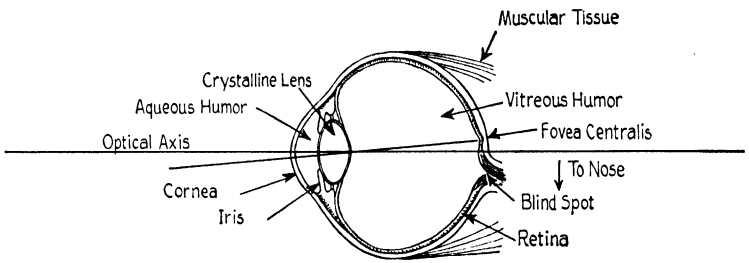


Fig. 10.—A cross-section of the human right eye.

Within the eye and along the path of entrant light are in succession the *aqueous humor*, the *crystalline lens*, the *vitreous humor*, and the all-important *retina.* The aqueous humor is essentially a slightly saline solution; the vitreous humor a watery jelly. The crystalline lens is a fibrous jelly, hard at the center and softer in its outer zones. The muscles shown attached to the crystalline lens are capable of adjusting the shape of this lens so that the image formed by the eye of an object at various distances can be focused sharply on the retina. With advancing age the crystalline lens slowly loses this power of *accommodation;* consequently, a person gradually becomes permanently short-sighted or far-sighted, according to the final shape of his cornea. The detail that an excellent eye can discern is limited somewhat more by the structure of the retina than by imperfections in its lens system. We can conclude that for most purposes the average eye, equipped

with suitable spectacles, is capable of forming a sufficiently sharp image on the retina.

The retina is essentially a fine-grained surface. We cannot hope to resolve details finer than the structure of the retina permits. It is here that magnification becomes important. A telescope is to the eye what a telephoto camera lens is to a miniature camera. The magnification by the telescope spreads out the image on the retina so that each small grain of the retina contains a smaller part of the image than before. Greater discernment of detail thereby results. For a near-by object the detail discernible by the unaided eye is greater than that obtained from the same object some distance away. Indeed, magnification is merely another way of saying that the object appears closer. Whether the object actually *is* closer or whether a telescopic lens has made it *seem* closer is of no importance as far as the retina is concerned.

The eye has the unusual property that the region of most distinct vision lies not on its optical axis but nearly three degrees to one side of the axis as seen from the center of the cornea. At this point of distinct vision there is a slight depression in the retina. The sharp field of view of the human eye is surprisingly small.* Consequently, the eye is continually roving about, examining the field of view for extra detail; when the range of rotation of the eye is insufficient for surveying an object, the head moves and then even the body.

The small region of distinct vision in the retina is called the *macula lutea* or yellow spot. Anatomical investigations show that this region contains a number of light-sensitive cells called *rods* and *cones*. The cones are predominant in the central part of the field of view and are replaced more and more by rods in outer zones. The retina beyond the macula lutea consists mostly of rods and clumps of rods. The very center of the macula lutea contains nothing but cones; this is the region of the *fovea centralis*

* You should ascertain the field of sharp vision of your own eye. See how far away these two crosses (+ +) must be before you can no longer look at one more critically than the other.

(about 0.25 mm in diameter). In the fovea centralis the cones vary in diameter from about 1.5 microns to 5.4 microns. The cones are not altogether contiguous, and therefore the resolving power or acuity of vision of the retina for foveal vision corresponds to the separation of the cones, or about 10 microns, for point images, and about 6 or 7 microns for line images. The impulses delivered to the brain over the optical nerve travel one at a time from individual cones.*

The threshold sensitivity of the retina (the ability to observe faint light) depends tremendously on the presence or absence of a substance called *visual purple.* In the daytime visual purple is lacking and the retina is relatively insensitive. At night or in darkness, especially after the eyes have been rested, the visual purple reforms and the eyes are extremely sensitive. At the same time the pupil of the eye varies in diameter and regulates the light needed by the eye in conformance with the amount of visual purple present.† The range of aperture of the iris diaphragm is only a factor of four in diameter and sixteen in area, but variations in the visual purple extend the range of sensitivity to a billion or more. The eye can adjust itself to viewing without discomfort a piece of white paper illuminated either by sunlight or by the light of a bright star. The range in the brightness of the source of light may be over ten billion times.‡

* The reader should make the following test for himself. A piece of red cellophane held over the right eye transmits only red light to the right retina; a piece of green cellophane over the left eye transmits only green light to the left retina. A white light will appear either red or green to the observer, or the color may alternate. In other words one eye is blind while the other is active.

† The visual purple is associated with vitamin A. Normal people have such a store of this vitamin that several months of deficiency diet may be required to exhaust it; when visual purple is absent, the subject has night-blindness, a condition of reduced retinal sensitivity.

‡ Rods are more sensitive to light than cones. A star-gazer soon becomes familiar with the phenomenon of *averted vision.* Images of luminous surfaces, for example, far off the center of the fovea, although not sharply defined, fall on clumps of rods that send a collective impulse to the brain. Whereas the

The cones of the eye are individually connected to the optical nerve and thence to the brain cells. Consequently, if two starlike points on the fovea are so close together that the light from both strikes the same cone, the brain can distinguish but a single point of perhaps double brightness; but if the starlike points fall on separate cones, then the brain perceives them as separated and the points are resolved.

Telescope Objectives

The most important function of the telescope objective is to collect light for the eye or photographic plate. For visual purposes a second important function is to magnify the object under surveillance, so that difficulties other than the structure of the retina limit the resolution. For both purposes it is of fundamental importance that the image of a point-object in space like a star be as sharply defined as possible.

Two types of telescope objectives are widely in use at the present day, the reflector and the refractor. Figures 13 and 14 show cross-sections of the two kinds in their simplest forms.

The simple refracting telescope contains a lens or objective at one end of the telescope tube. The image formed by the lens is at the other end of the tube where a magnifying glass called the eyepiece enables the eye to examine the image critically.

The reflector forms an image at the upper end of the telescope tube by means of a concave mirror called the primary mirror, which is located at the lower end of the tube. The light must therefore traverse the length of the tube twice before reaching the focus. A fundamental difficulty of the reflector is that the image lies in the path of the approaching light. In order to bring the focal plane into a more convenient observing location, one may insert a small plane mirror or prism, called the secondary, into the converging light beam. The focal plane is thereby shifted to the side of the telescope tube.

energy absorbed by a single rod may be insufficient to send an impulse to the brain, the energy collected by a clump of rods may be sufficient to do so.

Since the simple lens is composed of a single variety of glass, the various spectral colors are focused at different points along the optical axis, as shown in Figure 11. Accordingly, there exists a considerable color aberration in the image of a star viewed through such a simple lens. This lens error, called *chromatic aberration* or sometimes *primary spectrum*, has the property that the size of the image in any color at some point of best mean focus on the axis depends geometrically only on the diameter of the lens and not at all on the focal-length. When the focal-length is increased for a given diameter of object glass, the geometrical

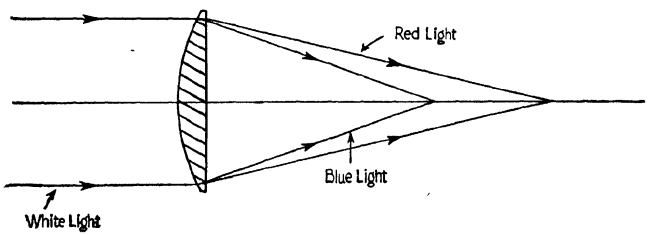


Fig. 11.—The chromatic aberration of a simple lens.

color aberration at the focus is unaffected, but the diameter or size of the planetary or nebular image at the focus is increased; accordingly, the color defect subtends a smaller fraction of the image, and greater detail becomes discernible in the object.

When the wave nature of light is considered, the focal-length must also be taken into account. A long focus simple lens actually yields better resolution than the geometrical concept of rays would indicate. Newton was once involved in debate on this very point. Indeed, the focal-length can be increased to such an extent that the color error becomes concealed in the image formed by diffraction. The focal-length of a simple lens objective with unobjectionable color aberration is necessarily large and is given in inches with sufficient accuracy by the formula

$$f = 100D^2,$$

where D is the linear diameter of the objective in inches. If only

the unreal concept of rays of light were considered, one would arrive at the approximate expression

$$f = 1000D^2$$

which, evidently, is much too severe. This formula is based on the maximum useful magnification of $50D$ and on the resolving power of the eye.

In the seventeenth century refracting telescopes often were made of prodigious length in order to correct for the chromatic aberration of the simple lens. In many cases the astronomers were forced to dispense with tubes. The lens was squared on as well as possible to the line of sight; many feet away the patient astronomer groped for the image.

Chester More Hall about 1733 discovered that by combining a crown glass collective lens with a flint glass dispersive lens it is possible to make the combined lens achromatic (without color). John Dollond in the period around 1759 was the first to produce such achromatic lenses. Up to his time the refracting telescope was none too useful, either because of the color errors or because of the awkward mountings needed to accommodate enormous focal-lengths. For a given color error Dollond's telescopes (if fully corrected), were approximately $\frac{1}{20}$th as long as a simple lens telescope of equal performance at the same magnification.

Sir Isaac Newton believed erroneously that the color dispersion* of glasses is *exactly* proportional to the index of refraction less one (i.e., $n - 1$), which would lead to the result that a combination of two glasses can never produce a colorless lens. Newton was both right and wrong. The color-dispersion curves of glasses differ sufficiently to make it possible to choose lenses of crown and flint glasses so that the combination is about 95% achromatic. The residual 5% (mostly red and blue) may be termed the *secondary spectrum.*† It is impossible, however, to make a

* For example, the difference in index of refraction between red and blue light.

† The owner of a refracting telescope may easily observe the effects of secondary spectrum by using a method due to Sir G. Stokes. The telescope is first

two-element objective completely achromatic with optical glass of the usual sort. There exist a few combinations of glasses that have a residual color equal to only 1% of the equivalent simple lens, but in general such lenses require very steep curvatures of the surfaces. Combinations of a few kinds of natural crystals are even more achromatic, but can as yet be used only for lenses of very small diameter.

The easily attained 95% correction of the modern objective is sufficient for smaller instruments. The 5% color residual is, however, an obstacle to the users of large refractors and is very troublesome indeed in photographic cameras used for covering a wide range of wave-lengths. In the absence of perfect achromatism the best procedure is to correct the lens for the color of greatest importance.

Figure 12 shows the variation of sensitivity of the retina with color. The maximum sensitivity of curve *A* comes in the green at wave-length 5500A. Under conditions of low illumination the maximum of the curve shifts to the left. Visual telescopes are ordinarily corrected for the green region.

The ratio of focal-length to lens diameter is called the *focal-ratio* or *f*-number of the telescope. Since the *f*-number is a measure of the light concentration afforded by the telescope, it is a measure of the speed and effectiveness of the lens. Visual telescopes as a rule have focal-lengths between 15 and 20 times their aperture. In practice we therefore speak of *f*/15 or *f*/20 telescopes.

Several advantages accrue from a choice of about *f*/15 for a refractor. First of all, it should be noted that the visual refractor is ideally suited to the study of fine detail in planetary images. The performance of a lens is many times less sensitive to flexure than that of the mirror of a reflector, small errors in the lens surfaces during manufacture are much less important, and temperature effects are not so troublesome as in the reflector. The lens ab-

focused on a bright yellow star, and then one-half of the telescope lens is covered. The various out-of-focus red and blue rays coming through the eyepiece ordinarily blurred together are then well segregated.

sorbs or scatters less light in practice than a two-mirror reflection,* and is likewise more or less permanent. Since ordinarily only the first lens surface can become dirty, the telescope rarely needs dismounting for cleaning. Moreover, the inherent imper-

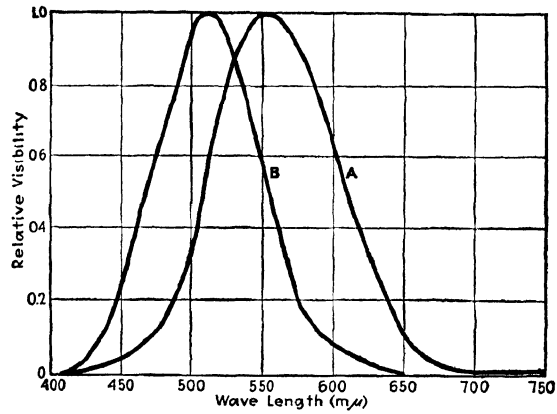


Fig. 12.—The sensitivity curve of the retina of the eye.

Curve *A* represents the sensitivity at normal levels of illumination. Curve *B* represents the sensitivity at low levels of illumination. Both curves are plotted on such a scale that the maximum is unity. (*From Hardy & Perrin, "The Principles of Optics," McGraw-Hill Book Company, Inc.*)

fections of both objective and simple eyepiece are negligible a $f/15$, although not at $f/5$ or less.

* The objective lens of many refractors of small size is composed of crown and flint lenses "cemented" together with Canada balsam. Cementing the internal surfaces of crown and flint, necessarily of the same radius, prevents loss of about 9% of the light by reflection; moreover, there is no possibility of flares or ghost images in such a cemented lens. Large refractors cannot bear the strain of cementing because of differences in expansion and contraction with temperature between crown and flint and because of markedly increased flexure. Consequently, there are four glass-air surfaces. Such a lens transmits about 82% of the incident light (but see Appendix I). Except for losses from silhouetting, a two-mirror reflecting telescope *freshly* silvered is nearly as efficient.

The only important aberration or optical imperfection of a well-designed visual refractor is the *secondary spectrum*, the 5% color residual discussed above. This defect is important because it limits definition at the very center of the field of view. Unless the builder of a refracting telescope has special requirements in mind, he will do best to keep to $f/15$. For a refractor to be used only for the study of critical planetary details $f/15$ is still not quite long enough; $f/20$ is better. (See Appendix IV.) As a rule the $f/15$ choice is an admirable compromise. The secondary color aberration, like the primary color error of the simple lens, when expressed in linear size of image error in the focal plane, is again independent of focal-length but dependent on the diameter of the objective. When the focal-length is increased, the color aberration in terms of seconds of arc becomes smaller.*

Because of the wave nature of light the secondary spectrum, though bad enough, is not as detrimental as the concept of light traveling in mathematical rays would suggest. The focal-length of an achromatic objective with unobjectionable color aberration is given with sufficient accuracy by the formula

$$f = 5D^2.$$

A three inch objective at $f/15$ obeys this formula. Its color is evident only when a large color range is visible, as in the case of a bright object outlined against a dark background.

Table 1 contains recommended glasses and approximate curves for both cemented and uncemented objectives. The ordinary cemented objective of telescope crown and flint is slightly inferior in optical performance off the axis to the uncemented objective which has four air-glass surfaces. There are

*A small yellow filter may be included in the eyepiece. The purpose of such a filter is to transmit only the sharply focused yellow-green, and to absorb the defectively focused blue and red. Filters of the required type are relatively inefficient, even in the yellow-green. They cut down the light intensity and should be used only if sufficient light is available.

four possible forms of about equal correction for such an unseparated objective of crown and flint glass. The best astronomical combination is called the *Fraunhofer* objective, shown in Figure 13. The so-called *Harting* objectives are cemented and yet as fully corrected on and off the optical axis as the four surface type. Such good correction is made possible by combining glass pairs other than ordinary crown and flint. For example, a light barium

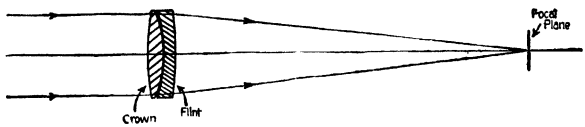


Fig. 13.—The Fraunhofer objective.

crown and flint will produce such a fully corrected lens. Since large cemented objectives suffer impaired definition from flexure and thermal changes, the Harting objectives are useful only in relatively small telescopes and auxiliary instruments.

TABLE 1

The objectives listed below are corrected for visual use. They are all designed from catalog indices of refraction for Bausch & Lomb optical glass types BSC-2 and DF-2. The BSC-2 glass was chosen for the front element because of its extreme hardness and resistance to aging. Type BSC-2 has an index of refraction in sodium light of 1.5170; type DF-2 has a corresponding index of 1.6170. The ν-values are 64.5 and 36.6, respectively.

All of the figures below are given in units of the equivalent focal-length. For example, one needs only to multiply the tabulated values of radii and thicknesses by the focal-length in inches to obtain the radii and thicknesses in inches. Positive radii are curved toward the eyepiece, and negative radii toward the distant light-source.

All four objectives listed are about equally well corrected for color, and are designed for best correction for spherical aberration at $f/15$. The use of precisely spherical curves leaves in the performance a slight residual spherical aberration known as zonal aberration. The usual Foucault test will show its presence if the objective is of large diameter. A slight amount of zonal figuring will render the final image as good as diffraction at $f/15$ will permit. (Cf. Chapter 4 for undefined terms.)

a. Cemented Type: Corrected for spherical aberration, but not for coma.

b. Cemented Type: "*b*" has only 40% of the zonal aberration of "*a*." Its coma is about equal in magnitude but opposite in sign to "*a*."

recent attention has turned to rhodium, whose average reflectivity is about 80%.

The films of metal are ordinarily about a wave-length of light thick. Since any irregularity in a well deposited film will likely amount to but a small fraction of a wave-length, the optical performance of the mirror surface will not be marred significantly by silvering or aluminizing.

The single-mirror telescope has several advantages over the refractor. Since it is completely achromatic, one may work in light of any color. Furthermore, in view of the property of perfect achromatism, the focal-ratio can be made smaller with consequent reduction of the tube-length. This practical advantage is very important. The building of a 20-inch aperture refractor with a 300-inch telescope tube and large dome is a major undertaking. The building of a 20-inch aperture reflector with a 100-inch tube is relatively easy and in fact has been accomplished by a number of amateurs, who must necessarily work with limited facilities. The usual choice of focal-ratio for a professional reflector instrument is $f/5$,* but for small reflectors it can be almost anything. The great practical advantages of the reflector in comparison with a refractor are cheapness and possible size. Since the light never enters the glass behind the silvered or aluminized reflecting surface, low quality but well annealed glass can be employed. Such glass can be cast into discs of enormous size. The largest *reflector* in operation in the world today is 100 inches in diameter; and everyone by now knows of the current building of the 200-inch telescope. The largest *refractor* in the world, on the other hand, is the 40-inch of the Yerkes Observatory.

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protected; they can be washed with detergents and distilled water at long intervals. When the reflectivity of the mirror falls below 70%, the film should be renewed.

* In order to save tube-length the 200-inch telescope is to be $f/3.3$. See Appendix III for data on mirrors larger than 30 inches in diameter.

Since the focus of a parabolic mirror lies in the way of the on-coming light beam, one must sacrifice some light in order to put an eyepiece, diagonal mirror, or a photographic plate at the focus. With very large instruments what is known as the primary focus on the axis of the tube is often used for the sake of efficiency. The 200-inch telescope is so large that the observer and his equipment will all be placed inside the telescope tube at the primary focus in the way of the on-coming light. Only about 10% of the incident light must be lost in the reflector by such *silhouetting* by observer and equipment. Smaller instruments usually have a diagonal *flat* mirror near the prime focus to

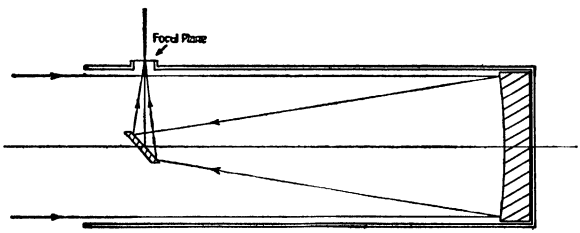


Fig. 15.—The Newtonian telescope.

divert the focal plane off to the side of the telescope to a place convenient for both visual and photographic use. This point is called the Newtonian focus, proposed in 1672 by Sir Isaac Newton. One thereby loses both about 7% from silhouetting and 15% from the extra reflection. Nevertheless, this loss is not serious for many purposes, unless the two mirrors have tarnished films. Auxiliary instruments like the photoelectric cell or spectrograph can be fastened in place on the side of the tube, when used at the Newtonian focus, without obscuring more light.

Another arrangement of the reflecting telescope employs a hyperbolic mirror inside the prime focus to form a new focal plane at the bottom of the telescope through a hole in the primary mirror.* This type, shown in Figure 16, is called the Cassegrain-

* In some mounts as in the 100-inch Hooker telescope the primary has no hole, but the Cassegrainian focus is diverted to the side of the tube by means of a

ian telescope, after its inventor of the seventeenth century. The image is formed sufficiently far beneath the telescope mirror to shield the eye or the photographic plate from the direct light of the sky. This position of the focus is even more convenient than the Newtonian for the use of auxiliary instruments. The

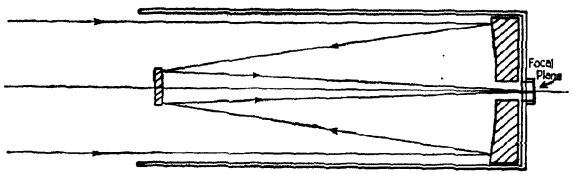


Fig. 16.—The Cassegrainian telescope.

observer can easily reach the focus, and can guide the instrument with convenience.

Like the Cassegrainian type is the Gregorian of Figure 17 named after its inventor of the seventeenth century. Instead of the convex hyperbolic mirror, the Gregorian employs an elliptical concave mirror beyond the primary focus. In performance the Gregorian is somewhat superior to the Cassegrainian, but has the disadvantage of needing a much longer telescope tube. Conse-

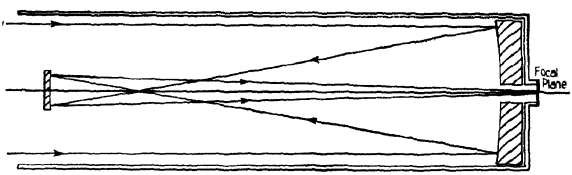


Fig. 17.—The Gregorian telescope.

quently, the Gregorian is almost never used. On the other hand, the Gregorian mirror is easier to make.

Sir William Herschel employed a mirror of such long focal-ratio that he was able to tilt the mirror *off-axis* without appre-

flat mirror. The arrangement is therefore similar to the Newtonian telescope, but may fairly be called the *Nasmyth*. (Suggested in 1851.)

ciably destroying image quality, and thus observed from the side of the tube. In Herschel's day an extra mirror meant a large loss of light. His speculum metal mirrors reflected only 60% of the incident light. Two mirrors plus an eyepiece would have delivered only 30% of the incident light to the eye. The Herschel type with fresh silver film (Figure 18) used with a single convex lens eyepiece is unquestionably an efficient telescope. The Herschel type is sometimes constructed by amateurs but almost never by professionals because of their wider demands on instruments. Even the amateur should be careful not to make a Herschelian type of low focal-ratio because of the rapid appearance of image

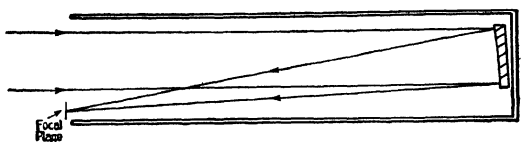


Fig. 18.—The Herschelian telescope.

aberrations off the optical axis. The Herschel type may be either a mirror of large *f*-number tilted off-axis or an off-axis portion of a paraboloid.

In order to put the focal plane in still more convenient places for observation other mirrors may be added. A most practical type called the *coudé* employs a plane mirror at the intersection of the declination and right ascension axes of the telescope. This mirror diverts the rays from the Cassegrain mirror down the telescope polar axis to a focus *in a fixed position*, where stationary instruments of almost any size can be mounted on the solid floor of the observatory, and laboratory studies made of light from the stars. Visually, the observer may look into an eyepiece from a fixed and comfortable observing station. The field of view of the instrument must slowly rotate about the polar axis, but visually this is of no concern. It is true that inefficiency is involved in the extra mirror systems, but the advantages frequently outweigh the disadvantages.

Eyepieces

We now come to the other essential part of the visual telescope, the eyepiece. In its simplest form the eyepiece is only a magnifying glass, and consequently enables the eye to see an image sharply over an enlarged angle of vision. (Figure 19.) The ordinary eye can view an image comfortably in focus from a distance of about ten inches. The magnifying glass permits

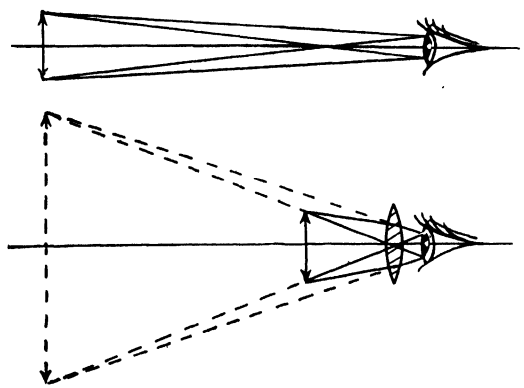


Fig. 19.—The nature of the magnifying glass.

the eye in effect to get a number of times closer to the object. The eye then sees the image subtending a much larger angle, yet the focus is as sharp as before.

The telescope forms an image of a distant object in the focal plane. The eyepiece used as a magnifying glass enables the eye to survey this image as critically as possible. The amount of telescopic power, called the *magnification* or angular enlargement of the object, is simply the ratio of the focal-length of the telescope objective to the focal-length of the eyepiece ($m = F/f$). For terrestrial purposes a magnification of a hundred, for example, of an object seen through a telescope is equivalent to viewing the same object with the naked-eye from a point one-hundredth of the distance. An idea of the possible detail may be obtained

from this example. A boy a mile distant viewed through a telescope under 100 power appears to be but 50 feet away. A boy 100 feet away, viewed through the same telescope, appears as large and distinct as if he were a foot away. Stars, however, are so far away that magnifications up to the limit permitted by the resolving power of atmosphere and telescope combined are still incapable of revealing stellar discs.* Planets and satellites, on the other hand, can be considerably enlarged. A crater on the moon, viewed in a large telescope under 2000 power, appears to be only 120 miles away.

The range of magnifying power available to a telescope depends on the focal-lengths of the various eyepieces employed. That is to say, the image formed by the telescope can be viewed under low or high power magnifying glasses with corresponding magnifications of the object.

Since the prime purpose of the visual telescope is to collect light for the eye, it is essential that all of the light from a given star collected by the telescope objective enter the eye. At night, the iris opening of the eye is very nearly eight millimeters. Somehow, light from a star collected by a large telescope must be squeezed into eight millimeters at the eye and, in order to be brought to focus on the retina, it must be nearly parallel light on entering the eye. The visual telescope fortunately can meet this requirement.

The eyepiece receives rays of light sent to it by the objective and as a separate optical system forms an image of the objective, small compared with the objective itself. If the focal-length of the eyepiece is 20 mm and the objective is $f/5$, the image of the objective formed by the eyepiece is a disc 4 mm in diameter. All

* The 200-inch telescope under perfect atmospheric conditions may reveal slight discs for stars of largest angular diameter. *R* Hydrae, at maximum diameter, for example, is about 300,000,000 miles in diameter, and about 1,000,000,000,000,000 miles away. Thus its diameter subtends an angle at the earth of one part in 3,000,000 or $0''.065$. The resolving power (see below) of the 200-inch for discrete points is $0''.023$ when the atmospheric turbulence is negligible.

of the light sent out by the telescope mirror or lens and intercepting the eyepiece must pass somewhere through this 4 mm image, since it is light proceeding from an object to an image. But the light we are interested in is starlight. Consequently, if we focus the eyepiece to produce parallel emergent rays from any star in the focal plane, the pencil of parallel rays of starlight emergent through the eyepiece must be 4 mm in diameter and can therefore enter the eye.

Figure 20 reveals graphically the work of the eyepiece. If the iris of the eye is placed at the 4 mm image of the objective, the light collected by the objective that strikes the eyepiece must

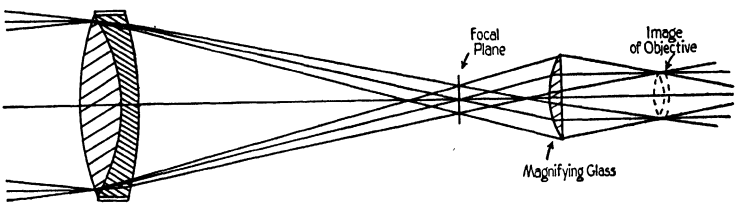


Fig. 20.—The magnifying glass as an eyepiece.

enter the eye. The image of the objective must therefore be behind the eyepiece where the eye can reach it. The Galilean type of telescope (with negative lens inside focus) cannot form a real image of the objective and consequently, the eye cannot be placed in such a position as to see all the light gathered by the objective at any one time. The field of view of the Galilean telescope is therefore very limited.

If we place a positive lens called the *field-lens* exactly at the focus of the objective, as in Figure 21, this lens will have but small influence on the magnifying power. On the other hand, this lens intercepts a much larger cone of rays from the objective and diverts them through the *eye-lens* and hence through the eye. Thus, the field of vision is extended.

The useful range of eyepiece focal-lengths in use with a given objective is limited above by the size of the opening of the eye and below by either the atmospheric turbulence or the spreading

out of the available light under higher power. Indeed, since the eye at night is never open more than 8 mm or about ⅓ inch, the lowest useful magnifying power is three times the aperture in inches. (The image of the objective formed by the eyepiece is about 8 mm in diameter.) Thus, a six-inch telescope should not employ a magnifying power less than 18, for a lower power would merely reduce the effective aperture of the telescope. For an $f/15$ refractor this principle requires a focal-length of 5 inches for the lowest power eyepiece. A useful upper limit to the magnifying power may be taken as 50 times the aperture in

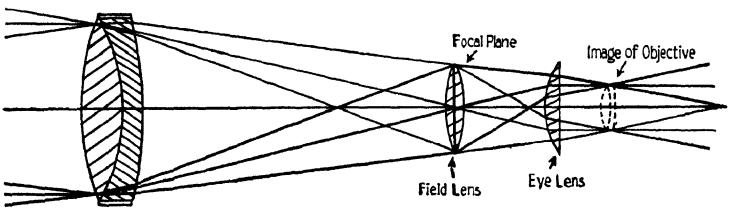


Fig. 21.—The nature of the field lens.

inches. Thus, this same six-inch $f/15$ telescope should not use a power greater than 300, or about a ⅓-inch eyepiece.

The *field of view* of the telescope as a whole depends on the focal-length of the objective and the focal-length of the eyepiece, and therefore on the magnifying power, m. If the focal-length of the eyepiece is f, the diameter of the field in its focal plane surveyed by that eyepiece is $\frac{1}{2}f$ approximately. (Some eyepieces have a greater field of view; it would be unfair, however, to say that an eyepiece has a large field, if the outer part is so poor as to be unusable.) The linear field in the focal plane corresponding to an angle θ on the celestial sphere given by a telescope of focal-length F is $F\theta$. Thus, we have

$$F\theta = \frac{1}{2}f \quad \text{or} \quad \theta = \frac{30^\circ}{m} \text{ approximately.}$$

The angular field of view therefore becomes smaller with increase of power, as one would expect. The Yerkes 40-inch refractor

(760 inches focal-length) with a one-inch eyepiece covers a field of less than 3′ of arc (30°/760) in the sky.

Types of Eyepieces

The field-lens placed exactly in the focal plane of the eyepiece and telescope objective has the disadvantage that any dust or scratches on its surface are brought into ugly prominence by the eye-lens, and mar the telescopic performance. Consequently, the field-lens should be shifted either in front of or behind the focal plane of the telescope.

Any lens may have two types of color aberration. The first of these corresponds to each color coming to a focus at a different point on the optical axis. A star image on the axis of an uncorrected lens will be a point surrounded by a color halo. The halo is of similar appearance anywhere in the field. We may call this color defect type *A*, identical with the *primary spectrum* of the objective. The second color aberration involves the variation of focal-length with color. A star image at the edge of the field looks like a short spectrum or streak of color directed toward the center of the field. The effect is proportional very nearly to the distance of the star from the center of the field. We may call this type *B*. In eyepieces type *B* is more serious than type *A*. The presence of type *A* is nearly immaterial because of the small aperture of the eye. The presence of type *B* is objectionable because of the large field of vision desired.

In 1703 Huygens proposed a type of eyepiece widely in use even today. Figure 22*a* shows a cross-section of this popular type. Because the focal plane lies between the lenses, the composite lens cannot be used as a magnifying glass. The Huygens for this reason is often called a *negative* eyepiece. Although it would be possible to mount cross-wires in the focal plane between the lenses, the cross-wires would show strong color effects (Type *B*) in the outer parts of the field. Consequently, the Huygens eyepiece is never used for precision measurements. When the field-lens is in the position shown in Figure 22*a*, the color error

(type *B*) of the field-lens cancels that of the eye-lens with a resultant nearly colorless performance. Thus, stars in the outer part of the field of view will not look like short spectra, as in the case of the simple lens eyepiece. On the other hand, since both lenses are positive, the color errors (type *A*) on the optical axis are additive; at *f*/15 the Huygens performs sufficiently well; but, at *f*/5 its type *A* color errors are quite noticeable.

In 1783 Ramsden proposed a second type of eyepiece also widely in use today. Figure 22*b* shows a cross-section of this

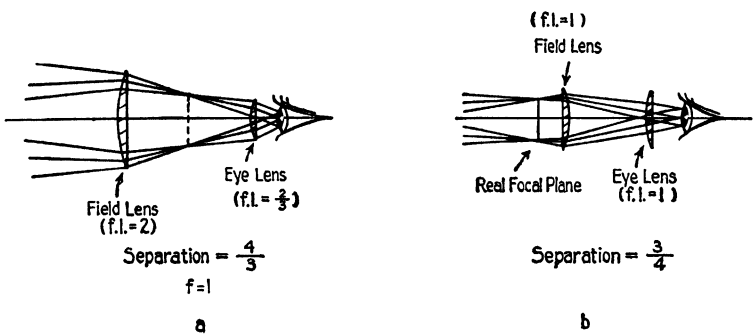


Fig. 22.—(a) The Huygens eyepiece. (b) The Ramsden eyepiece.

useful type. In this eyepiece the focal-plane lies before the field-lens. Consequently, the eyepiece may be used as a simple magnifying glass, and thus is called *positive*. Cross-wires mounted in the focal plane show much less color than if a simple lens of equal power were used (type *B*). However, the Ramsden eyepiece is not as highly corrected for type *B* as the Huygens for objects viewed through the telescope. The color errors along the optical axis (type *A*) are smaller than in the case of the Huygens, since a given power of the eyepiece can be obtained by weaker positive lenses. Consequently, the Ramsden at *f*/5 performs better than the Huygens at *f*/5.

In 1849 Kellner proposed a somewhat more complicated type of eyepiece. (Figure 23*a*.) In order to overcome the color

defects, he achromatized the eye-lens by use of a flint and crown combination. By turning the flint lens toward the eye, he was able to obtain a highly corrected and color-free performance. Although it would be desirable to achromatize the field-lens also, this is almost never done. The eye-lens, for the sake of light efficiency, is always a cemented pair.

The above three types of eyepieces are not as convenient in practice as one would desire. Although the experienced observer does not mind placing his eye close to the eye-lens in order to

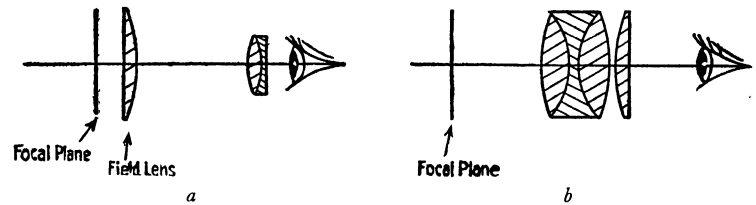


Fig. 23.—(a) The Kellner Eyepiece. (b) The Orthoscopic eyepiece.

reach the image of the objective, the average user tends to hold his eye rather far from the eye-lens, and thus loses part of the field. Moreover, if the user wears eye-glasses, he will be unable to place his eye near the eye-lens. Consequently, it would be desirable to form the image of the objective at a greater distance from the eye-lens.

The type of eyepiece called the Abbe *orthoscopic* (Figure 23*b*) is really but a complex eye-lens without field-lens. The eye-lens is so large in diameter, however, that it intercepts a very large portion of the field-rays. The image of the objective is about as far from the eye-lens as the focal plane of the telescope is from the eye-lens on the opposite side. Consequently, for a one-inch eyepiece the eye may be three-quarters of an inch behind the eye-lens, a rather convenient distance. The orthoscopic eyepiece properly designed can yield a fairly large, highly-corrected, colorless field of view. It is to be recommended, in spite of its expense, as a fine eyepiece to go with a telescope used by the public.

Comparison of Lens and Mirror Objectives

The gain in performance of the lens objective over the mirror objective is due to the complexity of parts and freedom from aberrations caused by flexure, but not particularly to the superiority of the lens, as far as image errors of a refracting compared to a reflecting surface are concerned. A single refracting surface would be optically no better than the single mirror, and in addition would have color errors. The compound lens, having three or four effective surfaces, can be highly corrected for image errors on and off the optical axis. But a three-mirror system properly designed would give even better performance, except for the silhouetting, which cannot, like chromatic aberration, be overcome. On the other hand, if we consider the practical matter of the accuracy needed in making optical surfaces, we find that the single lens surface is about one-fourth as sensitive as a mirror surface for the same image quality. Suppose that we have a mirror and lens with equally accurate surfaces. An angular error in the perpendicular at a point in a mirror surface is doubled in the reflected ray; an error in the perpendicular at any point in a lens surface is divided by either two or three, depending on whether the light is emerging from or entering glass; in the final image in air the divisor is two. Consequently, for the same performance a mirror surface must be four times more accurate than a lens surface.

When a single mirror surface in a telescope flexes, its optical performance is immediately affected. When a lens flexes, the positive flexure of one side cancels out very nearly the negative flexure of the other. Hence a lens is very insensitive to flexure. Those who say that the making of a refractor is too difficult for the average amateur are in error. The making of four spherical surfaces, each to a given accuracy, will in combination yield sharper star images on axis than a single parabolic mirror of the same surface accuracy. Moreover, the refractor can employ spherical surfaces, although certainly not of arbitrary radii,

with consequent gain in precision and ease of making. The steeper curves of the refractor surfaces, as long as they are spherical, ensure great smoothness and accuracy with minimum figuring.

Two of the principal difficulties experienced by the amateur in producing a good refractor have been the use of inferior lens curves and optical glass. The curves given in Table 1 will prove to be good first approximations for the types of optical glass specified. Larger lenses often suffer from variations of index of refraction within the discs. The surfaces of the larger refractors made by Clark depart on a microscopic scale rather considerably from spheres in order to compensate as nearly as possible for imperfect glass.

Summing up, we find that for visual purposes the great advantages of the reflecting telescope are freedom from color, simplicity in mount and manufacture, and resultant cheapness. The sharpness of image provided by the refractor is usually slightly superior to reflector definition in practice because of insensitivity to flexure and temperature, accuracy in manufacture, and freedom from diffraction patterns caused by secondary mirrors in the incident light beam. The optical aberrations of eyepieces, especially the Huygens, show up more with an $f/5$ reflector than with an $f/15$ refractor. Thus a perfect $f/5$ mirror might seem inferior to a perfect $f/15$ refractor with the same positive or negative eyepiece. Finally, the great focal-length of the refractor provides high magnification without too powerful an eyepiece. But we must not overlook the fact that a properly made and properly mounted $f/5$ mirror can give sufficiently satisfactory performance for most purposes.

Visual Limiting Magnitude

The question is often asked as to how faint one can see with a telescope of given diameter. The maximum diameter of the pupil of the eye is about $\frac{1}{3}$ inch. Consequently, a telescope of diameter D inches produces a light gain over the unaided eye

of about $9D^2$. Converting this into stellar magnitudes (see Chapter 6), we find that if the unaided eye can see to 6.2 and if m be the limiting magnitude through the telescope, then

$$m = 8.8 + 5 \log D^*$$

This expression holds only under good atmospheric conditions and must be decreased by an amount depending on the magnifying power and atmospheric turbulence, as well as on the efficiency of the telescope. The 100-inch telescope, for example, should render stars of magnitude 18.8 visible, but in bad seeing, this limit may drop to 16 or even brighter. The Yerkes 40-inch refractor under good conditions should show stars of magnitude 16.8.

Resolving Power

The image of a star formed by a perfect telescope is not a pure mathematical point but instead is of definite diameter depending on the aperture and focal-length of the telescope, or more strictly, on the focal-ratio. The diffraction theory of light provides us with a simple formula for ascertaining the resolution of a given lens system. If the linear diameter of the telescope objective is D inches, then

$$\text{resolution} = \frac{4.56}{D} \text{ seconds of arc (Dawes' rule)}$$

By definition the resolution is the smallest distance between the centers of two star images that can be distinguished as double. If the separation of the star images is smaller than the value given

* *Diam. inches*	*m*	*Diam. inches*	*m*	*Diam. inches*	*m*
1	8.8	3	11.2	6	12.7
2	10.3	4	11.8	10	13.8

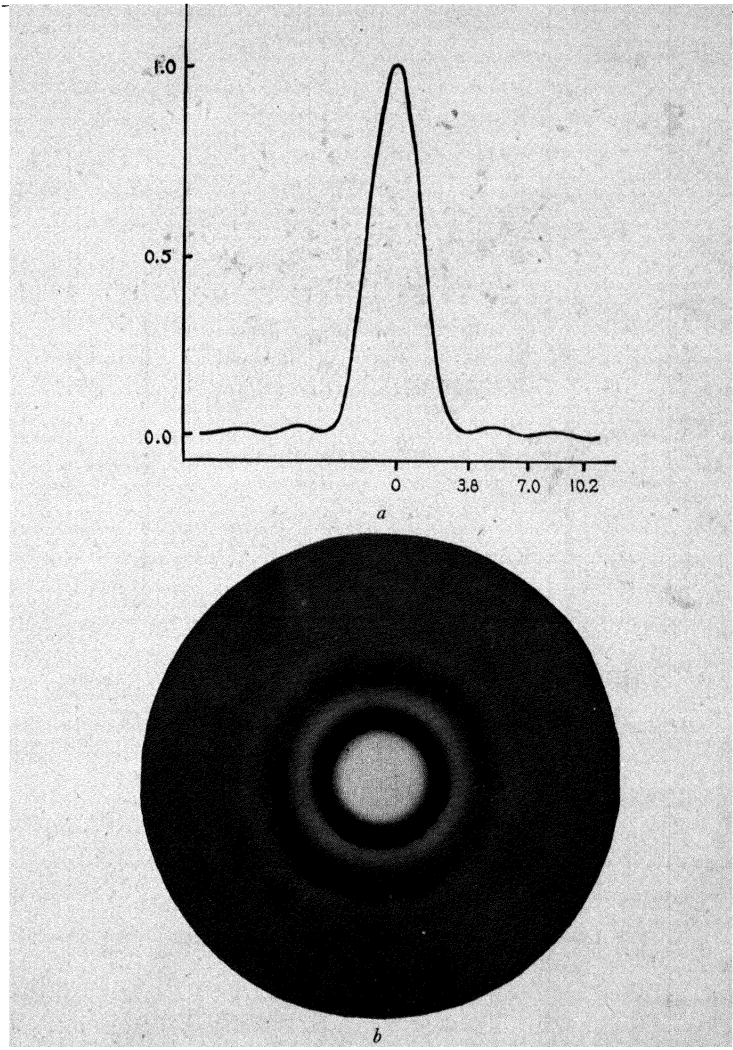


Fig. 24.—(a) The cross-section of the diffraction image of a point-source. (b) A greatly enlarged photograph of the diffraction image of a point-source.

(From Monk's "Light Principles and Experiments." McGraw-Hill Book Company.)

above, the common image of the stars may be either elliptical or just circular and therefore totally unresolved.

The diffraction image of a star formed by a perfect telescope under perfect atmospheric conditions is shown in Figures 24*a* and 24*b*. The central blur is called the spurious disc of the image, and this disc is surrounded by an indefinite number of diffraction rings of successively lower intensity. About 86% of the starlight goes into the spurious disc and the rest into the diffraction rings.

The above formula indicates that the 40-inch Yerkes refractor should be able to resolve stars as near as 0.11 seconds of arc to one another, a figure substantiated by observation. A perfectly made 40-inch reflector under ideal conditions should be able to resolve stars just as close.*

The various mechanical devices employed to support the secondary mirror of a Newtonian or Cassegrainian telescope cause diffraction lines to appear in bright star images. Notwithstanding their occasional conspicuousness, the total intensity of such lines is but a small percentage of the incident light in the image. Only over-exposed star images show them on a photographic plate, and such star images are ordinarily not used in researches on the stars. In some cases, however, the diffraction lines are annoying, as in the attempt to detect a faint companion to a bright star. One must rotate the vane system that supports the secondary mirror until the faint star appears between the diffraction lines. In planetary observations such diffraction images cause a slight loss of contrast. Couder has found that if the supporting fins are suitably shaped, the resultant diffraction pattern will resemble that given by a circular aperture. (See *Amateur Telescope Making, Advanced.*)

To every kind of geometrical aperture whether triangle, circle, or rectangle, there corresponds a definite diffraction pattern. By study of the diffraction patterns reproduced in Appendix

*In practice the resolving power will depend somewhat on color, magnitude, and magnitude difference of the stars.

VII, one can see how to retain resolving power while reducing the light-gathering power. Observations of the transits of Mercury in the past have employed to their disadvantage the simple *stopping-down* of telescope aperture. The resultant diffraction pattern between Mercury and the sun's limb caused by reduced aperture prevented accurate determination of transit time. It would have been much better if the astronomers had reduced the sun's intensity by reflecting the light from an unsilvered surface somewhere in the optical system.

3

STORING LIGHT—THE PHOTOGRAPHIC PROCESS

IT IS NOT POSSIBLE TO GIVE EVEN A BRIEF ACCOUNT OF THE development of the telescope without devoting some space to the development of the photographic process. The application of photography to astronomy introduced not only a change in observational technique, but brought about fundamental changes in telescope design that ushered in the era of the photographic reflector of large aperture, the large field refractor, and recently the fast Schmidt-type lens-mirror combination.*

The first successful application of photography to astronomy was made in March, 1840, within a year of the announcement of the newly developed daguerreotype process, by Dr. John William Draper of New York, who obtained a daguerreotype of the moon. Ten years later (July 17, 1850), George Phillips Bond and John A. Whipple obtained the first photograph of a star with the aid of the visual telescope of 15-inch aperture at the Harvard College Observatory in Cambridge, Massachusetts (Figure 25). Although the results were obtained with considerable difficulty and it was possible to photograph only the brighter stars, the advantages of the photographic over the visual method of observing were apparent even at this early stage. In a letter†

* See Chapter 4. Also see Appendix III-VI for lists of large telescopes.

† A personal letter from George Bond to William Mitchell; E. S. Holden, Bond Memorials, p. 154.

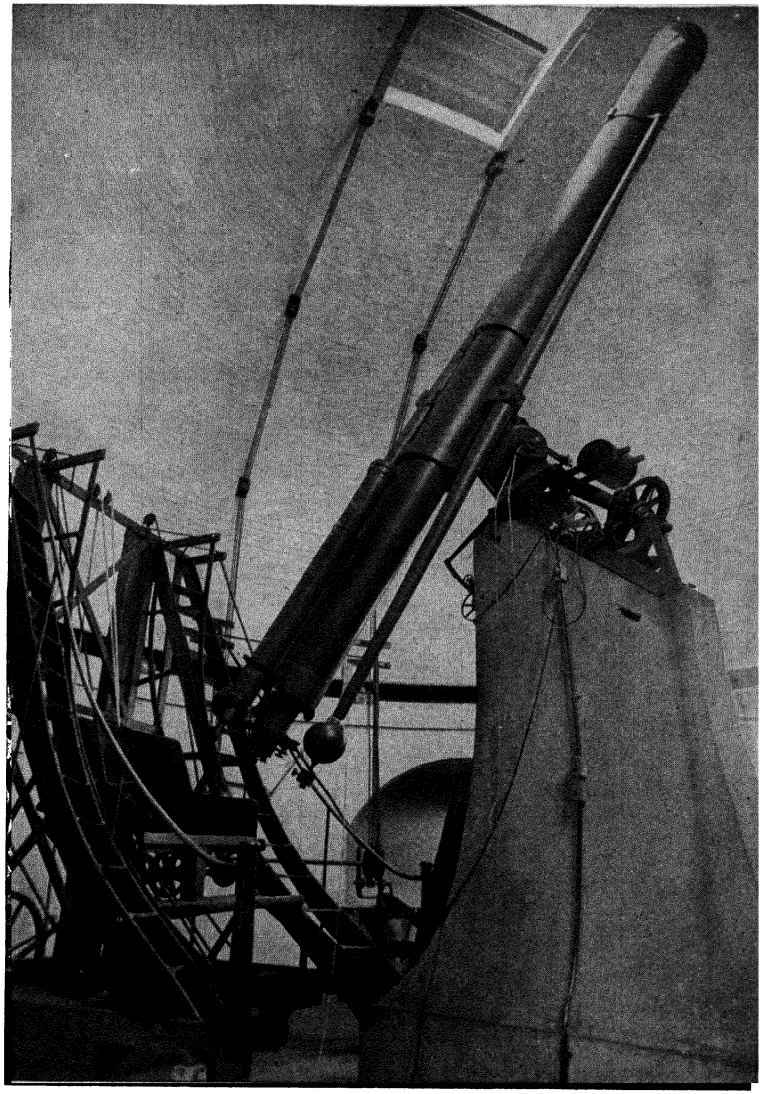


Fig. 25.—The 15-inch refracting telescope of the Harvard College Observatory, Cambridge, Mass.

With this telescope the first photograph of a star was taken by Bond and Whipple in 1850. (*Photo by Robert G. Cox.*)

dated July 6, 1857, Bond, the father of astronomical photography, writes as follows: "Of the beauty and convenience of the photographic process, you will scarcely form a correct idea without witnessing for yourself . . . On a fine night the amount of work which can be accomplished with an entire exemption from the trouble, vexation and fatigue which seldom fail to attend upon ordinary observations, is astonishing.

"The plates,* once secured, can be laid by for future study by daylight and at leisure. The record is there, with no room for doubt or mistakes as to its fidelity." That is, indeed, the great advantage of the photographic method of observing. It provides the astronomer with means of *storing* away the starlight until some future time when he can make thorough and perhaps repeated studies.

The experiments of Bond and Whipple were continued, and as the photographic technique improved, the Harvard Observatory began the systematic photography of the sky. Thus came into existence the great collection of astronomical photographs which at present contains nearly half a million original negatives —an invaluable and irreplaceable record of the sky for the past half century.

The successful adaptation of photography to astronomical observations is due to a great extent to the thorough appreciation of the causes of failure as well as to the skill and perseverance of the early pioneers. One of the greatest difficulties that accompanied the early experiments was the fact that a considerable length of exposure was required to make a photograph even of the brighter stars. It was apparent that the photographic material then in use was very insensitive, or as we commonly say, *slow;* but against this shortcoming there always stood out the great advantage of the photographic method, namely the cumulative action of the light-sensitive material. While to the eye a prolonged

* Astronomers still use glass plates instead of film as they are in some ways more convenient to handle.

observation does not make an object appear brighter or clearer, the photographically sensitive material accumulates the light which falls upon it so that the longer we expose, the stronger the recorded image. (Figure 26.)

During long exposures, however, it is difficult to keep the telescope pointing exactly at the star, which appears to move continuously along its diurnal circle because of the rotation of the earth. The introduction of a good driving mechanism

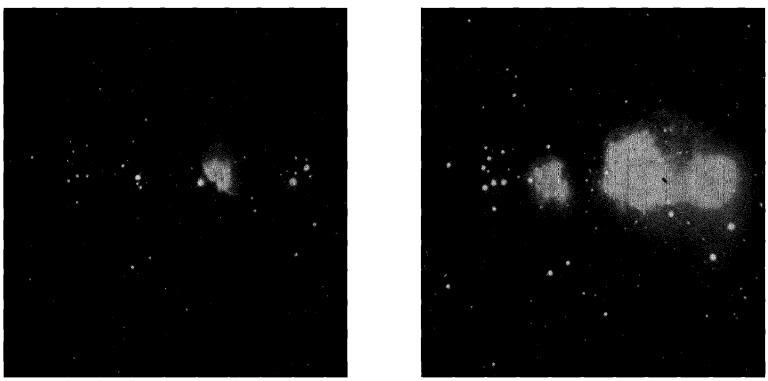


Fig. 26.—Two photographs of the Orion Nebula with exposures 3 minutes and 3 hours, respectively.

(see Chapter 8) was the first step necessitated by the photographic method of observing. Even more important than the driving mechanism was the improvement in the optics of the telescope. The visual telescope of long focal-length (see also Chapters 2 and 4) is not suited to photographic work. A visual telescope has usually a large focal-ratio, and is designed to bring to a good focus the yellow-green light to which the eye is most sensitive. The ordinary photographic material, however, is most sensitive to the blue-violet light. Thus again we find the need for specially designed telescopes for photographic work. Such considerations and many others rapidly accelerated the development of fast photographic telescopes which have

kept abreast and in many ways ahead of developments in photography.

The Photographic Process

The photographic process consists of three principal parts: the *photochemical action of light*, the *development*, and the *fixing*. The photochemical action of light occurs when light gathered by the telescope lens or mirror impinges upon the photographically sensitive material, and produces an impression. In the case of normal exposures this absorbed light produces no visible

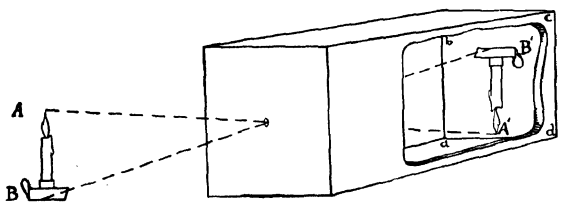


Fig. 27.—The pinhole-camera.

effect, and is called the *latent image*. Development is the chemical or physical process by which the latent image is made visible. Fixing is the last step whereby the developed image is made permanent.

Preceding all this, of course, is the fundamental requirement that we have a mechanism for producing an image of the object we wish to photograph. The simplest method for forming an image is the pinhole camera, Figure 27. A light-tight box with a pinhole in the side facing the object AB will suffice. Light rays from a point A on the object will reach only point A', and similarly light from a point B will fall only on B'. As a result upon the wall *abcd* there will be formed an image of the object (the candle stick in this case) which we wish to photograph. This image as viewed in Figure 27 will be reversed left for right and will be upside down. Such an image can readily be observed from the outside, if the back or focal plane of the box is made of ground glass. There is one great difficulty with this

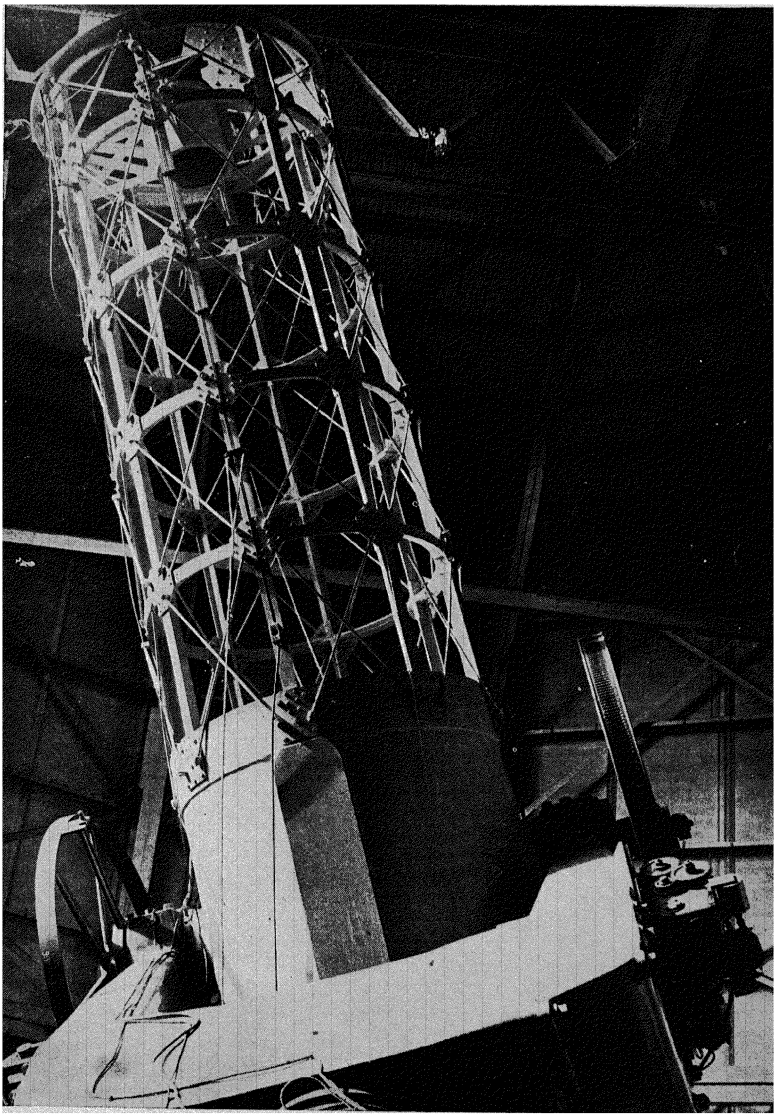


Fig. 28.—The 61-inch telescope at the Oak Ridge Station of Harvard College Observatory.

(*Photo by Reed.*)

box camera, namely, that the pinhole aperture is too small to admit much light and the image is very faint. The first improvement is to introduce a lens which because of its greater aperture, has the advantage of greater light-gathering power. A modern photographic telescope is just such a camera equipped with a telescope lens or mirror. Since most of the work is done at night, the counterpart of the box is frequently not light-tight but consists of a skeleton tube (see Figure 28) that holds the photographic plate in the focal plane at the proper distance from the mirror surface.

The Photochemical Action of Light

Even primitive man must have noticed the photochemical action of light as manifested by the bleaching or fading of color and by the tanning of the skin under the action of sunlight. Many early writers allude to this fact, while Johann Heinrich Schultze demonstrated as early as 1727 that silver salts, which are the basic material in modern photographic practice, darken upon exposure to light. In the early part of the nineteenth century many experiments were performed with sufficient success to deserve mention as the forerunners of photography. Nevertheless, the credit for a practical method of making a photograph which reproduced the original object with sufficient fidelity, goes to the French scene and panoramic painter, Louis Jacques Mandé Daguerre. His process, the daguerreotype, was highly successful and yet so simple that it captured the popular imagination almost at once after it was made public by the French government in 1839.

Because the daguerreotype process was the first photographic process of real importance and because it clearly demonstrates the three principal steps of the photographic technique, it will be useful to describe it briefly.

A silver plate or a copper plate covered with a thin layer of silver is placed in the fumes of iodine. The resultant silver iodide surface is sensitive to light; that is, after the plate is exposed in the

camera, there appears upon the silver iodide surface a faint impression of the image. Daguerre's real contribution was the discovery that he could bring out or develop this faint image by holding the exposed plate over a receptacle of boiling mercury. The mercury vapor deposits more readily on the parts of the plate where light has fallen, so that a silvery image is obtained upon a purplish background.

The final step is the *fixing* in order to make certain that any further action of light or developer will not affect the plate. This is done by washing the plate in common salt solution or better still in a solution of sodium thiosulphate commonly known as *hypo.** To summarize this process we have: first, exposure to light to form the latent image; second, development with mercury; and finally, fixing.

The Emulsion

Modern sensitive material is no longer a silver plate covered with silver salts. Instead, the silver salt crystals are held in gelatin much like the fruit in a fruit jelly, except that the silver salt crystals are very numerous and very small, the average size being 0.2 microns or of the order of 8 millionths of an inch in diameter. This suspension of silver salt crystals in gelatin, called the emulsion, is prepared with utmost care and accuracy, for the photographic properties of the final product depend mainly on the composition, the size, and the condition of the silver salt crystals. The chief salts in use are the halides, silver bromide, chloride, and iodide. The bromide emulsion is prepared by adding slowly a solution of silver nitrate to a solution of potassium bromide and gelatin. The resultant silver bromide is held in suspension by the presence of the gelatin. The emulsion is next *digested* by treatment with heat or ammonia in the *ripening process.* The effect

* The action of thiosulphate was discovered as early as 1819 by the English astronomer, John Frederick William Herschel, son of the great German-English astronomer, Sir William Herschel. This salt was thought by Herschel to be sodium hyposulphite, hence the name, hypo.

of this is to increase the size of the crystals and to increase the sensitivity from 100 to 1000 times. This sensitizing action is partially due to the presence in the gelatin of minute quantities of sulphur which, during the process of ripening, form small specks of silver sulphide on the surface of the silver bromide grains. The emulsion is then chilled, shredded and washed in cold water to remove the soluble potassium nitrate and leave only the sensitive silver halide salts. Finally the emulsion is coated on glass, film, or paper, depending upon the use to which it is to be put. Because small batches of specially sensitized emulsion can be conveniently coated on glass and because glass is rigid and does not shrink or swell during or after exposure or development, glass is commonly used for astronomical and spectroscopic purposes. For general pictorial work, however, the emulsion is coated on a film base, cellulose nitrate or acetate, because of its flexibility, light weight, and toughness.* The thickness of the glass base varies from 0.06 inches for the ordinary 8 × 10 plate to 0.19 ($\frac{3}{16}$) inches for a 30 × 40 plate, while the film base ranges in thickness from 0.0033 inches for ordinary film to 0.0079 inches for cut film. Motion picture film is approximately 0.0055 inches thick. The sensitive emulsion is only 0.0012 to 0.0016 inches thick. For some special astronomical purposes where the plates are used for measuring accurately the position of celestial objects, the emulsion has been coated on glass half an inch thick in order to minimize warping of the plate when the emulsion dries after coating and after development. In the process of developing, the emulsion swells during wetting and shrinks again during drying, thus setting strains which cause the glass or film base to

* Since the emulsion does not readily adhere to cellulose film, the film is first coated with a substratum or "sub" which contains an adhesive as well as a solvent. Often the sub affects slightly the characteristics of an emulsion. This accounts for occasional differences between an emulsion coated on glass compared with the same emulsion coated on film. No sub is used on glass, but the glass plates are sometimes washed with soda which slightly etches the surface, and causes the emulsion to adhere better.

bend or curl. For this reason some glass plates and most films are coated on the back with hardened gelatin whose shrinkage upon drying just balances that due to the emulsion, thus keeping the film straight.

Often emulsions are protected by an *overcoat* or *anti-abrasion* layer because the emulsion is very sensitive to mechanical action.

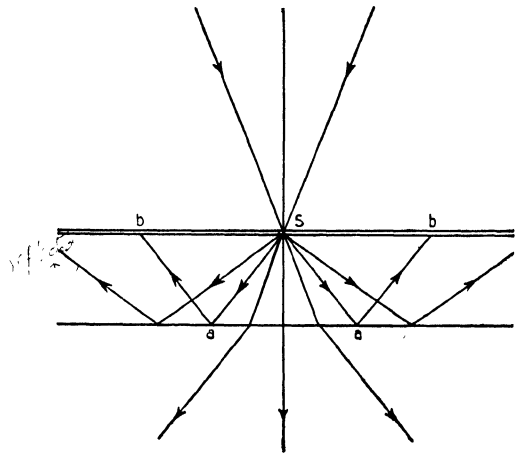


Fig. 29.—The star image is formed on the emulsion at S which becomes a source of illumination over a wide angle.

Rays, closer to the axis than *Sa* pass approximately 96% into air and 4% reflected. Rays outside of *Sa* are totally reflected, since their angle of incidence exceeds the critical angle whose direction is *Sa*. The star image *S* lies, therefore, at the center of a nearly clear circular area of radius *Sb*, beyond which a dark smear of decreasing intensity is formed.

Such overcoating is found especially on film-pack emulsion where the chances for scratching are fairly large. Sometimes the emulsion is made with two layers: the bottom layer (the layer next to film base) is usually slower than the outside layer and serves the double purpose of extending the *latitude* or useful exposure range of the emulsion and of reducing *halation.*

When a beam of light strikes the surface of an emulsion (Figure 29), it is scattered within the emulsion and strikes the glass suppor

or film base at different angles. All transmitted rays striking the glass-air surface of the plate at an angle greater than a certain critical angle will be reflected back and will re-enter the emulsion, producing a halo around the original spot where the primary beam had entered. To prevent this halation the plates are backed by pigmented coating which is decolorized during the process of development. The action of the dyed coating is to absorb the light of the particular color to which the emulsion is sensitive. Thus, yellow sensitive (orthochromatic) emulsions are backed with red material which absorbs blue and green light, while the dark green backing of red sensitive (panchromatic) emulsion absorbs the red and blue light.

When exposed to light the emulsion is affected in a manner not fully understood, but in such a way that the effect depends on the amount of light that has fallen upon the silver halide grains. The grains which have been affected by the light will be reduced to metallic silver if the emulsion, after exposure to light, is immersed in a *developer.* Such grains are said to be *developable.* The silver salts that have not been affected by the light will not be reduced to metallic silver. Corresponding to the bright portions of the original object, we thus have black portions, and vice-versa. Finally the plate is bathed in hypo which dissolves the unaffected silver salts leaving transparent those portions which have not received any light. The resultant picture when viewed by transmitted light is an exact reversal of the original object and is called a negative. If this negative is now placed over a piece of film or paper which has been coated with a sensitive emulsion, and light is allowed to shine through the negative, the dark portions will cast a shadow and the transparent portions will transmit the light so that after development the second film will be the reversal of the first, and will present the same pattern of light and dark areas as the original object. This second photograph is called the positive. The advantage of the modern process is that as many positives as desired can be made from the original negative. As we shall see presently,

the *characteristics* of the emulsion, that is, the ability of the emulsion to give a true representation of the light variations in the original image, depend not only upon the emulsion itself but also upon the method of treatment at each individual step in the complex photographic process. Thus the amount and the color of the light, the color sensitivity of the emulsion, the type of developer, the method of developing, fixing and drying, as well as the physical conditions of humidity, temperature, etc. at the time of exposure and development, all contribute to the final result. The intermediate steps in the process of printing give a great amount of freedom of manipulation and are a distinct advantage to the technician in pictorial photography, in that they permit of varying effects in the final print. These intermediate steps are nevertheless of distinct disadvantage in accurate photometry for in every successive repetition of the process we are likely to introduce additional uncertainties. For this reason in astronomy one seldom, if ever, uses anything but the original negative for measurements.

Development

Although certain facts concerning the mechanism of development have been established, the exact action of the developer in reducing the developable silver halide grains without affecting the grains that have not been rendered developable is not perfectly clear. The developing agent is, chemically speaking, a reducer, i.e., it oxidizes in the presence of compounds and liberates free metal. The grain consists of a positively charged silver ion and a halide. The reducing agent takes the negative halide from the silver salt and provides a negative electron to the positive silver ion, thus forming metallic silver. But while all developers are reducers, not all reducers are developers, for a developer is a reducer that distinguishes between exposed and unexposed silver halide grains. This discriminating action is connected in some way with the presence of gelatin, for silver halide crystals produced without presence of gelatin can be

reduced by ordinary developers even though they have not been exposed to light. On the other hand the action of the developer is a matter of time, for as we prolong the development, the unexposed portions of the emulsion begin to develop, producing general blackening of the plate or *fog*. The developers therefore are reducers so chosen that their rate of reduction of exposed silver halide grains is greater than their rate of reduction of unexposed grains.

There are two general methods of development which are commonly distinguished by the name *chemical* and *physical*. The resultant metallic silver images produced in the emulsion by either process are exactly the same chemically, but it is the method of reduction that causes the distinction. In the chemical developers the silver for the final image is supplied by the silver halide of the emulsion itself, while the physical developer contains silver salt in solution which is reduced to metallic silver and is deposited upon the nuclei formed by the latent image. A developer contains the following constituents:

1—developing agent
2—preservative
3—accelerator
4—restrainer

The majority of the modern photographic *developing agents* have their origin in the aniline and phenol dyes, the base of which is benzene. The photographic developing agents are the *colorless* dyes or the *reduced* form of dyes and dye intermediates, the chemical formulas of which are beyond the scope of this book.*

The developing agents are fairly stable when dry, but in solution they oxidize rapidly and hence require some form of *preservative* to increase their storage life. The most commonly used preservative is sodium sulphite, although in some formulas bisulphite or metabisulphite is used. The action in either case is

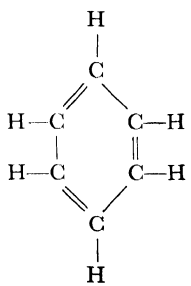
*An example of the derivation of some of these compounds can be found in the following illustration. The benzene molecule consists of six carbon and six

essentially the same. The sulphite oxidizes rapidly into sulphate and since the oxidation of the sulphite is more rapid than that of the developing agent, the deterioration of the developer is retarded. The amount of preservative varies with different formulas from three times to ten times that of the developing agent, but even a small amount of sulphite has a tendency to improve the keeping quality of the solution. In some cases, as in Metol-Hydroquinone developer, the presence of a second developing agent helps to improve the keeping qualities of the first. Such a developer ordinarily calls for two developing agents, one of which is Hydroquinone. If mixed without the Hydroquinone the fresh developer will show very little difference in its developing action. It will, however, oxidize much more rapidly than the normal developer in which Hydroquinone is included.

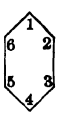
On the other hand the sulphite preservative also helps the action of some developing agents which are not so energetic in the absence of sulphite. The sulphite also acts as a solvent o

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hydrogen atoms and has the following structure



which is represented simply thus.

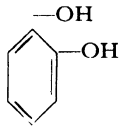


By substituting radicals or groups for one or more of the hydrogen atoms, chemists have derived numerous developing agents. Thus the substitution

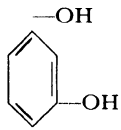
the silver halides, thus increasing the separation of the grains in the emulsion and decreasing the clumping of neighboring silver deposits. This gives the developer *fine-grain* characteristics.

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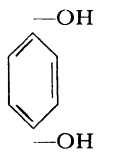
of two hydroxyl groups (OH) in the one-two, one-three and one-four positions gives the following.



Ortho-hydroxy-benzene or Pyrocatechine
(an unstable developing agent)

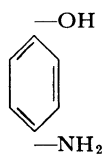


Meta-hydroxy-benzene or Resorcinol
(not a developing agent)



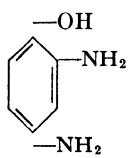
Para-hydroxy-benzene or Hydroquinone
(a developing agent)

If the amino (NH_2) instead of the hydroxyl groups are introduced, we obtain:



Paraminophenol
(the base for Rodinal developers)

or



Diaminophenol or Amidol developer

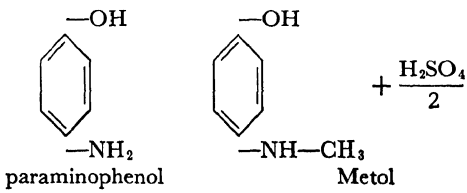
An example of a more complicated compound is the developing agent commonly known as Metol. If one hydrogen atom of the *amino* group in the

The action of the developer generally increases with an increase of alkalinity; for this reason the alkali in the developer is called the *accelerator*. Sodium carbonate is commonly used as an accelerator but is occasionally replaced by borates and phosphates, especially in developers which are used at higher temperatures. Under such conditions the carbonate from the developer when carried over into the acid fixing bath will react with the acid, forming dioxide bubbles known as *blisters*. Borates and phosphates do not form gases under similar treatment. The use of special alkali depends upon the formula recommended, but in general it is better to use a weak alkali at higher concentration than a strong alkali at lower concentration. This gives a better chance for controlling the alkalinity and forestalls any change in the alkalinity owing to possible reaction of the carbon dioxide of the air with the hydroxide.

The action of the developing agent, as we have seen, depends upon the difference in the rate of the development of exposed and unexposed silver halide grains. To produce greater differential in rate a *restrainer* is used, such as potassium bromide, chloride, and even iodide. Once again the exact action in differentiating between exposed and unexposed silver halide grains is not clear, yet experience shows that the background fog, the blackening of the unexposed mass of silver halide grains, is restrained more readily than the latent image, thus increasing the desired differential in the development.

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paraminophenol is replaced by a methyl (CH_3) group, we have monomethyl-paraminophenol, the sulphate of which is *Metol*.



"Fine-grain" Developers

It has become increasingly popular to speak of fine-grain emulsions and fine-grain developers in connection with pictorial work, especially in connection with miniature camera work. This quality, however, is no less desirable in scientific photography and especially in astronomy, for one of the most useful properties of the finished photographic picture, negative or positive, is its resolution. If we consider the picture pattern as made up of individual silver grains, no smaller detail can be represented than the silver grains or clumps of grains from which the pattern is made. The graininess or, more properly, the granularity or clumpiness of the silver, for we are now considering particles of a size many times larger than the original silver halide grains, depends primarily on the original size of the emulsion grains. Thus for a given emulsion the size of the halide crystals increases in the ripening process in proportion to the speed or the sensitivity so that the faster the emulsion of a given type the coarser the grain structure. But in the final reduction from salt to metallic silver, several silver grains can clump together to form very grainy patterns, especially when the distribution of clumps is not uniform. This clumping depends upon the developer as well as the method of development.

The outstanding difficulty in discussing the subject of granularity is the lack of standard methods for measuring graininess. This lack results often in contradictory results even when two careful experimenters are doing the test. A common method is to enlarge the negative and to evaluate visually the resultant pattern. Another more objective method consists of making microdensitometer tracings of the grain (see Chapter 6 for description of the microdensitometer), as shown in Figure 30. The general method of decreasing graininess during development is to add a reducing agent to the developer which dissolves the surface of the silver halide grains, thus keeping them separated from each other. This is the process with the borax

developer. Another way is to find a developing agent which has intrinsically fine-grain characteristics, such as paraphenylenediamine. This particular developing agent, however, requires long development and does not give as high effective emulsion speed as ordinary developers. To offset the slowness, the paraphenylenediamine developer is used in connection with

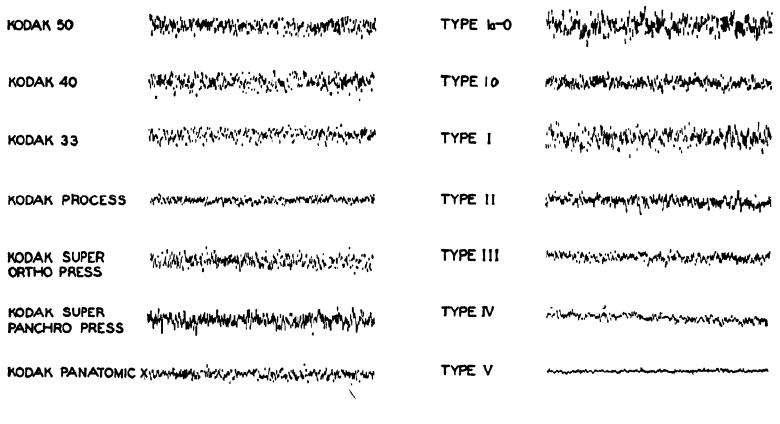


Fig. 30.—Microdensitometer tracings showing the granularity of some standard emulsions.
(*Kodak Research Laboratories.*)

other developing agents which do not affect the desirable fine-grain characteristics, but do lower the length of development time and increase the effective emulsion speed.

Characteristics of the Photographic Emulsion

If we expose a part of a photographic plate* to a light of constant intensity for one second, then another portion for two seconds, another for four seconds and so on, doubling the exposure every time, we shall find upon development that the

* The word plate as used here includes glass, film, or paper coated with an emulsion.

amount of deposited silver increases with increase of exposure, or as we commonly say, the *density* depends upon the exposure.*

This relationship of density and exposure is represented pictorially in Figure 31, in which the densities are plotted vertically and the lengths of exposure in seconds horizontally. We note that an exposure of two seconds gives a density of 0.1 and an exposure of 32 seconds a density of 1.4 and so on. This curve, first discovered by Hurter and Driffield in the last century, is known as the *characteristic curve* of the emulsion, for it indicates the response of the emulsion to the different gradations of light and shade. It also gives direct means for comparing one emulsion with another. We speak of the toe of the curve when we refer to the section from A to B, the straight line portion of the curve from B to C and the shoulder from C to D. The slope of the straight line portion, which is defined as the tangent of the angle between the straight line portion and the horizontal axis, is called *gamma*. An emulsion in which the straight line portion of the curve makes an angle of 45° with the horizontal axis, has a normal contrast or gamma of unity ($\gamma = 1$), and gives the best representation of the object we photograph. An emulsion of greater gamma ($\gamma = 2$) will give a picture more contrast because a small increase of exposure will produce relatively a much greater increase in the density. An emulsion with gamma less than one will, by the same token, produce a picture of

* The relations between intensity, opacity, transparency and density are defined as follows:

If a beam of light of intensity I falls upon a developed photographic image, and if a fraction of this light I_t is transmitted, or passes through, we write,

$$\frac{I}{I_t} = O \text{ (Opacity)}$$

$$\frac{I_t}{I} = \frac{1}{O} = T \text{ (Transparency)}$$

$$\log O = \log \frac{1}{T} = -\log T = D \text{ (Density)}$$

less contrast one than with gamma unity. Gamma depends markedly on the time of development as shown in Figure 32.

Whenever possible it is desirable to work in the straight line portion of the curve. This is the region of correct exposure where-

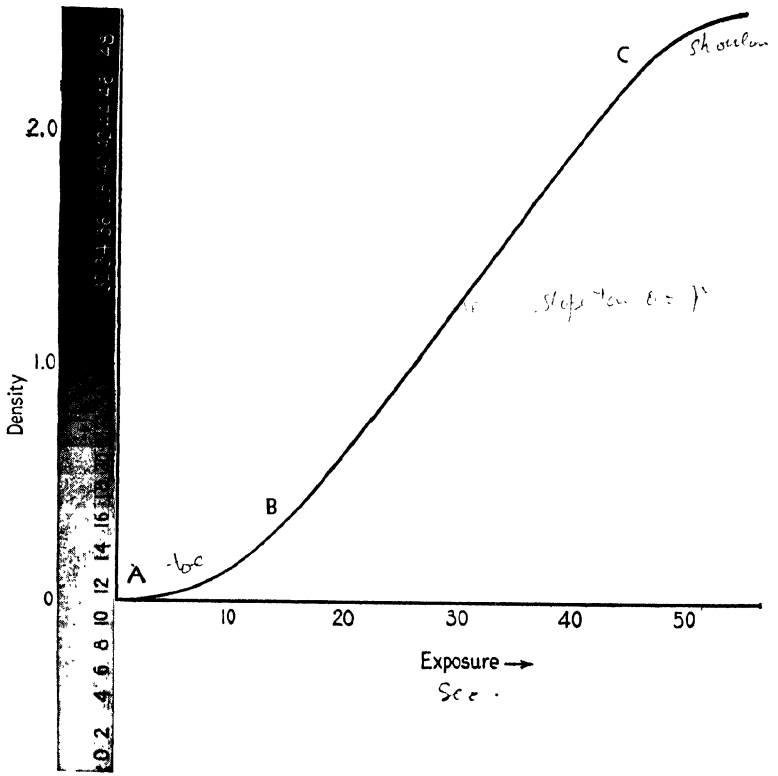


Fig. 31.—Photograph of wedge and drawing of characteristic curve.

as the toe and the shoulder are respectively the regions of under and over exposure. Unfortunately, however, in astronomy we have no choice since in most cases the intensity of starlight is very low. We are forced to work in the toe of the characteristic curve, which is at the same time the most difficult and the most

dangerous intensity level; for in this portion of the characteristic curve all the idiosyncrasies of the photographic emulsion become significant and should be taken into consideration, especially when we attempt to derive a quantitative measure of the light intensity on the basis of the density of the silver deposit.

Figure 33*a* shows the variation of contrast for seven basic emulsions used by the Eastman Kodak Company in the manu-

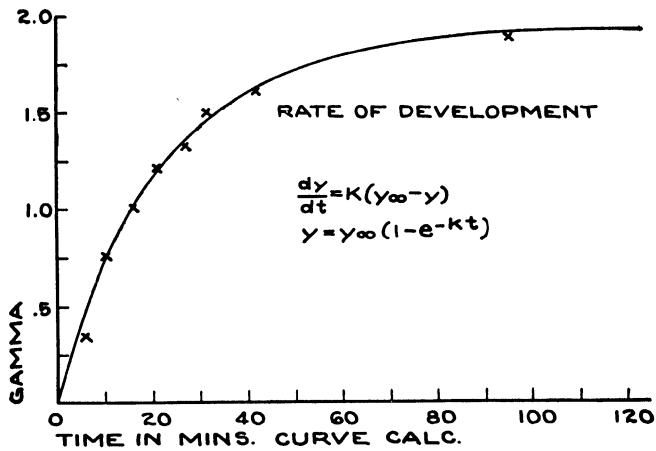


Fig. 32.—Curve showing relation of development factor to time of some standard emulsions

(*Kodak Research Laboratories.*)

facture of special spectroscopic and astronomical plates. The increase in the slope of the curves from 103 to *V* indicates a progressive increase in contrast, while the displacement along the horizontal axis indicates the change in sensitivity. If we compare the characteristic curves of two of these emulsions, we note that the curve 103 is displaced slightly to the left of emulsion *I*; that is, the emulsion 103 is relatively faster than emulsion *I*, since it is necessary to expose 0.5 seconds in order to obtain density 1.0 in the case of emulsion *I*, while an exposure of only 0.3 seconds will give the same density in the case of 103. It should be

emphasized that the comparison of speed can be made in this case directly because the curves are determined for a definite

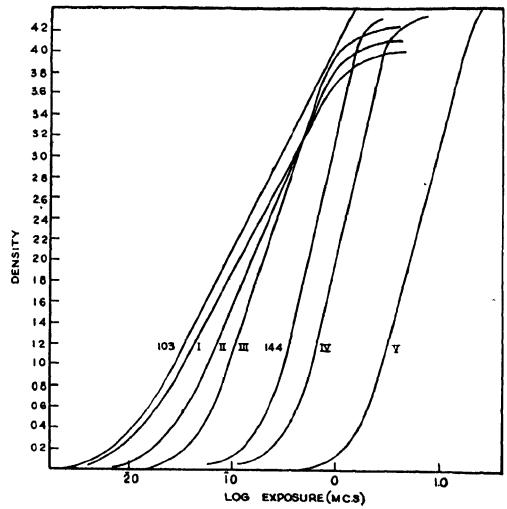


Fig. 33a. Characteristic curves of typical materials developed to $\gamma = 0.8\gamma_{\infty}$.

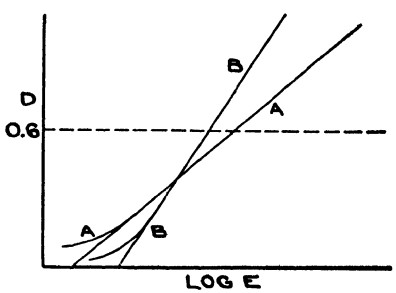


Fig. 33b.—Characteristic curves illustrating the relative speeds of two materials.

(*Kodak Research Laboratories.*)

and identical value of gamma. This standardization is necessary, for not only does the characteristic curve vary from emulsion to emulsion but it also varies for the same emulsion and is

determined by the method of handling in storage, by the temperature, and by the humidity of the atmosphere at the time of exposure as well as the type of developer, the length of development, and other physical characteristics at the time of processing.

These characteristic curves represent only one each of a family of such curves which will be necessary to specify completely all of the qualities of an emulsion. For this reason, it is not possible to give a single number or rating to the emulsion except in so far as the rating is representative of one quality or a combination of qualities which the manufacturer specifies. Such ratings are often obtained under ideal conditions that are seldom reproduced in general practice, and should be taken as a guide only when one emulsion is compared with another. It should be noted also that when we speak of speed or sensitivity of the emulsion, we mean in general the overall sensitivity, or as we commonly say, the sensitivity to white light. In astronomical photography, however, the sensitivity in a narrow spectral region is more important than the overall sensitivity. A panchromatic emulsion which is rated as five times faster than a certain blue sensitive emulsion, is actually five times slower when exposed to blue light alone (Figure 33*b*). The increase in overall speed of the emulsions in the past half century is due primarily to the extension of the sensitivity of the emulsion to include the yellow, red, and finally the infra-red region of the spectrum. As already mentioned, without the use of dye, ordinary photographic emulsions are sensitive to the blue-violet light. Thus a blue-colored object appears brighter to the photographic plate than to the eye, while a yellow or red object appears black. In 1873, H. W. Vogel discovered that naphthalene red, magenta, methyl violet and other dyes make the silver grains sensitive to the yellow-green. Since the beginning of the twentieth century the most important dyes have been the cyanines which are derived also from the benzene that forms the base for the organic developing agents. The dye is absorbed by the silver halide grains but not by the gelatin, and may be applied by bathing the ordinary plate in a

solution after the emulsion has been coated, or by incorporating the dye in the emulsion itself. Figure 34 illustrates the effect of different dyes in different regions of the spectrum. There is no

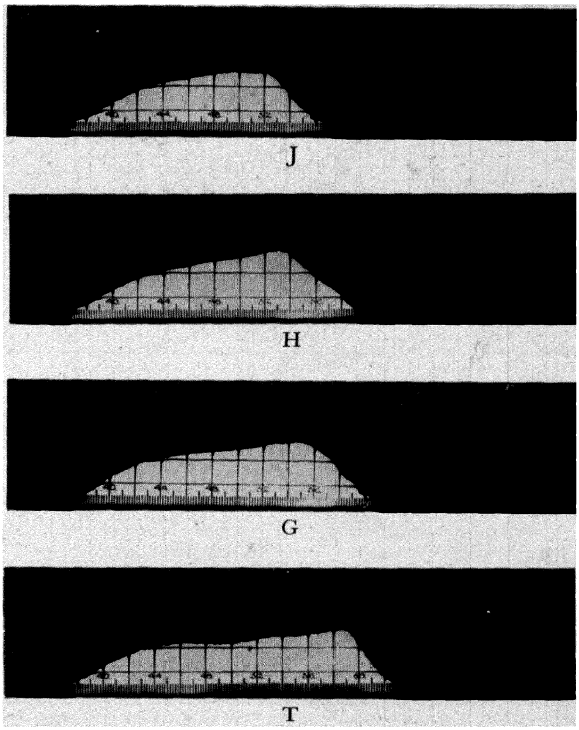


Fig. 34a.—Wedge spectrograms of green sensitizings.
(*Kodak Research Laboratories.*)

apparent connection between chemical composition and sensitizing properties of a dye.

Still another effect which enters in connection with sensitivity is the *reciprocity law failure*. The original reciprocity law was enunciated by Bunsen and Roscoe, and states that the blackening of the photographic plate depends simply on the total amount of light received by the silver halide grains, so that if the light

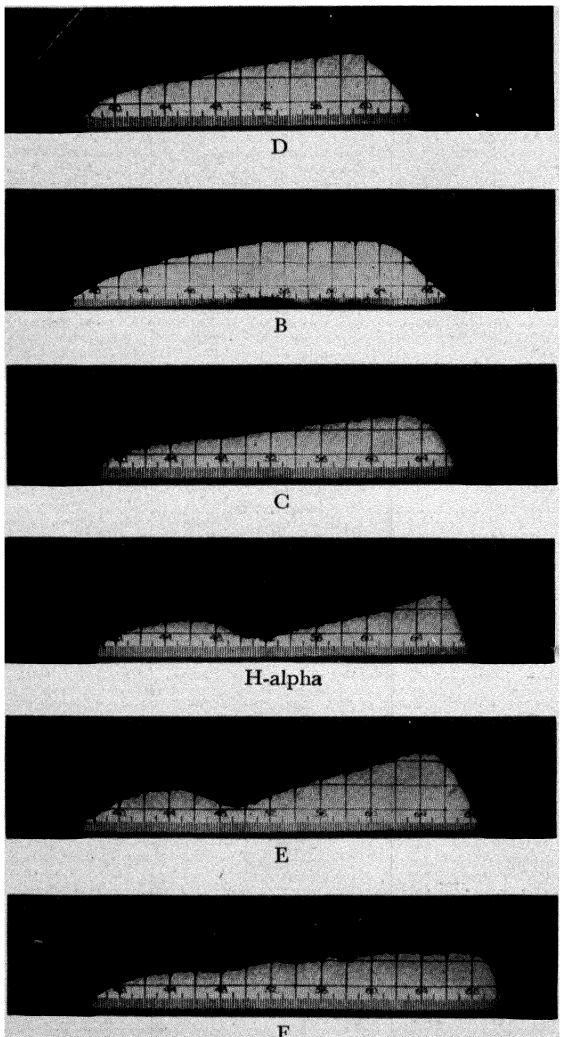


Fig. 34b.—Wedge spectrograms of panchromatic sensitizings.
(*Kodak Research Laboratories.*)

intensity is halved, the time of exposure should be doubled in order to produce the same final density. It is now known that this simple relation does not hold, and that in the case of long exposures such as we encounter in astronomical photography, the failure of the reciprocity law becomes a serious consideration.

In fact, astronomers use the rule of thumb that a factor of three is required in exposure time for a gain of one magnitude or 2.5 times change in light intensity. For example, if a certain

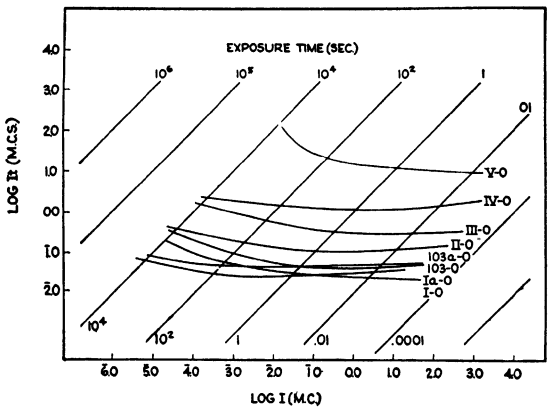


Fig. 35.—Reciprocity law failure on Eastman spectroscopic plates. (*Kodak Research Laboratories.*)

camera records stars of the fourteenth magnitude in ten minutes, then a thirty minute exposure would be required to reach the fifteenth magnitude.

Figure 35 shows a series of reciprocity law failure curves for several emulsions. These curves show practically *no* slope at the level of $\frac{1}{100}$ to 1 second exposure which encompasses the level of intensity and exposure for ordinary pictorial work, but at low intensity levels where the exposure is of several hours or about 10^4 seconds, the curves have definitely turned so far upward that it is necessary to increase the time of exposure, hence increase the product of time and intensity in order to obtain the same density.

4

PHOTOGRAPHIC TELESCOPES

WITH THE APPEARANCE OF THE PHOTOGRAPHIC METHOD astronomy embarked on its constantly expanding program of discovery, destined to acquaint mankind with worlds otherwise invisible. Human vision was increased a hundredfold through the peculiar ability of the silver halide emulsion to accumulate light too faint or of wave-length unsuitable for activating the retina of the eye. Faintly luminous veils of gas between the stars have made their existence known only on the photographic plate. Smudges of silver grains may represent glowing galaxies of stars many millions of light years away.

It would not be difficult to muse over the marvels of photography, but our subject demands a more analytical approach. We must examine the adaptability of the photographic plate to astronomical problems and study the nature of photographic instruments.

RESOLUTION

In order to obtain a measure of the resolving power of the photographic instrument we must consider the nature of a star image on the photographic plate. The ultimate in resolving power is important in photographing surface detail in objects like the sun and planets, or in the separation of close star images. A telescope designed for such photography must record star images as small as possible.

Stars are so far away that even the one of largest apparent diameter subtends an angle of only 0.065 seconds of arc, in effect

a geometrical point. The much larger size of a star image on the photographic plate, therefore, must be a result of the diffraction of light, the nature of the photographic emulsion, the quality of the instrument, and the atmosphere of the earth.

In the second chapter we found that the *image* of a star is not a pure point because of the wave nature of light (Figure 24*b*); an $f/5$ telescope, for example, produces at its prime focus a diffraction disc several microns in diameter.* Another factor contributing to the finite size of the photographic image is the *turbidity*, an effect caused by the diffusion of light within the photographic emulsion. Imagine the star image focused sharply on the slightly milky emulsion of the photographic plate. The starlight penetrates the emulsion until it is either absorbed, or goes completely through the emulsion to be absorbed by the anti-halation backing. For a given exposure the starlight scatters over a rather definite area of a given kind of emulsion. For an average emulsion and normal exposure we can adopt from observation the value of 0.02 mm for the turbidity effect.

Heat waves over a hot radiator produce in the appearance of distant objects a distortion easily detected by the small apertures of our eyes. In a similar fashion the angular diameter of a star image is enlarged by the turbulence of the earth's atmosphere before the light enters the instrument. On a good night, however, we are able to use telescope apertures up to 200 inches in peering outward through many miles of *turbulent* air. Such apertures still do not quite exhaust the possibilities of definition permitted us when our atmosphere is at its best.

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* A star image formed by a perfect optical system has an effective diameter of $4.56/D$ seconds of arc, where D is the aperture of the telescope in inches. (See Chapter 2.) The effective linear diameter of a focused star image will therefore be $\frac{F}{D} \times \frac{4.56}{206{,}265}$ inches, where F is the focal-length of the telescope in inches. Evidently, the linear diameter depends only on the focal-ratio (F/D) of the telescope. The factor 206,265 is the number of seconds of arc in one radian.

Astronomers call the blur at the focus of the telescope, caused by turbulence in the atmosphere of the earth, atmospheric *seeing*. It is necessary to make a distinction between the terms *visual* seeing and *photographic* seeing. Visual seeing may be considered excellent when the star image is as sharp as diffraction of light will permit, even though the star image may wander about over a limited small area of the field of view. Since vision is nearly instantaneous, the eye in following the small motion of the star can gather in a great amount of detail. Visual seeing may be considered poor when the star image is continually blurred, even though it may be stationary. Photographic seeing is the effective sum of the blurring of the image and its meanderings. Image pulsations and movement are faithfully recorded by the watchful but unimaginative photographic plate.

Average seeing is markedly dependent on the location of an observatory. Fortunately for American astronomy excellent seeing prevails in the western part of the United States, particularly in the belt through Texas, Arizona, and southern and central California. In many other regions of the world good seeing also exists.*

The last factor that can enlarge a star image is the quality of the telescope. A good instrument will give almost no trouble of this kind. Even the largest parabolic mirrors, for example, (see Table 2, p. 83) are so well figured and mounted that, apart from seeing, they yield a visual star image nearly as small as diffraction permits.

The minimum size of star image recorded on the photographic plate will be of the order of the sum of the above four effects. Table 14 (see page 115) contains the effective diameters of star images that perfect telescopes of the listed sizes should produce.

The angular size of the photographed star image may be designated the *resolution* of the photographic telescope. Resolution

* Danjon and Couder report visual seeing images as small as 0.03 seconds of arc at Forcalquier, France.

is a measure of the detail discernible in luminous surfaces like those of the planets; for such work excellent definition is vital. Because the turbidity of fast photographic emulsions is coarser than retinal structure, and because the eye is favored by its selection of moments of good seeing, visual resolution so far has

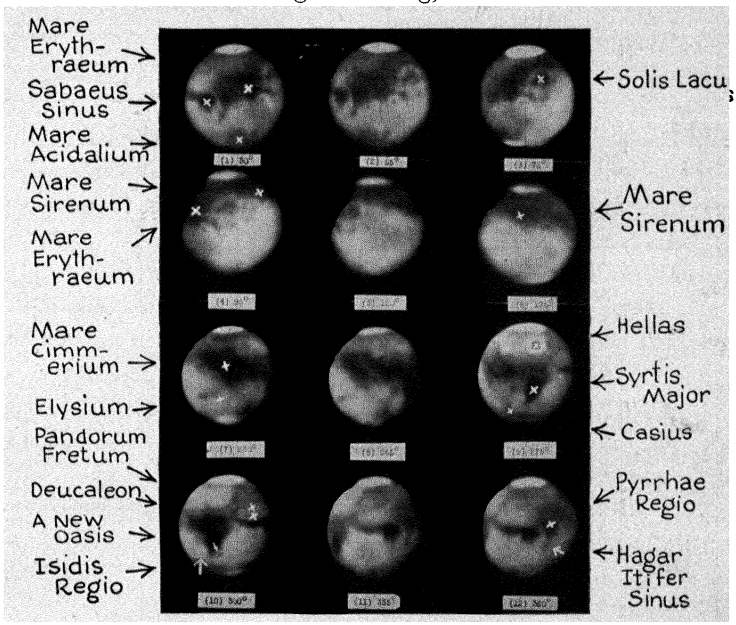


Fig. 36.—A panorama of Mars.

These photographs of Mars in 1939, show the planet turned successively through about thirty degrees. (*Photograph by E. C. Slipher, Lowell Observatory.*)

exceeded photographic resolution. For study of planetary surfaces photographic plates can act only as a check on the subjectiveness of the eye.*

* Probably the best set of planetary pictures ever taken were made of Mars in the summer of 1939 by E. C. Slipher with the 27-inch refractor at the Lamont-Hussey station of the University of Michigan. Figure 36 reproduces several of these photographs (see F. L. Whipple, *Earth, Moon and Planets*, page 218).

Measurement of star positions on the photographic plate is greatly facilitated by the use of an instrument with excellent resolution. Small departures from circular symmetry in star images, caused by defects in the optical system, reduce both accuracy and convenience of measuring. The position of a small unsymmetrical image is harder to measure than that of a large circular one.

Measurement of the total amount of light from a celestial object on the photographic plate requires no extreme standards of optical definition. Measuring accuracy is actually increased by inferior seeing and by photographic turbidity. In such work the greatest hindrance to accuracy is the variable transmission of our atmosphere, and skylight, followed by the lack of uniformity of the photographic sensitivity over the plate, or over a succession of plates. The quality of the instrument is involved in that the instrument must be sufficiently free of color errors in order that star images of different colors be approximately identical, and must yield images sufficiently similar in structure over the field of the photograph. Good work is frequently accomplished with rather poor observational material, but the required corrections are often subtle and untrustworthy. They can be avoided very often at the start by a proper choice and design of the instrument.

The Field of View and Plate Scale

Instruments for visual work need only a small field of excellent definition. If the observer wishes to examine a neighboring part of the sky, he merely has to move the telescope. In photography more rigorous demands are made on the instrument. The photographic plate gives equal attention simultaneously to all parts of the star field. Instruments *corrected* to produce good star images over a large field are therefore necessary.

Many variables govern the choice of the proper instrument for a research problem. Some of the most efficient and theoretically ideal instruments are at present impossible to construct with sufficient accuracy. We must select the instrument to fit the amount

of money available, the observing site, and the type of work. We must also choose an instrument that can be constructed in a reasonable amount of time.

An important consideration in the photography of the heavens is that of *plate scale.* By plate scale we mean the linear distance on a photographic plate corresponding to angular distance in the sky. Should one square degree of the sky occupy a one-inch square or a 10-inch square on the plate? For research on small distant objects, plate scale is important if only to separate star images as much as the atmosphere permits. Of the various quantities that make up the linear diameter of a star image on the plate, turbidity and diffraction are independent of focal-length. Consequently, their importance is diminished when the focal-length is so great that the seeing disc is essentially the size of the star image. The entire Milky Way has been pieced together onto a photograph about the size of a postage stamp; but, of course, the scale is so microscopic that the star images are blurred together. On the other hand, direct photographs exist with a scale of only a few seconds of arc to the millimeter of plate. For accurate star positions and parallax work large scale is a prerequisite.

The choice of plate scale depends, of course, on the number of square degrees of sky to be covered * and on the size of instrument planned. A large plate scale usually implies a great focal-length and large aperture for the instrument. A large aperture usually implies a restricted angular field. *Patrol* cameras, on the other hand, cover many square degrees of the sky (about 2500 square degrees on an 8-inch × 10-inch plate) because of their small focal-lengths and moderate focal-ratios.

If all dimensions of a given patrol camera and lens were enlarged twofold, the new lens would produce at a given field angle off the optical axis a linear image on the plate twice as large as before. If the image size at the edge of the plate is just usable in the original camera, the image at the same field angle

* The entire sky contains 41,253 square degrees.

will be intolerable in the enlarged camera; for the same limiting image size, the field may have to be reduced to a smaller angular diameter. Such a reduction leaves the linear dimensions of the photographic plate more or less fixed as the instrument grows in size. At least the plate size increases only very slowly with instrument size. A good illustration of this effect is the case of the reflector. If an observer uses a plate two inches square with an $f/5$ mirror of 6-*inch* aperture, his resultant photograph will be just as sharp, or just as blurred, at the edge as a plate two inches square taken with an $f/5$ mirror of 60-*inch* aperture, although the larger mirror covers but one-tenth the angular field and one-hundredth the area of sky of the smaller mirror. For refractors and patrol cameras the exact relations are more complicated, but of similar nature. Thus we see that the requirements of photography of the heavens are radically different in character and emphasis from requirements of visual observation.

The Reflector as a Photographic Instrument

In the second chapter we discussed the use of visual reflectors. We found that they are usually constructed of a single parabolic mirror with auxiliary plane mirrors. Since large instruments are expensive, the question arises as to their performance in photographic work. Certainly their light collecting power can be superior to the photographic refractor, and then, too, the prime focus of a large reflector can provide a plate scale as large as 15 seconds of arc to the millimeter, a scale especially valuable for critical study of special objects.

After a photograph has been taken at the focal plane of a large telescope and developed, the scientist may use a magnifying glass or even a microscope to examine it in the laboratory. The result therefore is as if a magnifying glass had been used visually in the telescope. Photographically, we have the advantages of studying an unchanging picture at the most convenient time to the extent we desire, and the opportunity to compare parts of the photograph.

The parabolic mirrors, especially the large ones, are used today almost entirely photographically. Because of the simplicity of such telescopes, it is possible to achieve a degree of efficiency and size scarcely possible in more elaborate instruments. The telescope is easy to keep in adjustment inasmuch as the only requirement is that the photographic plate be properly focused with respect to the optical axis of the mirror.

The parabolic telescope is used photographically mostly at the prime focus or at the Newtonian focus. Rarely are direct photographs made at the Cassegrain or the coudé focus. (See Chapter 2.) The longer focus Cassegrain or coudé requires a somewhat longer exposure time, which, combined with more pronounced flexure in the tube, makes guiding more difficult. Moreover, for large telescopes with prime focal-lengths of 150 inches or more, the linear diameter of the photographic seeing image already exceeds the resolving power of the emulsion, so that the smaller scale photographs at the prime focus reveal detail nearly as fine as obtainable at the longer focus Cassegrain. With smaller instruments that have not exhausted seeing possibilities, and with large instruments when the seeing is perfect, some gain would be had by Cassegrain photography.

Photography at the prime focus requires that the plate-holder be central in the telescope tube and that it obstruct some light, although in general not as much as the Newtonian secondary. With large telescopes it is desirable to guide the instrument by movement of the photographic plate and to guide on a star at the edge of the field. A small telescope at the edge of the tube, focused through a small auxiliary prism or mirror on a star in the focal plane of the large mirror, is quite feasible. The illustration (Figure 37) shows such an arrangement at the Goethe Link Observatory. A small guiding telescope on the side of the large telescope tube is untrustworthy unless the tube is exceedingly stiff, a condition not usually obtainable.

The prime focus arrangement requires a slightly longer telescope tube than the Newtonian telescope. Also a somewhat

larger dome is required and the telescope is more expensive. At the present time most photography with large reflectors is carried on at the simple Newtonian focus with a plate-holder free to move laterally or vertically in guiding.

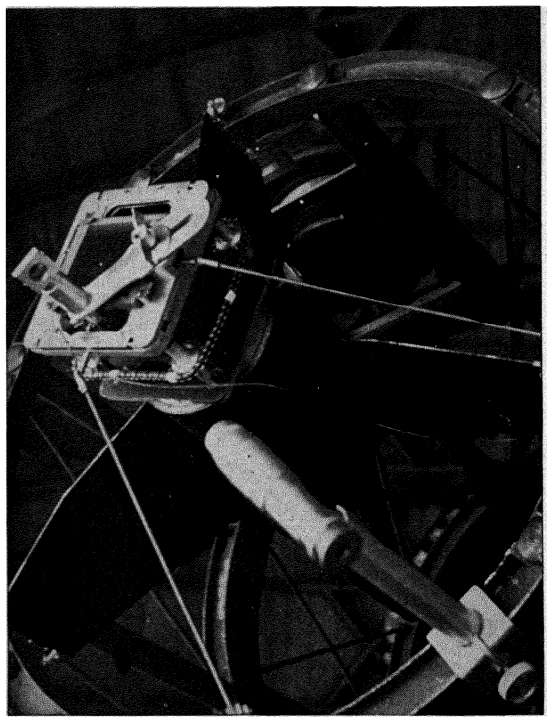


Fig. 37.—Prime focus double slide plate-holder, and guiding arrangement, Goethe Link Observatory.
(*Photo by Cuffey.*)

Image Errors

The comments made in the first section of this chapter on the sizes of star images hold, of course, for the reflecting telescope. There we assumed that the instrument was optically perfect. An optical system that does not produce visual images as sharp as

light diffraction permits has *spherical aberration*, the amount of which can be measured either by the linear size of the image in the focal plane or by the angular diameter of the circular image. The term arises from the inability of a spherical surface to bring incident parallel light to a sharply focused point-image. A single surface mirror can be made into very nearly a perfect paraboloid, as indicated by the data in Table 2. The other factors are concerned with seeing and photographic spreading as before.

TABLE 2

RESIDUAL SPHERICAL ABERRATION OF LARGE TELESCOPES

Telescope and observatory	*Image size at prime focus*		*Determined*
	seconds of arc	*millimeters*	
82-inch McDonald	0.10	0.004	Visually
74-inch Dunlap	0.40	0.018	Visually
72-inch Dominion	0.24	0.011	Visually
69-inch Perkins	0.28	0.010	Visually
61-inch Harvard	0.46	0.018	Photographically
	0.13	0.005	Visually

Although a star image should be as small as possible on the optical axis of the well-made reflecting parabolic mirror, it is bound to deteriorate off the optical axis or away from the center of the field of view. The paraboloid has the mathematical property of reflecting incident parallel rays of light accurately to a focus, provided the bundle of light is accurately parallel to the axis of symmetry or optical axis of the mirror; but parallel rays of light coming in at an angle with respect to the optical axis of the instrument no longer pass through a common focus. The deterioration of image quality as we go off-axis is not so rapid that the paraboloid has no field at all. At $f/5$ its field is small relative to other more complicated types of instruments, but for many purposes a large field is unnecessary.

The illustration in Figure 38 shows the pattern of a star image formed by a parabolic mirror as seen through a microscope at varying distances off-axis. The spurious enlargement of the image into a flare-like pattern comes from the image defect called *coma*

The simplicity of the large reflecting telescopes must be paid for by the restricted field permitted. It is not easy to specify exactly the extent of the *useful* field. That depends entirely upon the type of research. For example, for photoelectric observations, the images at the edge of the field are as usable as those at the center, merely because exceedingly poor images can be used.*



Fig. 38.—Comatic star images formed by a parabolic mirror.

Photographically, star images become undependable at the point where they depart noticeably from symmetry, and where important errors in magnitude measurement may be made by the observer in the comparison of images over the plate. We may define the *useful* field as contained within the circle on which the photographed star images cover twice the *seeing* disc. Ordinarily, the photographic plate used with a paraboloid is much larger than this definition would require, and the observer can adopt the diameter of field most useful for his particular research.

* Images as large as a centimeter in diameter can be used, but there are a few exceptions. Sometimes one object must be segregated from another nearby, as in the determination of absolute quantities of light from either of two close stars. More frequently, however, near the limit of photoelectric sensitivity a small star image is necessary in order to pass through a small diaphragm used to cut out skylight.

Table 3 gives the angular radial extension of coma of the ordinary parabolic reflector, at various angles off-axis in terms of the focal-length and aperture. If a larger field of good definition is desired for any special purpose, the aperture of the telescope can be reduced so that coma is less serious. For example, if an $f/5$ telescope is stopped down to $f/15$ by a diaphragm, coma is decreased at any point to $\frac{1}{9}$ of its former value, or for the same tolerance on image size, e.g., twice the seeing, the field may be nine times larger in diameter or eighty-one times more in area of the sky.



(*a*) A fully corrected cone of light converging to and diverging from a focus.



(*b*) An astigmatic cone of light converging to and diverging from a circle of least confusion.

Fig. 39.—The smallest circular image in the second diagram lies on the focal surface.

A third type of image defect called *astigmatism* makes its appearance at greater distances off-axis. An astigmatic image, as the term implies, is not a point, nor is it a flare, like coma; but instead it is a line. Suppose that we have a lens system whose only aberration is astigmatism. An incident beam of parallel light will in general focus into either of two straight lines at right angles to one another, lying at slightly different distances from the lens. Figure 39 presents the changing appearance of such a star image when the photographic plate is placed at different distances from the objective. Half-way between the line-segment images the starlight forms a round image, but not a point. The diameter of this *circle of least confusion* at a specified angle off-axis is a measure of the amount of astigmatism present. In a system with no astigmatism the diameter has vanished to a point. For convenience these circles of least confusion should lie on the plane surface of the photographic plate.

If these circles of least confusion lie on a curved surface, the instrument is said to have the aberration called *curvature of field.*

In the case of larger focal-ratio, where coma is small, astigmatism may appear first, as we observe farther and farther off-axis, and will remain larger than coma. For example, an $f/15$ reflector has its field limited as much by astigmatism as by coma. Table 3 shows the contribution of astigmatism to image size, as measured by the angular extension of the astigmatic line in a flat focal surface in the radial direction from the center of the field.

TABLE 3

THE IMAGE ERRORS OF THE PARABOLIC TELESCOPE

	Field diameter (degrees)	*Astigmatism (seconds of arc)*	*Coma (seconds of arc)*	*Astigmatism and coma (seconds of arc)*
$f/10$	0.5	0.4	1.7	1.9
	1.0	1.6	3.4	4.2
	2.0	6.3	6.8	10.0
	4.0	25.2	13.6	26.2
$f/3$	0.5	1.3	18.7	19.3
	1.0	5.0	37.4	39.9
	2.0	20.0	74.9	84.9
	4.0	83.8	149.8	191.7

Table from K. Schwarzschild, Gött. Mitt. IX–XI, 1905.

Professional reflecting telescopes are almost invariably used at speeds faster than $f/15$; therefore, one can say that coma is the more serious error of the off-axis images. Since coma happens to be independent of the curvature of the field, one obtains equally limited performance in an $f/5$ reflecting telescope whether the photographic plate is plane, or whether it is curved to fit the focal surface.*

* In many instruments free from coma a curved plate will still further improve the performance. The Harvard 16-inch Metcalf doublet regularly employs slightly curved plates. If at all possible, a photographic instrument should be designed at the start with a plane field.

In order to overcome the coma of the ordinary paraboloid, F. E. Ross has designed a special achromatic lens of zero power to be placed in the converging beam of the telescope. This so-called *zero-corrector* has negative coma equal to the positive coma of the paraboloid. Unfortunately, the combination can have zero coma only at the expense of reintroducing spherical aberration into the reflector. At $f/3$ the spherical aberration caused by the

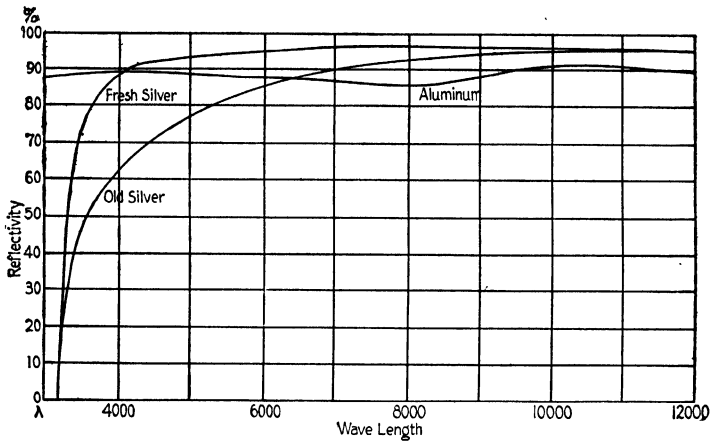


Fig. 40.—Reflectivity of evaporated aluminum and chemically deposited silver.

(Adapted from J. Strong, Ap. J., June, 1936.)

correcting lens is prohibitive, a situation that has resulted in the nearly complete idleness of some large $f/3$ mirrors made for European observatories by Zeiss. Without a zero-corrector these mirrors have excessive coma.

Reflecting telescopes are ideal for comparisons of starlight of widely different colors. One can work in the ultra-violet or in the infra-red without change of focus. The only possible difficulty arises from the changing efficiency of the instrument in light of different colors, a difficulty present to some degree in any type of optical system of lenses or mirrors. The deposited film of metal

reflects some colors better than others. For example, silver reflects better than any other metal the entire visual spectrum and, indeed, a good part of the infra-red. However, the reflectivity of silver falls off in the ultra-violet; at wave-lengths shorter than 3300 A., a silver film is so transparent to light that it may be used as a filter to transmit the far ultra-violet. Since this region of the spectrum is still transmitted through the atmosphere,* aluminum coated mirrors are better suited than silver to extreme ultra-violet work. (Figure 40.) In addition, the reflectivity of aluminum is nearly constant with wave-length. Many of the large mirrors are now coated with evaporated aluminum films.

The Refractor as a Photographic Instrument

The largest existing refractors were built at the close of the nineteenth century at a time when visual observing was still of great importance. As more large telescopes of the reflecting variety were constructed and photography began to replace visual observations, attempts were made to convert the visual telescopes into photographic instruments. Several difficulties are involved. The visual refractor is truly visual to the extent that light of wave-lengths other than the yellow-green fails to come accurately to the same focus. We have met this defect already and have called it the secondary spectrum of the refractor. The curve in Figure 41 shows the departure along the axis of the focus in each color for an average visual telescope. Images of bright stars show a purple halo surrounding the focused yellow image. This purple fringe comes from the red and blue rays that do not come to the same focus with the yellow, but cross the optical axis farther from the lens. Visual refractors are corrected for the region of maximum sensitivity of the eye.

At the beginning of the twentieth century, photography was ordinarily carried on only in the *actinic* or blue-violet region of

* The atmospheric cut-off is complete only below 2950 A. The complete opacity beyond this point is due mostly to the presence of ozone in the upper atmosphere.

the spectrum. Consequently, telescopes built for visual use were unable to achieve as sharp definition on a photograph as they would have if redesigned with minimum focus at about 4340 A. Several methods were adopted to overcome the handicap. The first and most obvious of these was to build lens systems corrected for the photographic region of the spectrum. This remedy was not altogether practical for large telescopes because of the expense

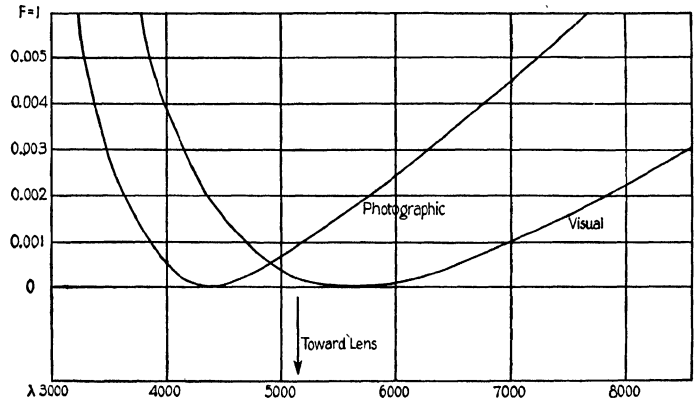


Fig. 41.—Secondary spectrum of ordinary crown and flint objective.

The vertical scale represents distance along the axis of the lens of the focus for the wave-length on the horizontal scale with the minimum back focus as zero point. The vertical scale is in units of the focal-length, the horizontal in Angstrom Units.

of the lens, and the undesirability of changing from one lens to another and back again. Twin lenses and tubes were sometimes made. The largest of these is the 33-inch (visual), 25-inch (photographic) twin telescope at Meudon, France.* The most feasible procedure consists of placing a properly designed correcting lens in the converging beam of the instrument. This lens

* A rather interesting type was constructed for Harvard many years ago. The 13-inch Boyden refractor has a reversible front lens. In one position it is the usual visual instrument. With the crown lens reversed, and separated from the flint, it becomes a photographic instrument.

has the property of changing the color correction to the blue without affecting the good imaging quality of the refractor.*

After the introduction of yellow-sensitive or orthochromatic plates, visual refractors became quite usable photographically. Ordinarily a yellow filter is used to eliminate the poorly focused blue light; an orthochromatic plate does not record red light.

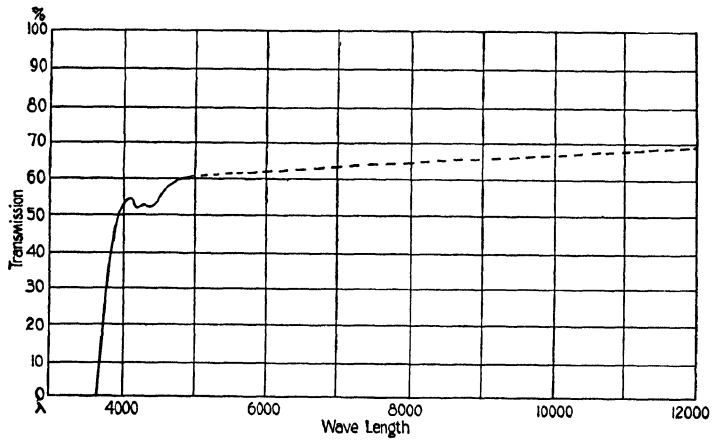


Fig. 42.—Transmission curve of the Lick 36-inch refractor and its photographic correcting lens.

Compare with efficiency of prime focus reflector, Fig. 40. (*Adapted from Fred L. Whipple, P.A.S.P., vol. 47, p. 305.*)

The glass lenses used in refractors absorb some of the transmitted light in a way markedly dependent on wave-length. The transmission curve of a typical large refractor, the Lick 36-inch, shows a marked drop in the ultra-violet. Like the silvered reflector, the large refractor has low efficiency in the ultra-violet. The loss of light increases with the thickness of the lens, not only in proportion, but also because it is more difficult to manufacture clear discs of great thickness and diameter. The largest refractors

* E. C. Slipher used such a lens in his South African photographs of Mars. Such auxiliary lenses are useful in slit spectroscopy with visual instruments.

lose quite seriously in magnitude over the reflector of equal size in the blue and violet regions of the spectrum. Because of these high transmission losses and appreciable flexure difficulties arising from supporting large discs of glass by their edges, no lens larger than the 40-inch Yerkes has ever been used astronomically.

A two-lens refractor properly designed for astronomical work has neither spherical aberration nor coma. It is possible for one to reduce these errors to negligible amounts, and at the same time to correct the primary color error by choosing types of glass and curvatures of the four glass surfaces. All these corrections may be accomplished without departing from spherical curves. Such an objective is often called the *Fraunhofer* type.* (Cf. Chapter 2.) It is possible by the technique of figuring to make a telescope spherically corrected for more than one wave-length, but at $f/15$ such an additional correction is appreciable and advisable only in the largest lenses.† The first image error to appear in the properly designed refractor is that of astigmatism, an error that cannot be removed by the simple doublet design. The useful field of a refractor is quite large, particularly if the plate is curved toward the lens to a radius of 0.4 of the focal-length of the objective. The difficulties introduced by such bending are not serious, provided the work is photometric in character. If the plate is left flat, the images at the edge of the useful field are not round but are ellipses elongated in the radial direction.

Flat plates are advisable for the extreme precision of present day positional work where a plate error as small as 0.5 microns for the finest work can be obtained. A large refractor has several

* Fraunhofer's original objective is in the Deutsches Museum, Munich.

† Alvin Clark included this correction in his large lenses, not so much by aspherical deformations as by separation of the two lenses. This separation also enables the glass discs to reach equilibrium with temperature more quickly than discs in contact. A lens of crown and flint elements in contact, called the Gaussian objective, corrected for spherical aberration in two colors, has curves too steep to be recommended.

great advantages over a reflector for parallax and proper motion work. If properly mounted, the lenses need never be disturbed in the original cells. The properties of the telescope remain constant over a useful lifetime of perhaps a century or more. Proper motion and parallax programs covering many years can be carried out with almost no corrections required for changes in the instrument. Star positions can be compared year after year. Another advantage for positional work is the large scale provided by the large refractor.

The large refractors are almost invariably made with a focal-ratio between $f/15$ and $f/20$. The glass, then, has no great variation in thickness from axis to edge, and the color errors remaining are not too objectionable for most work, as they may be at $f/5$. The $f/19$ Yerkes refractor, largest refractor in the world, has a focal-length of 760 inches, surpassed only by the non-professional $f/31$ 27-inch Berlin-Treptow refractor.* A measuring error of one micron on a Yerkes plate corresponds to an angular error of only 0.011 seconds of arc in the sky.

The question naturally arises in the reader's mind as to the possibility of correcting the refractor for a greater range of color. The solution lies in the hands of the glass maker and chemist. The design of a perfectly color-corrected lens with suitable optical constants is as easy a matter as that of a partially corrected lens. At the present time there exist a few glass pairs of German manufacture that are partially corrected in the right direction. That is, the secondary spectrum has been reduced in amount. The trouble is that these glasses have too nearly the same dispersion, and consequently need very strong curves for a given focal-length. The situation can be somewhat improved by using three lenses and distributing the curves among the six surfaces, but unless the lenses are separated, no better monochromatic correction is feasible.

* Even the 200-inch has a focal-length of but 660 inches at its prime focus. Its coudé focal-length will, of course, be many times larger.

Highly Corrected Types of Photographic Reflecting Telescopes

No optical instrument can be corrected for all possible image defects, particularly when the defects are more complicated than the ones described above. The best one can do is to correct as well as possible for each special case. Thus, the design of a spectrographic camera covering a 90 degree field at $f/30$ is not impossible, because at $f/30$ the size of image may not become excessive. Similarly, one can design rather easily a camera covering eight square degrees at $f/0.6$ with satisfactory definition. For direct photography of luminous surfaces the second camera is 2500 times *faster* than the first; the *field* of the first, however, is many times that of the second. The requirements in the two cases are so radically different that the designer must proceed almost as if the problems were unrelated.

The simplest modification of the reflecting telescope adds another curved mirror to the system. The image defect of coma can then be removed by properly deforming the two mirror surfaces of the system. Unfortunately, the primary mirror, necessarily concave, with a non-parabolic curve, cannot be used separately for auxiliary instruments, as is the case with the familiar parabolic reflector; by itself the primary mirror is not corrected to produce sharp images. Such a two-mirror telescope having zero coma and zero spherical aberration must necessarily be used only as a unit. Since rather delicate adjustments are required to keep the two mirrors aligned properly with respect to one another, the mirror arrangement must be permanent and rigid.

The most familiar instrument of this form is called the *Schwarzschild* after its originator, the famous German astronomer. Schwarzschild derived the only physically possible family of such two-mirror telescopes free of spherical aberration, and coma. The most useful member of the family of telescopes proposed by Schwarzschild has no curvature of field but necessarily retains the image defect of astigmatism. (See Figure 43.)

Because of a relatively large secondary mirror the system loses about one-fourth of the light incident on the primary, but this loss is not serious. Two of these telescopes are now in existence, one at Indiana University, the other at Brown University. Table 4 gives constructional data for this type of instrument. Because both mirrors are concave, the tube-length of the

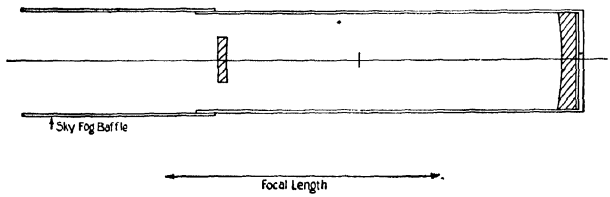


Fig. 43.—The Schwarzschild reflector.

The great separation of the mirrors relative to the focal-length and the precision required in their adjustment demand an extremely sturdy tube. The sky fog baffle prevents direct illumination of the plate by the sky. This baffle may be of very light material, but its disadvantage is that it requires a very large dome, unless wind shutters are put on the slit of the dome.

Schwarzschild is considerably greater than the equivalent focal-length.* Such a telescope is best suited to focal-ratios of about $f/3$. A sky-fog baffle must be added to the end of the tube to shield the emulsion from direct sky light (see Figure 43).

TABLE 4

Equivalent Focal-length	1.000
Diameter of Primary	0.333
Focal-length of Primary	2.500
Separation of Mirrors	1.250
Diameter of Secondary	0.167
Focal-length of Secondary	0.835
Distance of Focus from Secondary	0.500
Tube-length	2.400

Table from K. Schwarzschild, Mitt. Gött., IX–XI, 1905.

* The equivalent focal-length is the focal-length a simple lens or mirror would have that provides the same plate scale.

Schwarzschild sacrificed some optical quality in the two-mirror system for the convenience of a plane focal surface. The French scientist Couder chose to sacrifice convenience for performance by making astigmatism zero on a curved focal surface. The *Couder* type (Figure 44) of two-mirror reflector gives excellent performance on a focal surface whose radius of curvature is about one-half the equivalent focal-length. The constructional

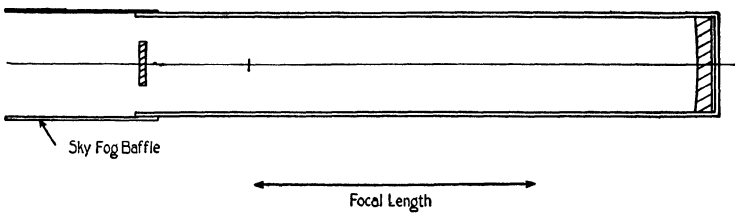


Fig. 44.—The Couder type.

The tube must be even sturdier than that of the Schwarzschild, but the sky fog baffle is shorter.

data for a Couder telescope are given in Table 5. Like the Schwarzschild the Couder type is best suited to focal-ratios of about $f/3$.

TABLE 5

Equivalent Focal-length	1.000
Diameter of Primary	0.333
Focal-length of Primary	3.250
Separation of Mirrors	2.000
Diameter of Secondary	0.163
Focal-length of Secondary	0.555
Distance of Focus from Secondary	0.385
Tube-length	2.500

Table from Danjon and Couder—Lunettes et Télescopes.

Another type of two-mirror telescope free of spherical aberration and coma is the *Ritchey-Chrétien* telescope. (See Figure 45.) This type has both astigmatism and curvature of field, and for best results requires a curved plate. The great advantage of such a telescope is that the tube-length is considerably shorter than the focal-length; it is therefore adapted to astronomical problems

requiring speeds no faster than $f/6$ but demanding large plate scale. The constructional data are given in Table 6.

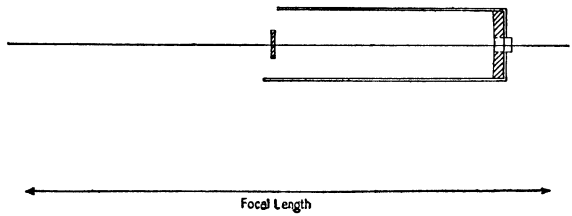


Fig. 45.—The f/7 Ritchey-Chrétien reflector.

The short tube and position of the focal surface more than make up for the slightly reduced field relative to the Schwarzschild.

TABLE 6

Equivalent Focal-length	1.000
Diameter of Primary	0.125
Focal-length of Primary	0.761
Separation of Mirrors	0.419
Diameter of Secondary	0.056
Focal-length of Secondary	1.436
Distance of Focus from Secondary	0.460
Tube-length	0.500

Table from Danjon and Couder—Lunettes et Télescopes.

The Schmidt Camera

In 1930 the most significant advance in astronomical instruments for several decades was announced quietly by Bernhard Schmidt, an associate of the Hamburg Observatory at Bergedorf, Germany. In brief, his discovery consisted of a camera capable of sharp definition at focal-ratios never before associated with a large field of view. Moreover, the camera contained but two optical parts, one a spherical mirror, easy to make, the other a thin lens of almost no power but hard to make, primarily because nothing like it had been attempted before. Figure 46 shows a cross-section of the *Schmidt* camera.

In order to explain the character of this type of camera let us try to follow through the reasoning Schmidt may have used.

When a mirror maker constructs a reflecting telescope the primary of which is a paraboloid, he ordinarily makes a spherical mirror first. The radius of the sphere is almost exactly twice the desired focal-length of the paraboloid. The mirror maker then *parabolizes* the sphere. This operation consists of deepening the sphere into a paraboloid by polishing away the central portion of the glass surface. The idea must have occurred to Schmidt as he was parabolizing a mirror that the figuring need not be done on the mirror itself. Instead he proposed to substitute for the slight variation in depth

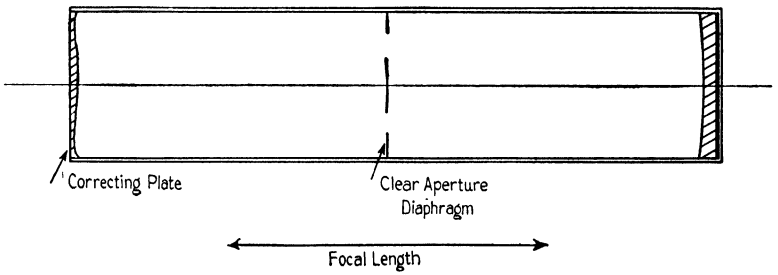


Fig. 46a.—The f/3 Schmidt camera.

The position of the diaphragm yields the maximum unvignetted field for the clear aperture and mirror size. The correcting plate is larger than it would be if the diaphragm were at the center of curvature of the mirror (and therefore coincident with the correcting plate). At *f*/3 this fact is of no special concern. The term "vignetting" refers to the increasing loss of light with distance off-axis caused by insufficient mirror or lens diameters.

of the mirror a slight variation in thickness of a thin plate of glass interposed in the path of the light. Since the parabolizing of an ordinary mirror rarely requires more than a few wave-lengths of glass to be removed, the departure of the glass plate from plane parallelism would be quite invisible to the unaided eye.

At first Schmidt probably thought to place the glass plate in contact with the spherical mirror; but such a location gives no better optical performance than the paraboloid. A bit more thought showed Schmidt that the best place on the optical axis for his *correcting plate* lay at the center of curvature of the spherical mirror.

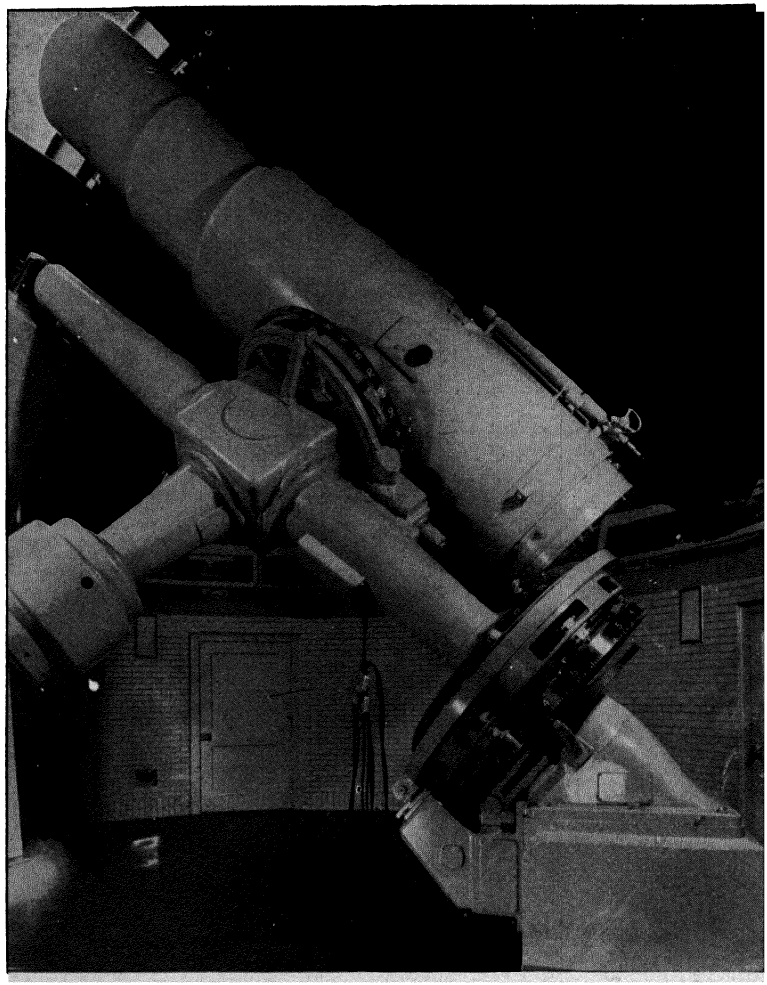


Fig. 46b.—The 24–36-inch Schmidt telescope of the Warner & Swasey Observatory of the Case School of Applied Science, Cleveland.

The tube is quite unusually sturdy, and the instrument as a whole is as convenient for the observer as a Schmidt can be. A 24-inch prism mounted at the upper end over the correcting plate provides small scale spectra of faint stars.

Any ray of light passing through the center of curvature of a spherical mirror that strikes the mirror is reflected back on itself. Every such ray may be regarded as an optical axis of the spherical mirror. Any bundle of rays parallel to such an optical axis will be focused by the spherical mirror into a blur or circle of confusion about one-half of the way between center of curvature and the mirror. Regardless of the direction of the optical axis considered, this blur will be of the same size. The

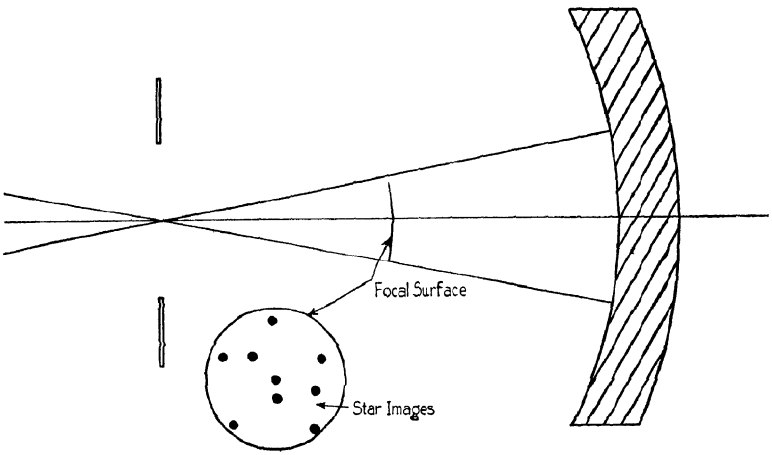


Fig. 47.—Spherical mirror and diaphragm.

The insert shows the character star images would have with such an arrangement.

spherical mirror used with a simple diaphragm at the center of curvature has spherical aberration constant over the whole field of view, and curvature of field. Figure 47 shows the nature of such an arrangement.

If we replace the diaphragm in Figure 47 by a thin plane-parallel glass plate, no change at all is observed in the spherical aberration; but if the glass plate is deformed by figuring in just the right way on either surface or on both together, rays entering parallel to any one of the optical axes will be deviated into a point focus. The introduction of the glass plate has scarcely

changed the symmetry of the arrangement. We can say that the spherical mirror has been parabolized in many directions at once. For such reasons the Schmidt camera has a very large field relative to most astronomical cameras. Indeed, at $f/5$ the field of sharp focus exceeds the diameter of the correcting plate.

Because the correcting plate curve is so nearly flat, the parabolization can be carried to very wide apertures relative to the focal-length. Schmidt cameras of $f/1$ are quite common, and some as fast as $f/0.6$ have been made. A Schmidt camera of short focal-length at $f/1$ may have a useful field of 25 degrees. An $f/1$ paraboloid has a field measured in minutes of arc.

The Schmidt camera has two main defects. Firstly, the tube-length is twice that of the parabolic telescope of equal focal-length. Secondly, since the focal surface lies on a sphere whose radius is accurately the focal-length of the system, the photographic plate or film must be curved to fit this surface very precisely, a cause of a good deal of inconvenience in observation. The latter problem has been solved in a number of ingenious ways. In addition to mechanical methods for bending the plate or film, an optical means proposed by Piazzi-Smyth in 1873 is very effective when used with cameras slower than $f/2$, although up to the present time no large Schmidt camera has employed the device. A plano-convex lens equal in diameter to the linear field to be covered is placed with its plane side close to the photographic plate. The spherical convex surface of this lens has a radius of about one-third the focal-length of the Schmidt. The central thickness acts to flatten the field. Such a lens may be called a *field-flattener*. Many workers have independently rediscovered the device. At $f/2$ the lens begins once more to introduce appreciable coma and at greater speeds ceases to be advantageous. The length of the Schmidt tube is a constructional expense and need not be regarded as a vital hindrance, unless Schmidt cameras of great size are contemplated. The two chief disadvantages of the Schmidt camera are therefore not insuperable.

The thin lens of the Schmidt does not correct all colors in the same way. If the camera is corrected perfectly for yellow light, blue light will not come to the same focus, nor indeed to any sharp focus, since overcorrected spherical aberration is involved and not the primary spectrum of the refractor. The reason is simply that the correcting plate is usually made of a single variety of glass. The plate is so curved as to produce full correction for

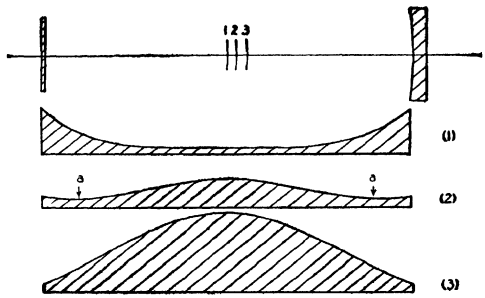


Fig. 48.—Three extreme forms of the Schmidt correcting plate.

The curves are greatly exaggerated in vertical scale. The central bulge in the correcting plate has the effect of shifting the focal surface toward the mirror by a small amount. In spite of the great apparent variation in form of these correcting plates they all depart from the nearest sphere by the same amount, and are therefore about equally hard to make. Form (2) is optically superior. See text. The maximum departure from the nearest sphere in the correcting plate amounts to only a few hundredths of a millimeter in cameras of reasonable speed. Such a small departure is invisible to the eye except for the slight distortion introduced in reflections from the surface.

one wave-length, say, yellow. Because of the variation of index of refraction with wave-length, the plate is over-corrected in blue light and under-corrected in red light. Fortunately the color error of the Schmidt is so small in seconds of arc that unless the camera is made of extreme speed such as $f/0.6$, definition still remains excellent. Large Schmidt cameras of lesser speeds are possible in which the color errors over a very wide range of wave-lengths are no larger than the seeing image.

The required shape of the correcting plate is very sensitive to the distance of the photographic plate from the spherical mirror.

Figure 48 shows three possible forms corresponding to the positions of the focal surface indicated. Form 2 is close to the design adopted by nearly all Schmidt makers. This type has the property of causing the least possible chromatic aberration in the image. (Form 2 has one-fourth of 1.)* Table 7 contains constructional data for an $f/3$ Schmidt.

TABLE 7

Equivalent Focal-length	1.000
Diameter of Primary	0.450
Focal-length of Primary	1.000
Diameter of Correcting Plate	0.450
Distance of Correcting Plate from Primary	2.000
Clear Aperture	0.333
Tube-length	2.100

Modifications of the Schmidt

Further efforts have been made to overcome the chief disadvantages of the Schmidt camera. F. B. Wright and Y. Väisälä independently have investigated the possible positions of the correcting plate and form of the primary mirror in more detail. Each found that by varying these quantities a coma-free and spherically corrected system is obtainable for each position of the correcting plate along the axis. One particularly useful type, in America called the *Wright* type, although any of the family may be called a Wright type, combines a correcting plate immediately behind the primary focus (see Figure 49) with an oblate spheroid primary mirror; the tube-length is therefore just one-half as long as the Schmidt of equal focal-length and the same length as a Newtonian-type telescope. Moreover, the focal surface is plane. Because of the departure from the Schmidt property of complete symmetry, the Wright camera has astigma-

* Form 2 has the radius of the zone of zero deviation (at *a* in the figure) equal to about 0.87 of the radius of the clear aperture. Many workers prefer that this zone lie slightly closer to the center of the plate. The central bulge in the correcting plate also has the effect of improving the *monochromatic* performance of the Schmidt.

tism. The field is therefore limited in comparison to the Schmidt. The color error of the correcting plate is just double that of the Schmidt of equal speed. For large-scale photography the Wright type is more convenient than the Schmidt. The speed should not exceed $f/3$, if the greatest value of this type of camera is to be

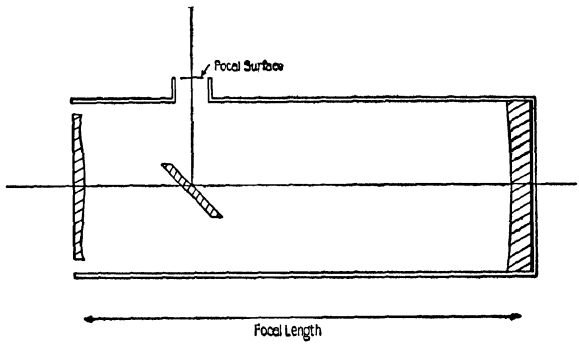


Fig. 49.—The f/3 Wright type.

The prime focus is quite accessible by placing the correcting plate slightly farther away from the primary; however, the convenience of the Newtonian arrangement recommends itself, and at $f/3$ the loss of light is of little importance.

realized, but an $f/3$ camera is amply fast with modern photographic materials. Table 8 contains constructional data for an $f/3$ Wright camera.

The correcting plate of either the Wright type or the Schmidt can be fully achromatized by constructing a paired correcting plate of crown and flint, both deformed from a sphere. Such a system is for practical purposes as completely colorless as a

TABLE 8

Equivalent Focal-length	1.000
Diameter of Primary	0.380
Focal-length of Primary	1.000
Diameter of Correcting Plate	0.333
Distance of Correcting Plate from Primary	1.000
Clear Aperture	0.333
Tube-length	1.100

mirror. Several workers have suggested making the correcting plate not as a lens but as a tilted elliptical mirror. Such a mirror lacks symmetry, however, and is not as good as the achromatic correcting plate.

In 1941 D. D. Maksutov of the State Optical Institute at Moscow made the discovery that the correcting plate of the Schmidt camera can be replaced by what is known as an achromatic meniscus lens. It is possible to devise a weakly negative meniscus lens that is nearly completely achromatic, even though made of only one piece of glass, and yet retain sufficient spherical aberration to correct a primary spherical mirror. Maksutov develops numerous ramifications of his systems as applied to astronomical instruments in the May, 1944, issue of the Journal of the Optical Society of America to which the reader is referred for a detailed account.

In general the Maksutov systems achieve wholly the purpose of the Schmidt camera in providing large highly corrected fields of view even at low *f*-numbers. Their immediate advantages over the Schmidt camera lie in ease of construction and shortness of tube-length. However, like the Schmidt camera the Maksutov systems have curved fields and in the two element form offer the same practical problems of arranging a convenient plate-loading device in the center of the tube.

At very low *f*-numbers the Maksutov systems can compete with Schmidt cameras only by increasing the overall size of the system for a given focal-length. Below $f/1$, although we must speak in approximate language, the Schmidt camera becomes superior once more in compactness and optical quality.

Because of the curvature of field the Maksutov systems fall short of meeting ideal requirements. Consequently, it is worth while to pursue the subject further.

A Two Mirror System with Correcting Plate

The practical lens and mirror systems resulting from a complete analysis of systems consisting of but two optical parts

have been discussed above. There are no other such systems of distinct type possible.* For further improvement we must consider optical systems containing three or more distinct parts. Three curved mirrors on the same optical axis under most conditions will hopelessly block the light from the plate. Two rather interesting exceptions exist. The first type employs a primary concave paraboloid, a flat mirror at the focal surface whose function is to divert the rays at right angles to the original optical axis, a collimating concave hyperboloid, and a tertiary concave sphere. The three concave mirrors combined yield a curved field free of spherical aberration, coma, and astigmatism. In this system the primary can also be spherical and the tertiary parabolic without change in performance. Apart from direct photography such a system can be useful for slitless spectroscopy (see Chapter 5).

The second type in its simplest form employs only three curved mirrors aligned on the same optical axis. This type has a primary concave paraboloid with central hole, a collimating convex hyperboloid inside focus, and a camera concave sphere. No alternate arrangement exists. This system yields a flat field free of spherical aberration, coma, and astigmatism. The sphere lies behind the primary, which must have a central hole about the diameter of the hyperbolic secondary. The hyperbolic mirror is more strongly deformed than the usual Cassegrain secondary. Such a system can also be useful for spectroscopy. The advantages of having a primary parabolic mirror are evident.

A system of two curved mirrors and one lens is possible, but unless the lens system be like a correcting plate or in the converg-

* Schwarzschild found an *im*practical system of two mirrors with zero spherical aberration, zero coma, zero astigmatism, and flat field. The primary mirror is convex, the secondary, concave; the photographic plate is unfortunately concealed behind the primary where no light can reach it except for a very small region around the optical axis. Its large mathematical field is therefore nonexistent physically. The corresponding two-surface thick lens, except for its color aberration, is completely corrected and practical.

ing beam, the system cannot be very large in diameter. We therefore should consider the properties of a system composed of a correcting plate, a large concave mirror, and a secondary mirror.

We can arrive at such a system from the Schmidt camera in the following way. Let us place a plane mirror in the converging beam of the Schmidt (Figure 50). The focal surface is reflected in the mirror to the position shown, but otherwise the imaging quality of the system is unaffected. Now let us keep spherical aberration, coma, and astigmatism all zero, but endeavor by varying separation and mirror curvatures to flatten the field.

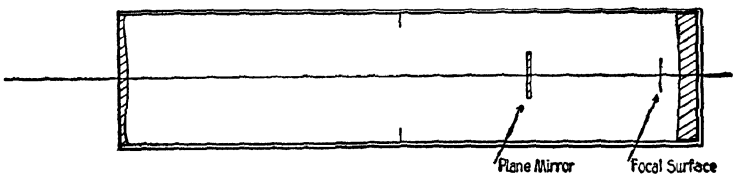


Fig. 50.—Schmidt with plane mirror.

The plane mirror must cut out a sizeable portion of the aperture if vignetting is to be avoided. With such an arrangement it would be better to tolerate vignetting.

We will find that the secondary becomes more and more convex, until finally the field is completely flat.

For each position of the photographic plate relative to the secondary mirror and for each distance of the correcting plate from the primary mirror there exists such a highly corrected system. Figure 51 shows three such telescopes relative to a Schmidt of the same equivalent focal-length, light efficiency, and size of field. Camera *a* has the virtue of a very short tube, but its mirrors depart from spheres. Camera *b* has a spherical secondary with the primary almost so. The departure of a 12-inch diameter primary for an *f*/2.3 system from a spherical surface amounts to only ¾ of a wave-length of sodium light, and hence is not difficult to achieve. Camera *c* has a spherical primary with the secondary almost so. To the eye it is indistinguishable

from Camera *b*. Any one of these cameras will provide equally good photographs over a large field.

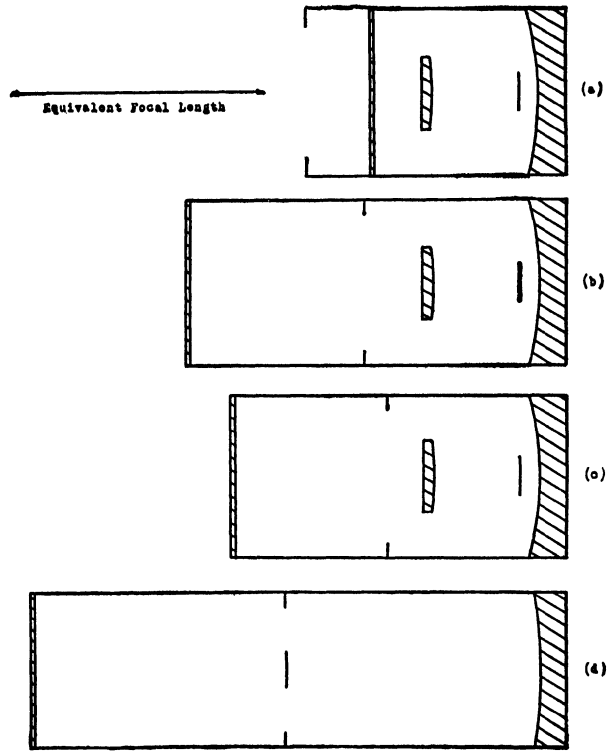


Fig. 51.—In the above diagrams.

(*a*) represents a very short camera with aspheric mirrors; (*b*) represents a medium length camera with one mirror spherical, the other nearly so; (*c*) represents a camera free of distortion; (*d*) is the Schmidt camera. All four have equal focal-length, plate area and effective speed. The first three have accurately flat focal surfaces.

Camera *b* is the most practical in that the primary can be figured zonally, and the secondary figured by interference-testing against the primary, since the central radii of primary and secondary are identical or nearly so. The tube-length is moderate,

and the field is accurately flat over as much as 10 degrees. Computation shows that such a system will yield images on a plane surface at a speed of $f/2.3$ smaller than the resolving power of fast photographic materials over a total field of eight degrees. Table 9 contains constructional data for an $f/3$ Camera *b*.

TABLE 9

Equivalent Focal-length	1.000
Diameter of Primary and Correcting Plate	0.333
Focal-length of Primary	0.650
Separation of Mirrors	0.423
Diameter of Secondary	0.167
Focal-length of Secondary	0.650
Distance of Focus from Secondary	0.350
Distance of Correcting Plate from Primary	1.394
Tube-length	1.500

Table from J. G. Baker, Amer. Phil. Soc., Vol. 82, No. 3, 1940.

A two-mirror and correcting plate system developed recently in England by E. H. Linfoot as an extension of some important general equations and concepts initiated by C. R. Burch is similar to the cameras in Figure 51, except that primary and secondary are exactly spherical, and the focal plane lies just behind the primary mirror. However, the optical performance suffers from astigmatism, which is approximately one and a half times as large as in the Schwarzschild type, from color aberration over twice as large as in the Wright type, and from considerable silhouetting by the secondary mirror. The Newtonian arrangement of the Wright type, if astigmatism must be retained, is as easy to build, and gives appreciably better performance.

H. Slevogt, in the Zeitschrift für Instrumentenkunde in 1942, contributed an important summarizing paper on the various types of systems described above, in which by altering Type *b* so as to reintroduce a relatively slight amount of astigmatism, he obtained a system with both mirrors accurately spherical.

Table 10 compares the various lens system described above for relative effectiveness. All of these systems are useful at the tabulated speeds, and in general have individual advantages.

TABLE 10

Camera Type	*Spherical Aberration*	*Coma*	*Astigmatism*	*Curved Field*	*Average Speed*	*Tube-length*
Paraboloid	0	*	*	*	*f*/5	medium
Refractor	0	0	*	*	*f*/15	medium
Schwarzschild	0	0	*	0	*f*/3	long
Couder	0	0	0	*	*f*/3	long
Ritchey-Chretien	0	0	*	*	*f*/7	short
Schmidt	0	0	0	*	*f*/3	long
Wright	0	0	*	0	*f*/3	medium
Maksutov	0	0	0	*	*f*/3	medium to short
Three-mirror	0	0	0	0	*f*/3	medium to long
Corr. pl. two-mirror	0	0	0	0	*f*/3	medium to short

The asterisk indicates the existence of a substantial amount of the designated aberration.

The Photographic Doublet

The type of lens system shown in Figure 52 has performed valuable work for astronomy. The doublet was introduced into photography nearly a century ago by Petzval of Vienna. There exist many possible forms of lens systems derived from his design. The combination shown in Figure 52 is called the *Astrographic* lens. Contrary to the original Petzval type its second achromat is negative, so that nearly complete correction for curvature of field is possible. Constructional data for such a lens are given in Table 11.

The astrographic doublet is well corrected for the image defects of spherical aberration, coma, astigmatism, and curvature of field. The most important residual aberration is that of secondary spectrum. The secondary spectrum of the astrographic doublet is greater than that of the simple objective, and similarly, with ordinary glasses cannot be eliminated.

The long focus doublet will yield a field of about ten degrees on a flat plate, and consequently can be useful for survey work.

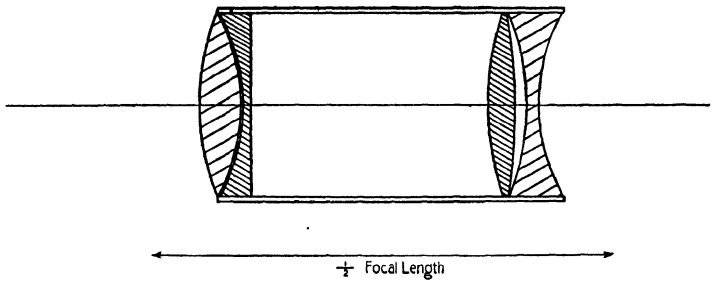


Fig. 52.—The Astrographic telescope.

This type has the advantage that its tube-length is appreciably shorter than the focal-length.

TABLE 11
Equivalent Focal-length 1.000

	First lens	*Second lens*	*Third lens*	*Fourth lens*
Index of refraction...	1.5	1.6	1.6	1.5
ν-value.....	65.0	38.3	42.5	65.0
Front radius.....	0.263	− 0.214	0.333	−0.264
Back radius.....	−0.207	−17.7	−0.678	0.194
Thickness.....	0.045	0.007	0.027	0.014
Distance to next lens..	0.000	0.259	0.014	

Recommended speed, f/7. Table from A. Kohlschütter-Thesis, Göttingen, 1908.

Another advantage of the doublet is that its tube-length is appreciably less than its focal-length.

The Cooke Triplet

The *Cooke* lens was designed by Dennis Taylor for the firm of T. Cooke & Sons before the turn of the century. Its announcement marked a distinct advance in lens design. Earlier investigators had either not appreciated the possibilities of three separated simple lenses, or were unable to exact the utmost from such a combination. Probably the first conjecture is nearer the truth in view of the many complicated lens forms on the market at that time. The triplet has been of great use to as-

Unfortunately, large effects of secondary spectrum, chromatic difference of spherical aberration, and astigmatism are likely to prove a handicap in many types of work.

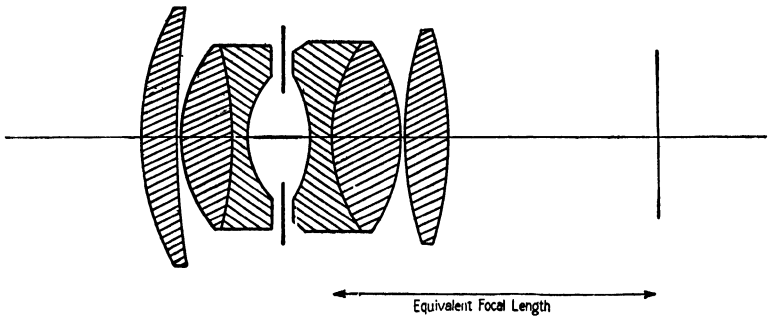


Fig. 56.—The Zeiss Biotar.

The normal photographic speed of this lens is $f/1.4$, and the field is about 45 degrees. Astronomically, good results will be obtained at $f/2.5$ over a total field of 30 degrees.

Miscellaneous Lenses

There exist at the present time a very large number of lens types produced for commercial use that may be used in astron-

TABLE 13
The Biotar
Equivalent Focal-length 1.000

	First lens	*Second lens*	*Third lens*	*Fourth lens*	*Fifth lens*	*Sixth lens*
Index of refraction	1.6424	1.6231	1.5757	1.6727	1.6424	1.6424
ν-value	48.0	56.9	41.2	32.2	48.0	48.0
Front radius	0.836	0.448	11.50	0.385	0.505	1.060
Back radius	3.21	11.50	0.283	0.505	0.532	1.200
Thickness	0.108	0.156	0.051	0.051	0.212	0.139
Distance to next lens	0.017	cement	0.189	cement	0.010	

Table from Handbuch der Wissenschaftlichen und Angewandten Photographie, Band I. Das Photographische Objectiv. W. Merté, R. Richter, M. v. Rohr. Page 328, 14. Recommended speed, f/2.5. Recommended field 30 degrees. Short focus.

omy. Astronomers have often found that commercial lenses tend to yield stellar images surrounded by considerable poorly focused light owing to excess coma, spherical aberration, or both. Many commercial lenses have so much spherical aberration that images slightly out of focus look much like doughnuts instead of presenting the uniform disc one desires. The only safe rule is to try out all available lenses before making any decision. Table 13 gives data for a six-component lens of proved quality.

Limiting Magnitude

In choosing the focal-length and aperture of a telescope to be used photographically, one must consider his needs very carefully. One of the most important questions involved is that of *limiting magnitude.** Regardless of exposure time a camera can photograph no extended object whose surface brightness is less than about a sixth of the sky background. The seeing disc of a star may be considered a small surface to which the same rule will apply. The magnitude of the faintest star discernible on the photographic plate, exposed sufficiently long to have a moderately dense sky fog, is called the limiting magnitude of the telescope. The limiting magnitude is independent of the exposure time, or at least nearly so.

The speed with which the luminous sky background is recorded on a photograph depends on the focal-ratio of the camera. For example, in an $f/1$ camera a medium fast plate can be exposed no longer than twenty minutes. In an $f/2$ camera the plate can be exposed perhaps one and one-half hours for the same fog density. In an $f/5$ camera the same medium fast plate can be exposed for many hours. Let us suppose that each of these cameras has an aperture of ten inches. If seeing and diffraction can be neglected, the star image in each case will be exceedingly small. Consequently the $f/2$ camera will go well over a magnitude fainter than the $f/1$; the $f/5$ will go about three magnitudes fainter than the $f/1$. Table 14 contains sufficient data for

*For discussion of magnitudes see Chapter 6.

determining the approximate limiting magnitude of a given telescope. These data were prepared by calculation from considerations of seeing, turbidity, and sky brightness, and are in very good agreement with observation.

For most purposes an exposure time of several hours is all the usual work should require. The exposure time should seldom be longer than several hours inasmuch as the star field should be near the celestial meridian. Changes in sky transparency during longer exposures are often ruinous to photometric accuracy. Consequently, cameras with speeds ranging from $f/3$ to $f/5$ are quite adequate for direct photography. Near cities, where the sky background is unusually strong, no camera faster than $f/5$ ought to be used.

TABLE 14

Aperture		*f/3*		*f/5*		*f/7*	
Cms.	*Inches*	*Image Diam. mms.*	*Lim. mag.*	*Image Diam. mms.*	*Lim. mag.*	*Image Diam. mms.*	*Lim. mag.*
1	0.4	0.023	10.20	0.026	11.18	0.028	11.84
2.5	1.0	.024	12.15	.027	13.12	.030	13.74
5.0	2.0	.025	13.61	.029	14.55	.032	14.28
7.5	3.0	.026	14.44	.031	15.36	.035	15.96
10.0	3.9	.027	15.03	.032	15.96	.037	16.51
15.0	5.0	.030	15.80	.036	16.71	.042	17.27
20.0	7.9	.032	16.35	.040	17.21	.047	17.77
25.0	10.0	.034	16.77	.043	17.62	.052	18.15
30.0	11.8	.036	17.10	.047	17.92	.058	18.42
40.0	15.7	.041	17.58	.054	18.39	.068	18.88
50.0	19.7	.045	17.96	.061	18.75	.078	19.21
60.0	23.6	.049	18.28	.069	19.01	.088	19.48
75.0	29.5	.056	18.61	.080	19.33	.103	19.79
90.0	35.4	.062	18.90	.091	19.59	.119	20.04
100.0	39.4	.067	19.05	.098	19.74	.129	20.17

Table from Whipple and Rubenstein, Pop. Astronomy, 1941.

5

SIFTING LIGHT—SPECTROSCOPY

THE INSTRUMENTS AND TECHNIQUES DISCUSSED IN PREVIOUS chapters make up only part of the quantitative methods used in studying the physical character of the universe. The complex bundles of light reaching us from various sidereal objects contain additional wealth of information accessible to us through the aid of an instrument called the *spectroscope*.

Newton's classical observation in 1666 that white light is made up of component colors was the first step in the development of the spectroscope, the most powerful single tool of astrophysics. This instrument, in a variety of forms, serves to spread out white light into its constituent colors. The spectroscope is to astrophysics what the telescope is to astronomy. Without the spectroscope our knowledge of cosmic physics would be seriously limited; with it the collective activities of atoms in the sun, stars, and space are rendered observable.

Figure 57 shows the arrangement of a typical prism spectroscope. The *slit*, a narrow slit-like opening, shown perpendicular to the plane of the paper, replaces the hole in the window-shade used by Newton. Light after entering the slit, diverges as if the slit were the source of the illumination, and is received by a lens at *A* called the *collimator*. The collimator is placed so that the slit lies at its focus and the light from the slit is therefore converted by refraction through the collimator into a parallel beam of light.

The beam of light on leaving the collimator passes into the prism and out again, undergoing two refractions with an accom-

panying change in the direction of the light beam. Blue light suffers a greater change of direction than red light. The direction of the light leaving the prism depends therefore on the color of the light. This action of the prism in differentiating between colors is called *dispersion* of the light.

The light leaving the prism enters a second lens and is brought to a focus. Since the various colors enter the lens or objective in varying directions, a spectrum is produced in the focal plane of this objective. Referring again to Figure 57, we

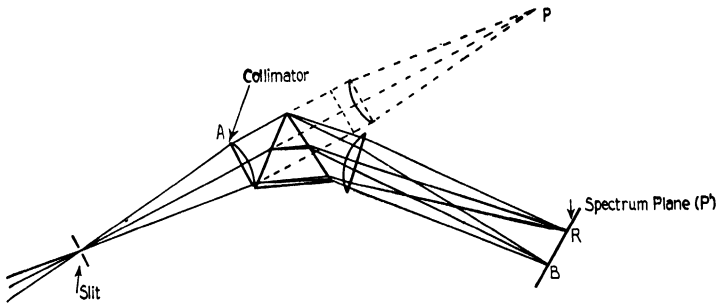


Fig. 57.—The elementary slit spectroscope.

see that red light is focused at *R*, blue light at *B*. The spectrum can be examined with an eyepiece, hence the term spectroscope. If, for the purpose of recording the spectrum, a photographic plate is placed in the focal plane of the telescope lens, the spectroscope is thereby converted into a *spectrograph*, the customary modern form of the instrument.

In order to understand the nature of this instrument, let us imagine that the slit is illuminated by light of a single color. Such *monochromatic* light will be deviated by the prism, but will not be dispersed. The collimator and telescope lenses together produce an image of the slit at P' in Figure 57. If the slit is narrow, the image will be simply a line at P' (and like the slit, perpendicular to the plane of the paper). The position of this line in the focal plane of the telescope will depend on the single color chosen for the observation. If red light is chosen,

a red-colored line will fall at R; if blue light, a blue-colored line at B.

Now let us imagine that the incident light is composed of a number of individual colors. Before entering the slit, these colors are mixed, but in the focal plane of the spectroscope they are resolved into a series of narrow slit images whose positions in the spectrum depend on the colors chosen. If we remove the prism and place the two lenses on a common axis, all colors will come to a single line focus at P, Figure 57, and are unresolved. The prism, therefore, is the essential feature of the spectroscope.

The Diffraction Grating

A glass prism is not the only device that can spread light into a spectrum. The action of the prism depends on the relation of refraction to color for the type of glass employed. It is also possible to make use of the principle of diffraction. Many thousands of narrow, parallel straight lines are ruled side by side and equally spaced on a suitable reflecting or transmitting surface. The resultant grating is called respectively a reflection or a transmission *diffraction grating*.

White light incident on the ruled surface of a transmission grating as shown in Figure 58 is diffracted in all directions by the effect of the narrow rulings. In accordance with Huygens' principle (Chapter 1) the transmitting interspaces between the rulings behave as new sources of light. From the various points a, b, c, etc. of Figure 58 we must consider the light as spreading out in spherical wave-fronts with resultant interference. The points on the wave-fronts proceeding in the direction $a0$, $b0$, $c0$, etc. are in phase on a plane surface and represent an advancing wave-front. If this advancing wave-front is brought to a focus by a lens, an image will be produced at 0. The sharpness of this image depends on the number of rulings contributing to the image. Light waves proceeding in directions different from $a0$, $b0$, etc. suffer destructive interference.

The points on the wave-fronts proceeding in the direction *a*1, *b*1, *c*1, etc. are also in phase along an advancing wave-front in the position shown. The light from *b* is a wave-length behind that from *a*, from *c* a wave-length behind *b*, etc. The direction 1 depends therefore on the wave-length. The advancing plane wave-front of red light is deviated more than blue light. A lens will focus a red image at *R*, a blue image at *B*. The various

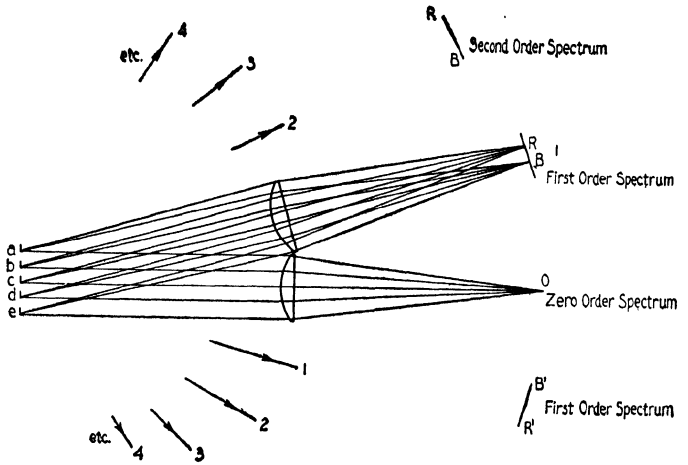


Fig. 58.—The diffraction grating.

The overlapping of spectral orders is eliminated to avoid confusion.

spectral colors will focus in the same sequence found in prism-made spectra.

Light waves proceeding in direction *a*2, *b*2, *c*2, etc. are again in phase along a plane wave-front. The light from *b* is two full wave-lengths behind *a*; from *c*, two wave-lengths behind *b*; etc. The resultant spectrum formed by a lens not only is deviated more than direction 1, but the spectral colors are spread out about twice as much.

Light waves proceeding from other points within any transmitting interspace must be considered as interfering in the above fashion with corresponding points of the other interspaces. In

the direction 0, 1, 2, 3, 4, etc. these light waves interfere constructively. In any other direction the light waves interfere destructively to a degree dependent on the number of rulings and on the direction. A spectral-line image formed by a lens and diffraction grating will have a sharpness increasing with the number of rulings. The highest quality optical gratings may have as many as 15,000 to 30,000 lines to an inch, and perhaps a hundred thousand lines in all.

The image formed at 0 of a slit illuminated by white light is called the *zero-order spectrum* (Figure 58). The sequence of spectral colors formed in direction $1R$-$1B$ is called the *first-order spectrum.* Another first-order spectrum is formed on the opposite side of the zero-order spectrum in direction $1R'$-$1B'$. Likewise the spectral colors in the direction $2R$-$2B$, and $2R'$-$2B'$ are called *second-order spectra,* etc.

In the first-order spectra the angular deviation of light is very nearly proportional to wave-length. Contrary to prism action blue light is least deviated and red light most deviated. In the second-order spectra the colors are spread out twice as much as in the first-order, in the third-order three times as much, etc. The red of the first-order overlaps the blue of the second. Wave-length 8000 A. of the first-order, one wave-length phase lag, coincides with wave-length 4000 A. of the second-order, two wave-lengths phase lag. Wave-length 12000 A. of the first-order coincides with 6000 of the second, 4000 of the third, 3000 of the fourth, etc. Such overlapping has proved to be of considerable importance in the determination of precise wave-lengths in bright-line spectra. In practice the confusion of orders is usually confined to first and second orders; the two colors overlapping at any one wave-length can be isolated from one another by suitable filter or photographic plate. For example, a red filter while transmitting first-order red light (8000 A.) blocks second-order blue light (4000 A.).

The opaque areas of the grating serve the purpose of blocking off those Huygens wavelets that point by point would lag

½ wave-length, 1½ wave-lengths, 2½ wave-lengths, etc. and which would therefore cause complete destructive interference in every direction except 0, as in the propagation of an uninterrupted beam of light. Since the wavelets spreading outward from the interspaces have a maximum of intensity in the direction 0 and diminishing intensity to either side (see Chapter 1), the zero-order spectrum contains a large share of the light, the first-order spectra much less, the second considerably less, etc.

Reflection gratings are generally ruled on either a polished metallic surface like speculum metal, or on an aluminum film on glass. A few gratings have been ruled on soft glass, which can thereafter be silvered repeatedly. Such gratings, if properly made, have a very high degree of resolution. Transmission gratings are made by coating a master reflection grating with some suitable material like collodion or one of the synthetic resins. After drying, the film is peeled off and mounted onto a glass plate; such gratings are mediocre because of unequal drying of the film, stretching, or inadequate mounting. The best transmission gratings are made by floating the film from the master to the final glass plate on which the drying takes place under the best possible conditions.

The amount by which the light is spread out in direction with respect to color, whether by prism or grating, is called the *angular dispersion.* The angular dispersion produced by a prism is not uniform with respect to wave-length; in the focal plane of the telescope objective, the red end of the spectrum is crowded together, the blue end spread out. The angular deviation produced by a diffraction grating, however, is nearly uniform with respect to wave-length. We speak of *prismatic dispersion* and *normal dispersion*, respectively.

Prismatic dispersion is usually inadequate for studies of the red end of the spectrum, and for such purposes the prism is often replaced by the grating. Prism spectrographs frequently contain two or more prisms in a *prism train* for the purpose of increasing the angular dispersion. Grating instruments use only one

grating, because otherwise there would be hopeless overlapping caused by each order from one grating being divided into a new series of orders at another grating.

The amount by which the spectrum is spread out in the focal plane of the spectrograph is called the *linear dispersion.* Linear dispersion is usually expressed in angstroms per millimeter. Because of the nature of prismatic dispersion it is customary to give the linear dispersion for a prism spectrograph at a specific wave-length, or to specify the number of millimeters between standard lines of the spectrum. The smaller the number of angstroms to the millimeter, the more detail one can measure in a photographically well-defined spectrum. By a twist of speech we speak of low dispersion spectra when the number of angstroms per millimeter is large; for example, 300 A./mm is called *low* dispersion, whereas 3 A./mm is considered *high* dispersion.

The linear dispersion of an instrument depends on both the angular dispersion and the focal-length of the telescope or camera lens. One sees immediately that a prism of very small angle will not help in producing a very high linear dispersion, nor will a prism of large angle used with a lens of short focal-length. In practice prisms have angles in the neighborhood of 60 degrees, although the exact angle is usually chosen to correspond to maximum efficiency at the wave-length deemed most important in the work of the instrument.

The angular dispersion obtained from a given 60-degree prism depends on the kind of glass employed. A crown glass is much less dispersive than a heavy flint glass at a given wave-length in the spectrum; for visual light, flint prisms are therefore employed. Crown glass is more transparent in the violet and especially the ultra-violet than flint glass. Spectrographs designed for ultra-violet photography therefore employ a light crown glass of high ultra-violet transparency. Because of the nature of prismatic dispersion, such a prism will provide a dispersion in the ultra-violet comparable to that produced by a flint prism in the violet.

Many astronomical spectrographs designed for ultra-violet work employ quartz (SiO_2), a rather common substance that is extremely transparent to ultra-violet radiations. Crystal quartz (as opposed to "fused" quartz or vitreous silica) is generally employed because optically perfect pieces are available. However, crystal quartz is birefringent (see Chapters 1 and 7) and would yield a double image if not compensated. Space is too limited here to discuss thoroughly how this compensation is achieved in practice. Fused quartz recently available as a commercial product is in principle isotropic, but to date in America and England it lacks sufficient homogeneity for precision uses in large sizes. (See Chapter 1.)

A single prism of dense flint glass with a 60-degree angle used with a 12-inch camera will produce a linear dispersion of 60 A./mm (Angstrom units per millimeter) at 4340 A.* At 6563 A. the dispersion of the same combination has changed to about 200 A./mm. A grating with fifteen thousand rulings to the inch, used with the same 12-inch camera lens, provides a dispersion of about 60 A./mm throughout the spectral range of the first-order, and about 30 A./mm in the second-order.

A highly dispersed spectrum ordinarily will reveal more detail than one of small linear dispersion, and its spectral resolution is therefore said to be better. The *resolution* is expressed by the minimum separation in angstroms of two lines barely detectable as distinct. For example, an instrument barely able to separate the two sodium lines at 5890 and 5896 has a resolution of 6 A.

Astronomical Spectroscopy

Wollaston at the beginning of the nineteenth century was the first to apply the principle of the spectroscope to a study of

* Wave-lengths 6563 ($H\alpha$ or C), 4861 ($H\beta$ or F), 4340 ($H\gamma$ or G), and others are the nearly monochromatic spectral lines of hydrogen which are prominent in the spectra of stars and nebulae. Since these wave-lengths can be produced in the laboratory, they are often used as reference points in the spectrum.

the sun. He found seven dark lines in the solar spectrum, but failed to interpret their significance. Fraunhofer followed with a much more extensive effort about 1814, and in the course of his investigations found nearly 600 such dark lines. Of these he recorded the positions of 324, but was unable to explain their origin.

In 1817 Fraunhofer turned to a comparison of starlight with sunlight. Only the spectra of the brightest stars could be examined and the results were uncertain. His observations of the planets Venus and Mars showed that as far as his eye could discern, the reflected light from the planets was identical with sunlight. With more efficient apparatus his observations of 1823 indicated that stars differ among themselves, and that some resemble the sun. The new astrophysical tool thereby opened the way to entirely new fields of research.

The first major effort to apply the spectroscope to the stars was that of the Jesuit priest and Italian astronomer, Father Secchi. About 1863 Father Secchi procured a spectroscope of relatively great light efficiency and resolution. Secchi's main advance over Fraunhofer's work and his own early work involved a new type of spectroscope employing a *direct vision* prism. The prism train consisted of alternate crown and flint prisms cemented together. Such alternate construction permitted the optical axis to remain undeviated, but retained dispersion. The cemented interfaces removed the loss of light by reflection. Father Secchi's work began shortly after the fundamental laws of spectroscopy had been enunciated by Kirchhoff, and he was therefore able to reach some conclusions about the true nature of the stars from the observed spectra. After Secchi's time spectroscopes began to fall into distinct types which are best examined in their modern forms.

The Objective Prism

Wherever incident light is already parallel, the collimator and slit of a spectrograph can be omitted. This requirement is

met by starlight before it strikes a telescope objective. The objective prism is simply a glass prism placed over the objective of the telescope. The telescope thus becomes a spectroscope that needs no slit or collimator. After passage through the prism the

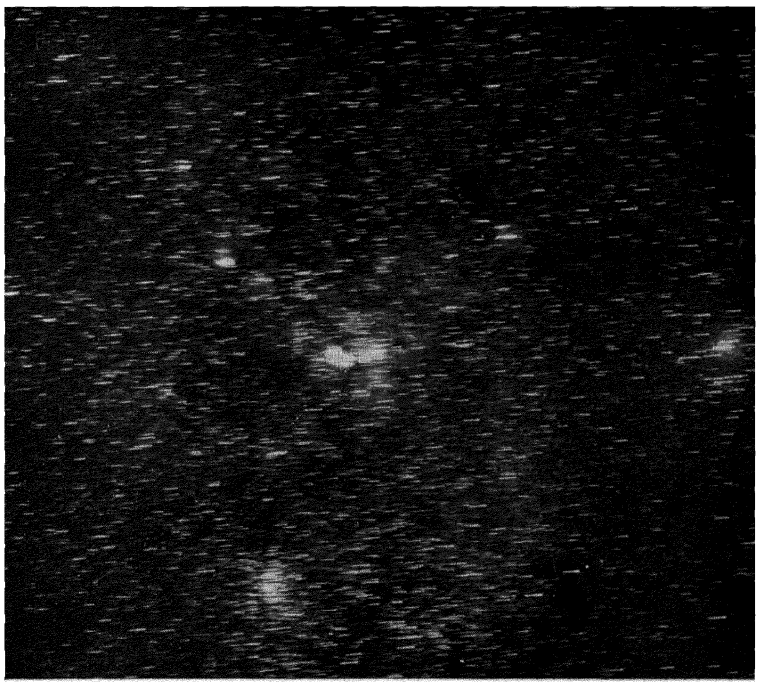


Fig. 59.—The region around η Carinae.

starlight is brought to a focus by the telescope as a narrow spectrum in the focal plane. (See Figure 59.)

The focal-length of the telescope used with an objective prism is ordinarily so long that the prism angle must be small in order not to disperse the starlight more than is necessary. A prism angle of the order of three to five degrees is quite customary, and indeed, the prism is made usually of crown glass of relatively low dispersion. The low prism angle is of practical importance, for

it means that a prism can be made from glass plates of rather small thickness with consequent adequate transparency and reduced cost.

The objective prism arrangement provides simultaneously the spectra of all stars in the usable field of the telescope. Moreover, the prism becomes an accessory of the ordinary photographic telescope, detachable, and insensitive to adjustment.

The light entering an objective prism from a star, except for atmospheric disturbances, is parallel in all colors, regardless of the angle of incidence. The only optical disadvantage introduced by the prism is a variation of dispersion over the plate; the variation is slight, and for most purposes is quite unimportant. The objective prism is a generally useful instrument, and is indispensable in astronomical research.

The stellar spectrum formed in the focal plane of an objective-prism camera is a narrow streak whose width, if the telescope is free of spherical aberration, depends on the seeing. In order that the spectrum be wide enough for observations of spectral lines, the entire telescope must be trailed back and forth. For this purpose, the prism is placed with dispersion in the declination direction. The widening of the spectrum can then be accomplished easily by weighting the driving clock fast or slow by the number of grams necessary to produce the desired width in the proper exposure time. The observer at the telescope must see that a star image in the guiding telescope follows the declination cross-wire as closely as possible, for on the accuracy of guiding depends the straightness and sharpness of the spectral lines. Because of slight irregularities in the clock drive, and changing atmospheric refraction accompanied by an atmospheric spectrum caused by dispersion within the earth's atmosphere, dependent on the altitude of the star field above the horizon, it is advisable to trail the star image back and forth a number of times during the exposure if it is desired for photometric purposes that the spectrum be of uniform density throughout its width. For best definition and resolving power, however, such as

would be needed in spectral classification, a single trailing and relatively broad spectrum is desirable.

What are the principles governing the design of a good objective prism camera? For a given kind of research the dispersion and desired width of spectrum must be decided upon. The area on the photograph covered by the light of any individual star is thereby determined. For a given area covered by the spectrum the photographic speed will depend on how much energy can be concentrated upon this area, and therefore on the amount of light collected by the telescope. For a given dispersion and width of spectrum, the larger the aperture, the fainter the stars whose spectra can be photographed at a given photographic density in a given time. A 24-inch objective prism camera will record spectra of stars about four magnitudes fainter than a 3-inch telescope can record for identical spectra and exposure time.

In order to eliminate the "seeing" from the spectral lines, it is desirable to have a camera with as short a focal-length as possible. The seeing disc in the focal plane of a camera of given aperture decreases in proportion to the decrease in the focal-length. As mentioned above, for the purpose of collecting as much light as possible, the aperture should be increased as much as practicable (but see below). After the design of the camera is decided upon, one chooses the prism angle and type of glass to provide the desired dispersion. So far, therefore, it would seem that we need a large-angle prism of high dispersive power in front of a very short focal-length camera of very large aperture (for example, an $f/1$ Schmidt). However, exposure times cannot be long with a fast camera because of the rapidity with which sky fog is recorded. Stars whose light is spread out into a spectrum of lower brightness than the sky background on the photograph will have no time to be recorded before the plate is blackened by sky fog. In order to eliminate the difficulties with sky fog, it is necessary to use a slow camera and small prism angle. This is an unfortunate conflict in requirements.

One must pursue a middle course by choosing the best observing location available in regard to blackness of sky and quality of seeing, and by adopting a moderate focal-ratio camera.

If a maximum exposure time of two hours seems reasonable, an $f/5$ telescope is recommended; it will not photograph excessive sky fog in that time. Longer exposures encounter serious atmospheric difficulties, particularly near the horizon. With such a camera, for minimum useful width of spectrum (about 0.3 mm), the attainable limiting magnitude depends only on the adopted dispersion. The resolution will depend on the seeing, and on the resolving power of the photographic material used. An 11-inch diameter objective prism camera giving a dispersion of about 100 A./mm at 4340 A. (violet) will furnish satisfactory spectra of 10th magnitude stars on the fastest plates in an exposure time of two hours. When the seeing is good, the resolution on the plate is of the order of 25 microns, corresponding to about 2.5 angstroms.

Most objective prisms in use today are low-angle crown glass prisms. Occasionally, large-angle prisms have been employed with short focal-length cameras, notably for the study of meteor spectra. Some progress has been made toward making prisms of glass of relatively high dispersion in order to minimize the angle of the prism. The Harvard Observatory possesses two 24-inch diameter objective prisms that have long been used at the northern and southern stations for low dispersion studies of stars down to the 12th magnitude. Plans are in progress for the construction of another 24-inch prism for the Harvard 24–33-inch Schmidt camera. A 24-inch prism made of flint glass for the 24–36-inch Schmidt camera of the Warner & Swasey Observatory has just been completed, and gives excellent spectra with a dispersion of about 250 angstroms per millimeter.

The Objective Grating

As in the case of the simple objective-prism spectroscope already described, it is possible to obtain the required dispersion

by the use of an objective grating. Until very recently objective gratings of sufficient size and light efficiency were unknown.

R. W. Wood in the last few years has perfected a technique of making transmission gratings of great light efficiency. By ruling a master reflection grating with a certain shape of groove, he has been able to concentrate most of the spectral light from the replica grating into one first-order spectrum. Each of the grating rulings is a very elongated small prism that refracts light in the general direction of the first-order spectrum desired. Some of the transmission gratings have achieved a light concentration of as much as 80% in one first-order spectrum.

Because of the limited size of the Rowland ruling engines that make these excellent gratings, the Wood gratings have been no larger than 4½ by 6½ inches, whether of the reflecting or transmitting variety. Wood has been able to piece together many such replicas onto a glass plate to form a larger composite or mosaic grating. As long as the number of lines per inch is exactly the same for all component gratings, and as long as the lines of the various gratings are sufficiently parallel, the stellar spectrum produced by the mosaic retains its purity. The already sufficient resolving power of the grating mosaic will not be higher than that given by one of the component gratings, but more light will have been gained. Fainter stars can be reached. The transparent films must be of constant thickness throughout in order to avoid a prismatic wedge which would deviate the spectra from the individual gratings in undesirable ways from the mean position. Such large mosaic gratings promise to be of considerable value in coming years, particularly for studies of the red, hitherto inaccessible to prism study because of the lack of adequate resolving power at low dispersion.

Most of the research in spectral analysis is now carried on photographically. As in direct photography one obtains the advantages of having a permanent and quantitative record of the spectrum. Also the available range of wave-lengths is greatly superior to visual work. The fastest types of photographic plate

can record faintly in about one minute what the dark-adapted eye can barely detect. If the light can be seen with some ease by the eye, the one-minute exposure will record the light with a reasonable density. The photographic plate has the advantage that it accumulates the light. For a given density on the photographic plate, tripling the exposure corresponds to a gain of about one magnitude. Thus in three minutes exposure the plate will record approximately one magnitude fainter than the eye can detect; in 9 minutes, two magnitudes; in 27 minutes, three magnitudes; in 243 minutes, five magnitudes, etc. Although in "slit" spectrography a record exposure of about eighty hours has been made, exposures are rarely longer than four hours. The photographic method will therefore record objects about five magnitudes fainter than those visible to the eye.

Slitless Spectrographs

A serious practical disadvantage of the objective prism is that it cannot be manufactured in sizes needed for giant telescopes. We have mentioned that the largest prisms are 24 inches in diameter; there are many telescopes (see Appendix) much larger than this. It is possible to overcome this disadvantage to some extent by using a *slitless spectrograph.*

A typical slitless spectrograph employs a negative collimator lens that intercepts the light from the objective *before* it comes to a focus. The collimator lens thereby makes the light once more parallel. After collimation the light may be sent through either a prism or grating for dispersion, and thereafter through a camera lens.

If the camera lens and collimator are of the same focal-length and type of glass, there is no need to achromatize the lenses individually. Moreover, the natural imperfections of the simple collimator lens are for the most part overcome. The two lenses, positive and negative, brought together without a prism have zero net power, and behave like a plane-parallel plate placed in the converging beam. Such a plate of moderate thickness

produces spherical aberration, but not enough to matter. Even through the prism the aberrations of the individual lenses are almost precisely cancelled, provided that the prism is placed so that the bending of the light beam at each surface is the same. Only simple, inexpensive lenses are needed with such an outfit, and the problem of optical design becomes quite elementary.

The slitless spectrograph utilizes the full aperture of the telescope regardless of the size of the telescope. The negative collimator lens must have such a diameter as to accommodate not only the converging beam to the center of the field but off-axis rays as well. The slitless spectrograph then has approximately the same usable field as that given by the telescope directly.

Every instrument has certain disadvantages. The earth's atmosphere imposes a limitation on the effectiveness of the slitless arrangement. Most large telescopes have great focal-lengths, and therefore produce images enlarged by the seeing. Although the seeing disc may still be useful for more accurate photometry, it destroys the definition of spectral lines. A doubling of the focal-length leads approximately to a doubling of the diameter of the star image. For the same spectral resolution therefore, the telescope with twice the focal-length must employ twice the dispersion. The larger telescope of the two generally has about four times the light-gathering power; therefore, for a given spectral resolution and for a constant width of spectrum, the light intensity within the spectrum in the focal plane increases directly with the linear aperture of the telescope. A 60-inch on average nights is only about twice as effective as a 30-inch. In summing up our remarks on the objective prism we noted that for best results an observing locality must be selected where the seeing and sky transparency are excellent. The same conclusion applies in even greater degree to the slitless spectrograph used on a large telescope.

A useful modification can be made in the slitless instrument by replacing the simple camera lens with a much more rapid

camera like the Schmidt. The combination of telescope and spectrograph behaves exactly as if it had the focal-ratio, and hence speed, of the Schmidt. For example, an $f/5$ telescope with an $f/1$ Schmidt camera attached will photograph the sky with the speed of an $f/1$ telescope. One thereby loses scale in the focal plane, but what is often more serious, the sky-fog recorded by the faster camera necessitates stopping the exposure in a few minutes. The latter objection is so serious, that the combination for most purposes should not exceed the speed of $f/3$. The slitless instrument in this modified form must employ a fully achromatized and spherically corrected collimator lens.

Another modification of the slitless instrument employs a positive collimating lens outside the focus of the telescope. Such an instrument is similar to the slit spectrograph with the slit removed. The collimator lens must again be fully corrected. The field of such a slitless instrument can be considerably enlarged by the interposition of a field lens in or near the focus of the telescope imaging the telescope objective on the collimator lens. All light that strikes both telescope objective and field lens will then pass through the collimator lens and thence to the spectral focus. The effect is identical with the action of the field-lens in an eyepiece.

The McCarthy Slitless Spectrograph

E. L. McCarthy has designed for the McDonald Observatory a type of slitless spectrograph that promises to be very useful. (Figure 60.) The collimation is accomplished by the use of a parabolic mirror the focus of which coincides with that of the telescope. The coma of the primary paraboloid (see Chapter 4), so serious to the use of the parabolic mirror in direct photography, is cancelled by the coma of the collimating parabolic mirror. The beam entering the prism is therefore fully corrected for coma and spherical aberration.

The prism is set for minimum deviation, although the nearly perfect type of collimation renders this consideration less impor-

tant than in the case of the elementary slitless spectrograph first described. Behind the prism an $f/2$ Schmidt camera collects the various rays and brings them to a focus. The focal surface of the combination is somewhat more curved than if the same Schmidt were used for direct photography.

The silvered spot on the prism face crosses the focal plane of the primary mirror. This location for the focal plane relative to the prism has the minor disadvantage that the defects in the silver, dust, and pinholes, are in focus on the final picture near

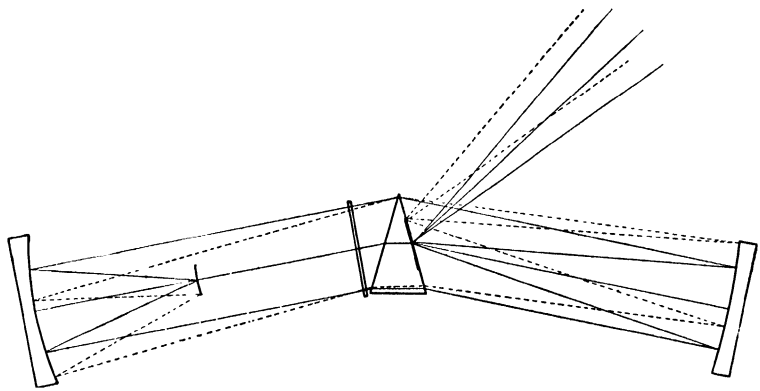


Fig. 60.— The McCarthy slitless spectrograph.

the line where silvered prism surface and focal plane intersect. The purpose of placing the silvered film in the focal plane is to obtain maximum field at full illumination for a collimating mirror of practical size.

The $f/2$ Schmidt camera used in the McDonald arrangement is made possible only by the excellence of the observing locality. In northern latitudes a slower camera should be employed in order to prevent sky-fog from stopping the exposure too soon for the recording of faint stellar spectra.

The forms of slitless spectrographs employing field-lens and positive collimator may be adapted to long exposures by masking off, with a diaphragm placed in the focal plane, the major part

of the sky-fog. If a star field is considered of sufficient importance, a thin metal mask can be made from a direct photograph of the region by punching a hole perhaps 0.1 mm diameter for each star image desired. After suitable orientation of the mask in the focal plane of the instrument, most of the light coming to the final photograph is starlight and not sky-fog. Long exposures can be made in this fashion without seriously fogging the plate. No one seems to have employed this method as yet. Let him who tries the procedure for the first time be forewarned of the need for good adjustments and careful guiding.

The Slit Spectrograph

When adapted to photography a spectroscope like the one described at the beginning of the chapter is called a *slit spectrograph*. The slit of this type of spectrograph serves two essential purposes. First, it can increase the resolution of the spectrograph. The slit opening can be made much narrower than the average diameter of the seeing disc of a star. The wandering of the star image on the slit face and its pulsation in size cannot affect the resolution, although for the sake of light economy an observer must keep the star image continually on the slit to let as much light as possible enter the spectrograph.

Second, the slit occupies a fixed position on the instrument relative to the final photographic plate. A *comparison* spectrum illuminating the slit, consisting usually of bright emission lines from a laboratory source of light, for example, a metallic spark or arc, can be photographed above and below the stellar spectrum. (See Figure 61.) The bright lines used for the comparison spectrum have wave-lengths known with great accuracy from high-dispersion laboratory studies. By measuring the positions of the stellar lines relative to the laboratory lines, one can obtain the wave-lengths of the stellar lines.

The high resolution afforded by good slit spectrographs is of utmost importance to studies of the physical characteristics of the stars and nebulae. Astronomers pay for this advantage by

being able to work on but one star at a time, and by losing considerable amounts of light on a narrow slit.

High-dispersion slit spectrographs are applicable to studies of only the brighter stars. Smaller instruments are necessary for

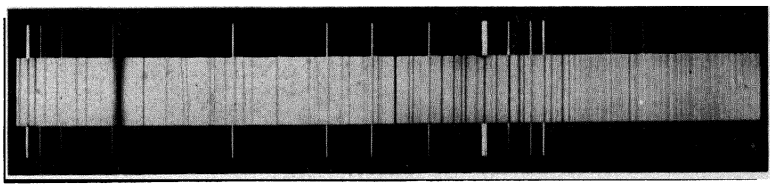


Fig. 61.—The spectrum of Eta Leonis.

The stellar spectrum is bordered above and below by bright lines of the comparison spectrum.

decoding the spectral messages from more distant or less luminous objects. A dispersion of about 100 angstroms per millimeter obtained with an efficient spectrograph on a large reflector at a good location is of considerable importance at the present time in astrophysical and statistical research.

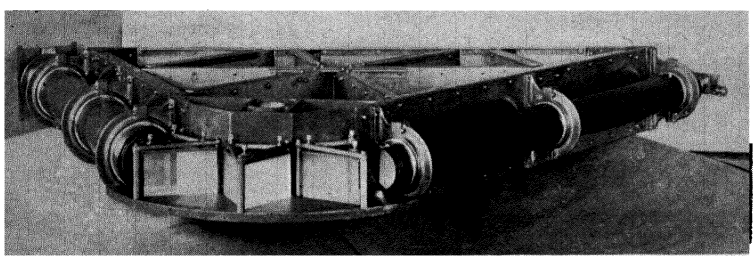


Fig. 62.—A view of a three-prism slit spectrograph.

The collimator is on the right. The three prisms are made of light flint glass for the purpose of transparency in the violet region of the spectrum.

Existing astronomical spectrographs cover a range of dispersion from 1.5 A./mm to about 1000 A./mm. The spectrograph providing the 1.5 dispersion is a coudé prism spectrograph for the 82-inch McDonald telescope. Spectra of stars to the

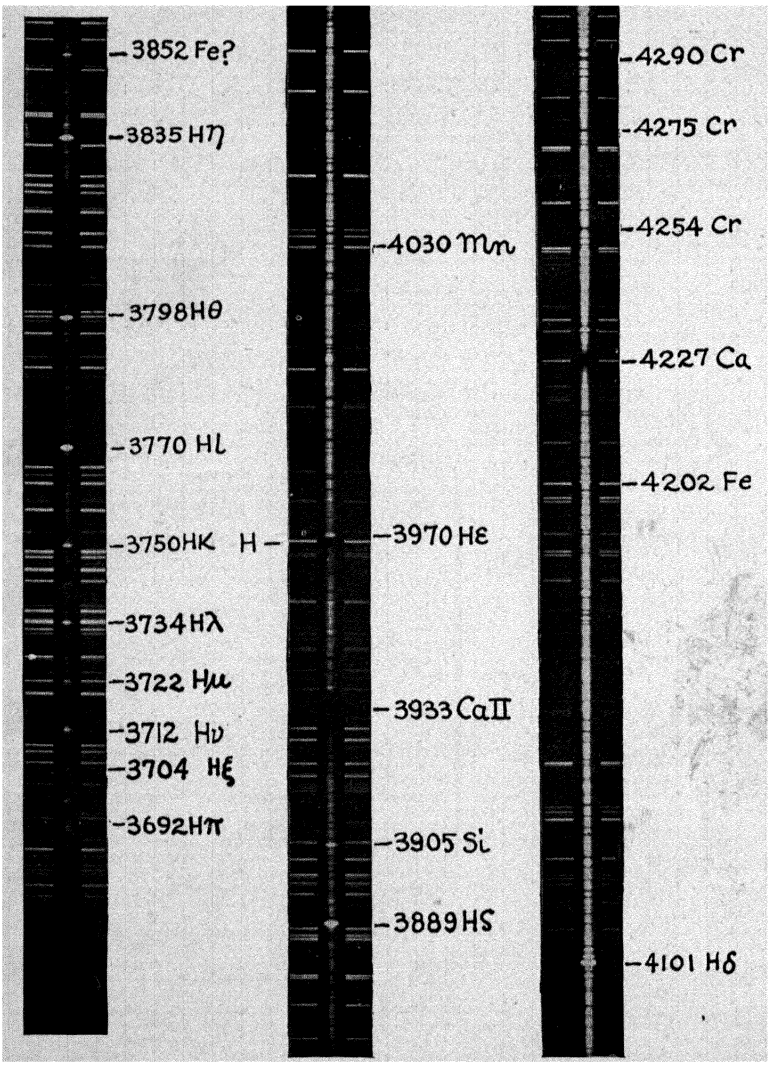


Fig. 63.—High dispersion spectrum taken at Mount Wilson Observatory.
(*Photographed with the 100-inch Mount Wilson telescope.*)

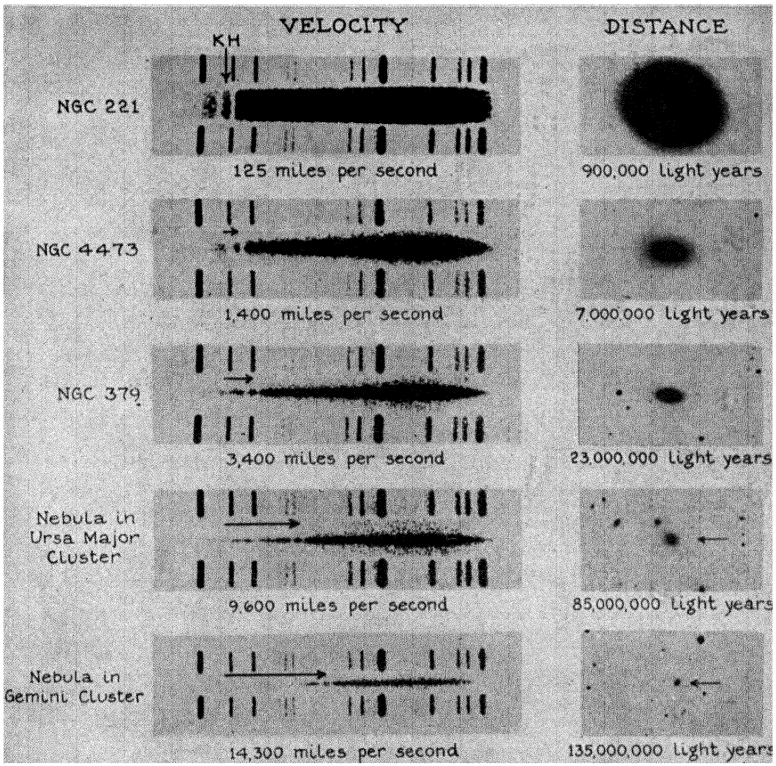


Fig. 64.—The nebular spectra reproduced above are greatly enlarged. (*From Hubble "The Realm of the Nebulae," Courtesy Yale University Press.*)

fourth magnitude can be obtainecl with this instrument. (See Figure 63.) A spectrograph providing 1000 A./mm used with the 100-inch telescope, obtains spectra of stars and galaxies to about the 16th magnitude. (See Figure 64.) The resolution of the larger spectrograph is nearly three hundred times finer than that of the smaller.

The first slit spectrographs were developed for use with the large refractors near the end of the nineteenth century. The first large successful reflecting telescope, the Crossley 36-inch, has

no greater light-gathering power than the Lick or Yerkes refractors, and its focal-ratio of $f/5.8$ was too fast for high-dispersion spectrographs. The converging beam from the Lick or Yerkes refractors is about $f/18$, and therefore suitable for high-dispersion spectrographs. On the other hand, the secondary spectrum of the refractors causes all but a narrow range of colors to be out of focus on the slit; a correcting lens several feet up the tube is used for changing the color curve of the telescope from visual correction to photographic correction, but the combination is still considerably short of perfection.

The slit of a high-dispersion spectrograph is so wasteful of light that a good fraction of the aperture of the telescope is more or less discarded. The star image appears on the slit face as a small, dancing, irregular disc bisected by the narrow dark line of the slit. Seeing, differential atmospheric refraction, and atmospheric dispersion combine to make it necessary for an observer to guide the star onto the slit and keep it there as well as possible throughout the exposure.

The usual manner of guiding is to have the slit face polished as a plane mirror and slightly inclined to the optical axis of the telescope. Thus, the starlight that fails to enter the slit is reflected off into a guiding telescope, safely out of the way of the on-coming starlight. The slit face may be illuminated obliquely by a faint green light to render it visible to the observer.

As in the case of the objective prism the stellar spectrum formed in the focal plane of the slit spectrograph is a narrow streak. It is therefore equally necessary to widen the spectrum on the photograph. As in the case of the objective prism, widening may be accomplished by weighting the driving clock.

Many medium sized and small slit spectrographs may be rotated about the optical axis in order that the slit may lie in a chosen orientation across the disc of a nebula, or in order to isolate the light of one star from a near companion. Widening can be accomplished by using the slow motion movements of the telescope.

Some slit spectrographs have the slit oriented in such a way that when the telescope is on the meridian, the slit is parallel to the meridian. The atmospheric dispersion, which for stars at low altitude produces a spectrum longer than the slit-width, is thereby oriented along the slit, and starlight of all colors passes into the slit. Such slit spectra are widened by slow motion in declination. The program is arranged so that the desired star is on the meridian at the half-way point of the exposure.

In spectrographs of the highest dispersion, like the one yielding 2.9 A./mm at Mt. Wilson, one scarcely needs to widen the spectrum by trailing the star image along the slit. The seeing image subtends a sufficient length of the slit to produce a final spectrum that is already wide enough. Wherever possible, spectra of bright stars may be profitably widened, however, for more precise measurement and for better visibility of very fine lines; stars of the fourth and fifth magnitudes near the limit of the spectrograph's penetration are generally not trailed, for trailing would increase the required exposure time markedly. (See Figure 63.)

The light from the source to be used as the standard spectrum is brought into the slit ordinarily by reflection through a small prism or prisms over the slit. Since it is desirable to disturb the mechanical parts of the spectrograph as little as possible during the star exposure, the small prisms should be permanently in place on the slit face. Slit spectrographs with such comparison prisms have an adjustment screw for spacing the prisms along the slit. This adjustment can therefore space the comparison spectra at any desired distance above and below the star spectrum on the final photograph.

For the determination of precise wave-lengths and radial velocities, it is desirable to have the laboratory illumination shining on the slit during the entire exposure. This procedure, however, is ordinarily impractical, especially when a spark discharge is used as a standard light source. It usually is sufficient to impress the standard comparison spectrum five or six times at

spaced intervals throughout the exposure. The mean position of the comparison lines will be then very nearly on the wavelength scale of the star spectrum.

The laboratory illumination should yield a spectrum of bright lines spaced at sufficiently uniform intervals along the spectrum at moderately uniform densities. The iron spark is ordinarily sufficient, but in the ultra-violet, alloys of various other metals have been used with success.

Resolution and Efficiency of the Slit Spectrograph

The width of the image of the slit formed in the focal plane of the camera lens determines the linear resolving power of the spectrograph. For high resolution at a given linear dispersion the image of the slit should be no wider than the resolving power of the photographic emulsion, or about 0.020 mm in practice. Photographic resolving powers are ordinarily given in terms of the number of white lines, separated by black lines of equal width, that can be resolved per millimeter. Resolution depends markedly on contrast, background density, emulsion characteristics, and development. A slit image of 0.020 mm width corresponds to a resolving power of 25 lines per millimeter, a figure within the range of the faster spectroscopic plates at astronomical densities of 0.2–1.0. On the other hand, it is necessary that the width of the real slit be large so that as much starlight as possible can enter the instrument.

Since the ratio of slit-width to slit-image-width depends entirely on the ratio of collimator focal-length to camera focal-length, it is desirable to utilize a fast camera lens. An $f/1$ camera lens and an $f/18$ collimator together produce an eighteen-fold reduction between slit-width and slit-image-width. If, as above, the slit-image-width is 0.020 mm, the slit can be 0.360 millimeters wide; under average conditions of seeing, all of the light in a star image will go through such a wide slit without loss. The $f/1$ camera will have a focal-length nearly equal to the cross-section of the light beam emergent from prism or grating.

The necessarily small focal-length means that the linear dispersion of such a spectrograph will be relatively low, even though several prisms or a high angular dispersion be employed.

An $f/1$ Schmidt camera used with a six-inch diameter grating of fifteen thousand lines to the inch in the second order produces a dispersion of 60 A./mm, which is in the middle range of useful dispersions. Higher dispersions can be obtained efficiently only by increasing the camera focal-length. Light intensity is lost in proportion to the length of spectrum, and still more because the slit must be narrowed in order that its image formed by the longer focus camera remain at 0.020 mm width. For these two reasons the spectrographs providing very high dispersion are very slow. High-dispersion spectrographs must depend for effectiveness on the excellence of the average quality of seeing at the observing site.

A narrow slit is inefficient with starlight because of diffraction losses at the slit edges. Much of the light diffracted from the slit edges passes outside of the collimator lens and is lost. To minimize. this loss the instrument design should favor any arrangement that will widen the slit. It is desirable that the collimator lens have the same focal-ratio as the beam of starlight coming to a focus on the slit. The slit will behave then like a pinhole camera, imaging the telescope aperture upon the collimator.

High-dispersion spectrographs coupled to reflecting telescopes are used at the Cassegrain focus, where the collimator is perhaps $f/18$ (slit-width 0.060 mm with $f/6$ camera lens), instead of the Newtonian focus, where the collimator must be perhaps $f/5$ (slit-width 0.017 mm with $f/6$ camera lens). Apart from the diffraction loss, there is no other gain or loss in light between the two arrangements. Although for the same resolution the $f/5$ collimator uses a slit 3.6 times as narrow, the image of a star on the slit formed by the $f/5$ combination will be on the average 3.6 times as small as the image at the $f/18$ combination.

The best position for a high-dispersion spectrograph is the coudé fixed focus on the polar axis of the telescope (Figure 65).

The 100-inch telescope coudé focus lies in a laboratory room kept at constant temperature during exposures. The high-dispersion spectrograph at the coudé is stationary relative to the ground, and can therefore be made perfectly free from flexure. Only the largest telescopes have a coudé focus. Most of the larger spectrographs actually ride on the telescope, usually in the Cassegrain position (Figure 66). Spectrographs used on the

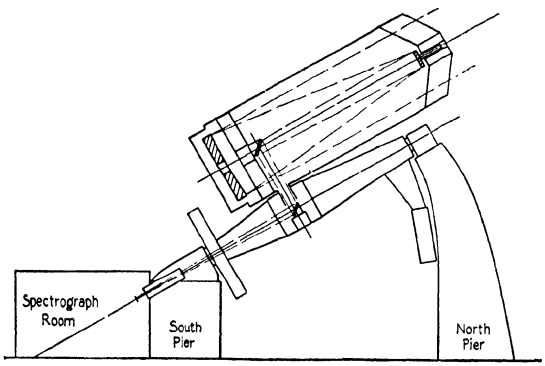


Fig. 65.—The coudé focus.

Telescopes mounted in a fork or yoke (cf. pages 242, 243) may have a coudé focus with only one flat mirror. However, the northern heavens become inaccessible to observation.

large refractors must necessarily be attached at the lower end of the tube.

Low-dispersion spectrographs employing fast camera lenses may use such wide slits that diffraction losses become negligible. Spectrographs designed for small dispersion work are therefore usually carried at the Newtonian, or better still, at the prime focus of the reflector. The shorter focal-length collimator adds to the lightness and compactness of the spectrograph.

Most astronomical slit spectrographs use from one to four prisms to obtain the desired angular dispersion. The collimator and camera lenses are designed so that the spectrum will come to a focus as nearly as possible on a plane surface. Achromatic

lenses can be used, but in many spectrographs the camera lens is a simple lens. By combining the chromatic aberration of the lens with the prismatic dispersion, one can obtain a spectrum focused on a plate inclined to the axis of the instrument. Blue light focuses nearest to the lens, red light farthest away.

Most of the light lost by reflection from prism surfaces reflects from the first few surfaces of the prism train. The prism angles are so chosen that light of the wave-length central in the final spectrum is incident on the prism surfaces at Brewster's angle (see Chapter 1). The light passing into the first prism surface is partially polarized by the refraction (cf. Figure 5). By continuing through the prism train at the same angles of incidence and refraction (minimum deviation) the light beam approaches the condition of full polarization.

Ideally in such a system of a great number of prisms, at least one half of the light transmitted by the collimator will reach the camera lens. In practice prism surfaces are soiled by contact with air and dust with the result that Brewster's angle is not precisely determined. Moreover, the dispersion introduced by the prism causes departures from Brewster's angle depending on position in the spectrum. In spite of these smaller difficulties, prisms arranged at Brewster's angle yield very good results. Polarization within the spectrum is usually of no importance.

High-dispersion prism spectrographs are designed to cover a certain region of the spectrum in critical focus, usually the violet or ultra-violet. Prism spectrographs designed for the determination of radial velocities should cover short regions of the spectrum with as sharp a focus as can be realized by designer and manufacturer.

Even astronomers often overlook the necessity for having nearly perfect optics in a slit instrument designed for the measurement of radial velocities (see Appendix II). It must be remembered that the accuracy of measurement for the position of a spectral line depends on the distribution of light within the line.

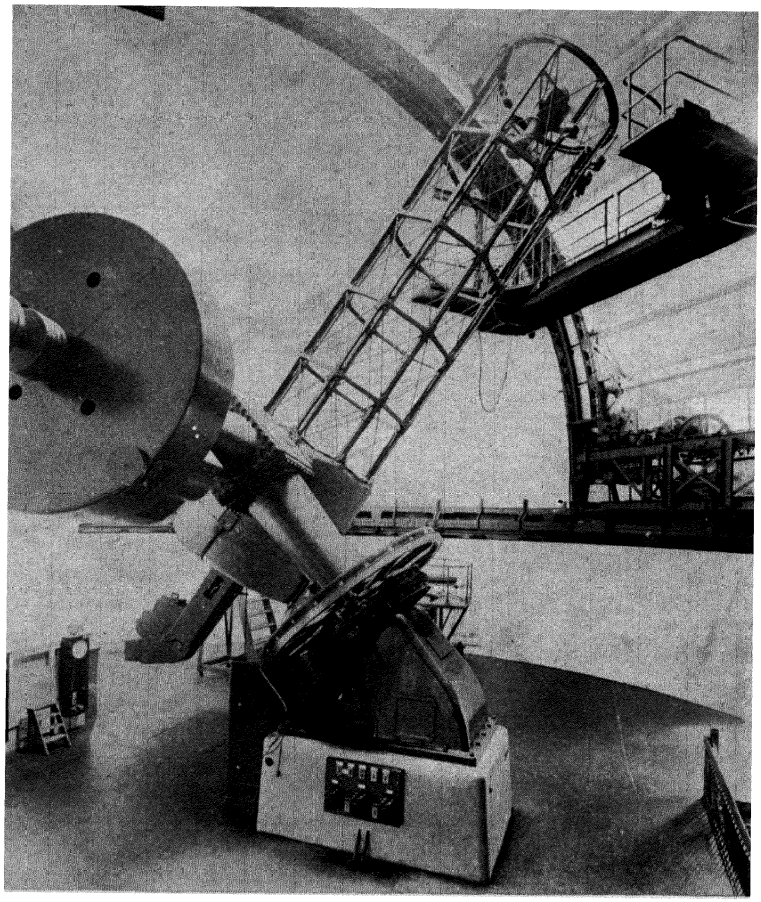


Fig. 66a.—The 72-inch reflector at the Dominion Astrophysical Observatory at Victoria.

Since measures of position in the spectrum can be reliable to about a fiftieth of the finest line width shown by the emulsion, a line distorted by image flare from imperfect lenses, even by photometrically imperceptible amounts, will cause the radial velocity obtained from the line to be appreciably in error. The

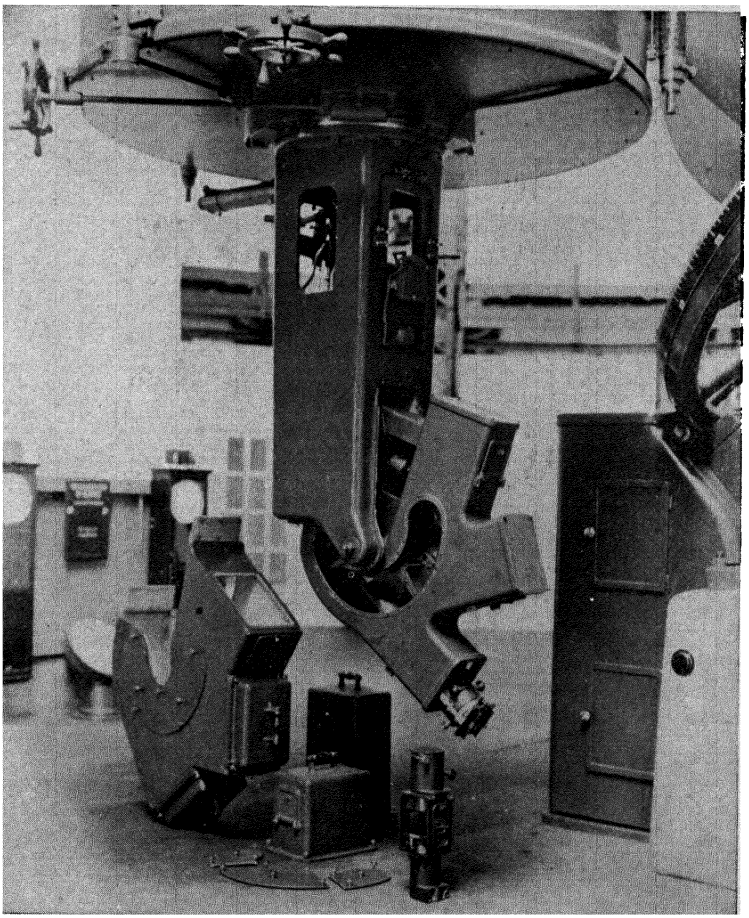


Fig. 66b.—A close-up of the Cassegrain spectrograph of the 72-inch reflector.

magnitude of the error caused by the defective instrument will depend on the intensity and intrinsic shape of the line.

A dispersion of 10 A./mm means that a single micron contains 0.01 A. In radial velocity measurements an Angstrom unit in blue light corresponds to about 80 kilometers per second.

A shift of a micron along the spectrum is equivalent to a speed of 0.8 kilometers of the star through space relative to the observer. With the best modern spectrographs the measuring errors for bright stars are as small as 0.2 kilometers per second in the coudé arrangements and 0.5 kilometers per second in the Cassegrain and refractor spectrographs. Many spectral lines and several independent sets of measures on many photographs are needed for such accuracy. Disagreements between measures on various spectral lines are often real and depend on the nature of the star rather than wholly on errors of measurement or imperfection in the instrument.

Much of the instrumental error can be taken out at the time the data are reduced by measuring positions of similar absorption lines in standard stars; nevertheless, small corrections are usually more accurately made than large ones. The only really safe procedure is to insist upon a perfect *diffraction* image in the focal plane of the completely assembled spectrograph. Visual sharpness of spectral lines may be inadequate.

Inferior optics will show up readily if the collimator is not uniformly illuminated by the comparison light as well as by stellar light. Comparison prisms and standard source ought to be perfected in the early days of an instrument and thereafter remain unchanged in adjustment.

Let us suppose that we want a grating spectrograph with a dispersion of 60 A./mm in the second-order ultra-violet; we would choose a six-inch plane grating with maximum efficiency in the ultra-violet of the second-order; we would employ a six-inch focal-length for the camera; the camera would therefore be $f/1$; the collimator would have about a five-inch clear aperture; when such a fast camera is used, the instrument may be mounted at the $f/5$ prime focus of a reflector; the slit-width will then be 0.080 mm, wide enough for practically all the starlight to pass through.

Prisms and gratings larger than six-inch clear aperture are either very expensive, or inefficient, or both. Optimum per-

formance for a grating spectrograph seems to come with the six-inch aperture with light concentrated in the second-order; the slit-width is therefore as wide as possible at a given dispersion. Optimum performance with a prism train seems to come with perhaps a three-inch clear aperture; larger prisms contain so much glass that too much light is lost by absorption. Finally, a dispersion system of large clear aperture used for high dispersion requires an instrument of such size that flexure cannot be avoided very easily, except at the coudé focus. A spectrograph used for radial velocities must be perfectly free of flexure. Prism spectrographs must have a constant-temperature jacket around the whole instrument to prevent expansion and contraction of metal parts and to prevent changes in the deviation of the prisms.

A high-dispersion spectrograph recently constructed at Mount Wilson employs a rather ideal optical arrangement. At the center of curvature of a spherical mirror is placed a six-inch plane grating ruled by Wood, a grating designed to concentrate light in the red of the first-order and the violet of the second. The radius of curvature of the spherical mirror is so long that it is unnecessary to employ a correcting plate for high quality focus, as in the Schmidt. The spherical aberration of a six-inch aperture slower than $f/9$ is inappreciable. Consequently, the varied colored light coming off the grating in any direction is brought to a focus on a spherical surface. The system is identical with that of Figure 47 except that the aperture is small relative to the focal-length. Permanently focused plate holders can be arranged along the spherical focal surface ready for loading at any time. Perhaps the only thing needed to complete the instrument is a set of gratings interchangeable with one another for the purpose of maximum efficiency in each region of the spectrum. The camera is relatively slow, but when maximum angular dispersion is used, as in this case, there is no other efficient way of obtaining with a grating the desired large linear dispersion (2.9 A./mm).

The Image-slicer

Bowen has proposed and used successfully an ingenious device to get the starlight into the slit. The slit may subtend only a fifth or so of the star image under average conditions of seeing. Bowen suggested that little mirrors be arranged, each of the width of the

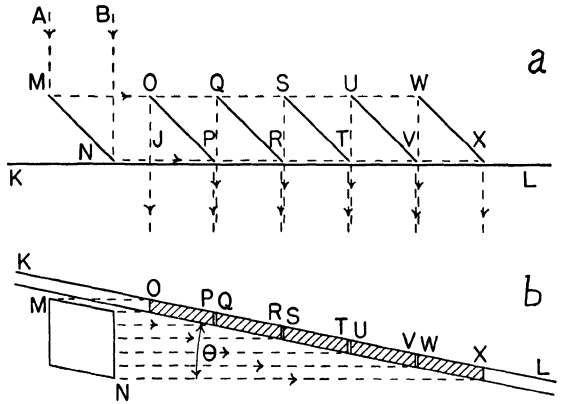


Fig. 67.—The Bowen image-slicer.

KL is the slit of the spectrograph. *MN* is a 45 degree mirror required merely to turn the beam of light *AB* from the telescope through a right angle to graze the slit face. *MN* can be eliminated by turning the spectrograph itself through a right angle on the telescope tube. *OP*, *QR*, etc., are small mirrors, nearly parallel, so arranged as to guide the starlight through the slit. The star-image under conditions of bad seeing will have a diameter about equal to *AB* or *JP*. The whole arrangement is smaller than the end of a lead pencil. (*Courtesy of Astrophysical Journal, Vol. 88, Page 115, 1938, and Yerkes Observatory.*)

slit, to reflect the starlight into the slit (Figure 67). The star image is thus divided into a number of equal strips. Each strip of light falls on a separate little mirror. The little mirrors are arranged along the slit, and are so inclined that the reflected strips of starlight are laid end to end along the slit. Although all the starlight now enters the slit, the image of the final spectrum is much broadened. To compensate, Bowen next places a strong cylindrical lens directly over the plate. The function of this lens

is to compress the widened spectrum once more into a narrow and brighter streak.

In practice the Bowen *image-slicer* provides a gain of from 2 to 7 times, depending on the quality of the seeing. The device is of importance particularly in the photography of spectra of faint nebulae of appreciable surface area. The image-slicer is useful mostly at a focal-ratio of $f/15$ or longer in combinations like the coudé or Cassegrain. Otherwise, the mirrors would be only a few hundredths of a millimeter wide, and it would be almost impossible to make and align them properly. Moreover, such small mirrors lose light seriously by diffraction.

The Bowen image-slicer is no longer an advantage when cameras of extreme speed are employed. A Schmidt camera working at $f/0.6$ used with exceedingly high angular dispersion already concentrates as much energy per unit area of emulsion as practicable. For high-dispersion work, however, the image-slicer is the only effective solution known.

Nebular Spectrographs

A spectrograph especially designed to photograph nebulae must be as fast as possible owing to the low surface brightness of these objects. Such a spectrograph is usually characterized by very low dispersion, of the order of 300–1000 A./mm. A large number of factors enter into the design of the fastest possible nebular spectrograph. By *fastest* one means a spectrograph that will photograph the spectrum of the night sky in a convenient interval of time. The night sky sets a limit to nebular photography. An increase in focal-length of a telescope in the case of a star under conditions of excellent seeing spreads out the sky-fog without, however, appreciably spreading out the starlight, so that the contrast of light becomes greater; fainter stars are accessible merely by prolonging the exposure time. On the other hand, the nebulae, being essentially luminous surfaces like the sky background, will be spread out along with the sky-fog and become correspondingly fainter, the relative

contrast remaining unchanged. Thus, in nebular spectroscopy there is a definite limit to the penetrating power of the spectrograph.

If the image of a galaxy at the prime focus of a telescope is a disc 0.5 mm across, and if all of this light is converted into a

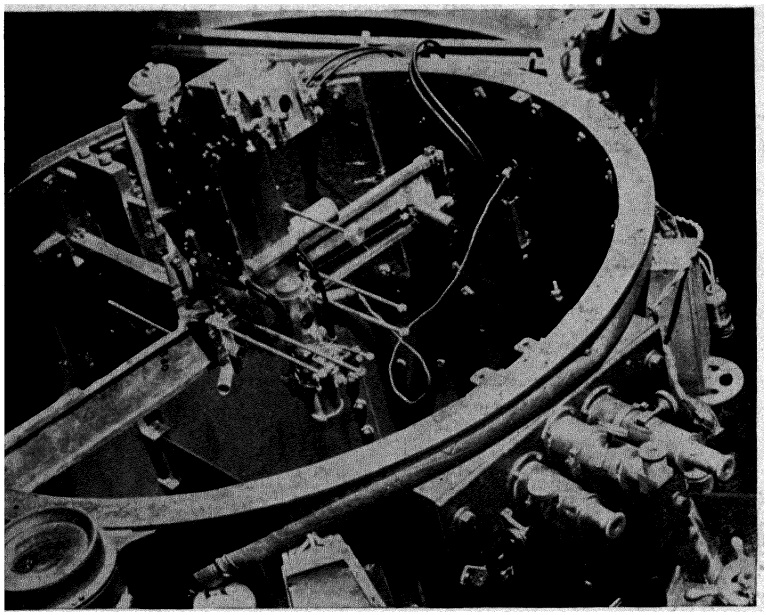


Fig. 68.—The Mayall nebular spectrograph for the ultra-violet attached at the prime focus of the Crossley 36-inch reflector at Lick Observatory.

spectrum of approximately the same area on the photographic plate, the spectrograph, except for instrumental inefficiency, will of course record the same density as the direct exposure. The size of the nebula in any one color is much reduced by the camera lens, but on the other hand the various colors are spread out into a spectrum.

As we proceed to fainter galaxies their images become steadily smaller in the focal plane of a given telescope. At

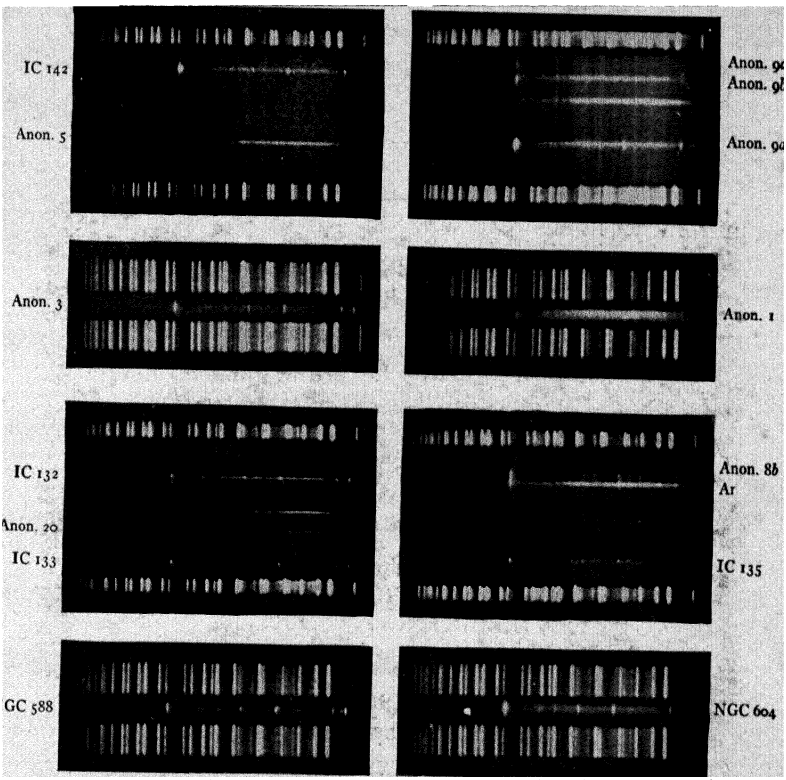


Fig. 69.—Typical spectra of emission condensations in a spiral nebula.

The scale of enlargement is 11 × the original negatives, on which the linear dispersion at λ3950 is 304 A./mm.

some point all of the nebular light will go through a slit, and hence for the fainter galaxies the utmost in fast cameras is not required. For example, the Mayall nebular spectrograph at the Lick Observatory employs an $f/1.3$ lens, a speed that seems adequate for the fainter clusters and galaxies. (See Figures 68, 69.) On the other hand, for photography of surface objects like the luminous filamentous nebulosities of the Milky Way or similar nebulosities in nearby galaxies, it is advantageous to adopt still

faster cameras in order to permit the maximum width of slit and hence admit more light.

Nebulosities and galaxies on the slit may not be visible to the eye; likewise faint stars whose spectra are desired may be beyond the limit of visibility. Consequently, the instrument is usually guided on field stars of sufficient brightness. The Mayall instrument is oriented so that the light of a previously chosen guide star enters the slit, whence a right-angle prism and lenses bring it to the eye. To be certain that an invisible object is on the slit, one needs to know from a direct photograph the position angle of the guide star relative to the object, and the linear separation of the guide star from the object.

At the Yerkes Observatory there has been employed a type of spectrograph built especially for the study of nebulosities and the light of the night sky. A telescope of fixed focal-ratio, regardless of size, cannot increase the light concentration of a nebula on the slit of a spectrograph. Although the telescope with twice the diameter may gather in four times the amount of light, the nebula in the focal plane is spread out by the double focal-length to four times the area. Indeed the light concentration on the final photograph within the spectrograph depends not even on the focal-ratio of the telescope, but on the focal-ratio of the camera lens. Thus, if the spectrograph is $f/1$, and the speed of the telescope $f/5$, the combination will operate at a speed of $f/1$. The Yerkes nebular spectrograph discards the telescope objective altogether. Such spectrographs without telescope were employed many years ago on the night sky by V. M. Slipher.

In the original form of the Yerkes spectrograph a slit was placed at the upper end of the Yerkes 40-inch refractor on the outside of the tube, and a prism over a fast Schmidt camera at the lower end. Because the slit is so far away, no collimator lens is necessary for the definition required. The prism projected back through the slit upon the sky covers a certain angular area of the sky. Conversely, any light from this area of the sky that passes through the slit enters the prism and camera, and is photo-

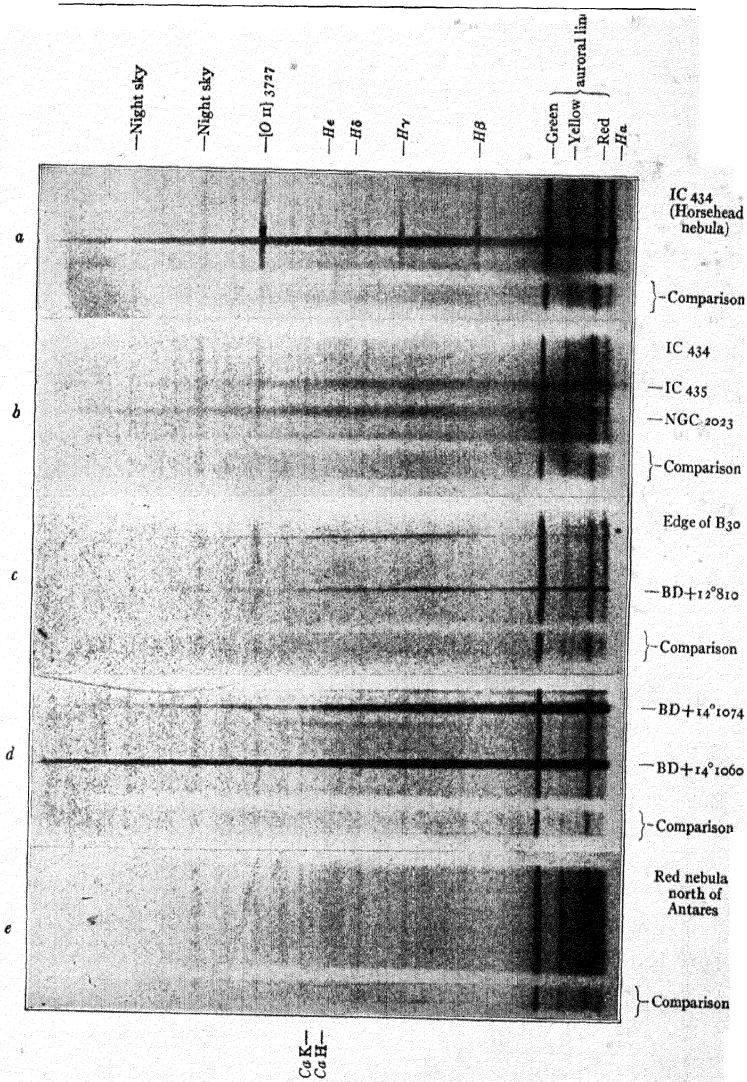


Fig. 70.—Nebulosities photographed with the McDonald nebula spectrograph.

Note the auroral lines originating in the Earth's atmosphere.

graphed. The speed of the outfit is determined by the width of the slit and the speed of the camera lens, as far as continuous spectra are concerned, but by the speed of the camera lens alone as far as emission spectra are concerned. Spectra of exceedingly faint nebulosities can be recorded with this equipment. (See Figure 70.)

Another instrument utilizing the same principle was constructed in 1938 on the side of Mount Locke in Texas. (See Figure

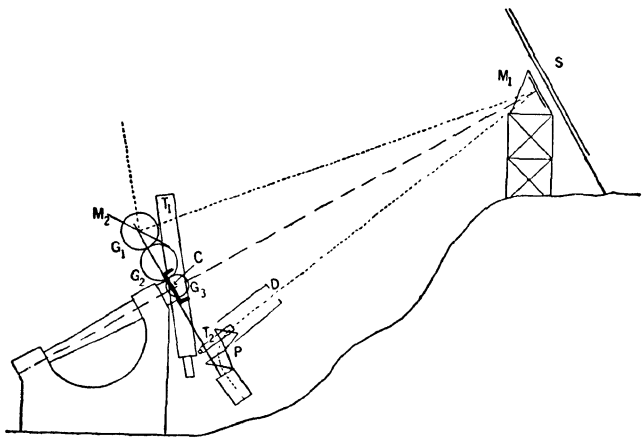


Fig. 71.—Cross-section of the optical system of the McDonald nebular spectrograph.

71.) The sky is reflected by mirror M_2 uphill to mirror M_1. The second mirror reflects the light back into the prism and camera assembly on the polar axis drive. Any portion of the sky may be brought into the field of the instrument merely by rotating the polar axis in right ascension and mirror M_2 in declination. The clock-drive on the polar axis keeps the chosen region accurately in the field of view throughout the exposure, although final small adjustments are made by means of a small guiding telescope. Mirror M_1 faces the south pole of the heavens. In this instrument the slit lies approximately 150 feet from the camera, as contrasted with 58 feet for the instrument on the side of the Yerkes refractor. The greater length has the advantage of isolat-

ing a smaller area of the sky and is suitable for the study of smaller objects (6 minutes of arc).

We have mentioned several times the need for a fast camera. Such a system is supplied by the Schmidt camera. (See Chapter 4.) The Schmidt in air can perform satisfactorily at a speed of $f/0.6$, and in solid glass at a speed of $f/0.35$ or even faster, depending on the composition of the glass. A solid Schmidt camera made of diamond could have a focal-ratio of $f/0.2$ and would be nearly four times faster than any existing instrument. The solid Schmidt camera is n^2 (where n is the index of refraction of the material) times faster than the fastest Schmidt of ordinary construction with correcting plate and mirror. Moreover, in spite of an increase in speed, the solid Schmidt is superior in definition to the ordinary Schmidt. The solid Schmidt is useful in spectroscopy only, inasmuch as the initial refraction into the glass is accompanied by dispersion. This difficulty can be overcome by more elaborate construction. In solid glass Schmidt cameras the photographic plate must be cemented to the glass during the exposure.

Microscope objectives, because of their small focal-ratio, have been redesigned with considerable success for nebular spectroscopy. The Rayton lens is a microscope objective used as a camera lens, operating at a speed of about $f/0.6$ (see Figure 64); the photographic plate is very nearly in contact with the lens. The Bracey objective is an oil-immersion microscope objective, operating at a speed of $f/0.35$. During an exposure the photographic plate must be cemented against the glass by means of a film of cedarwood oil or kerosene.

Trends in Spectroscopy

Until recent years almost all spectroscopy had been carried on in the blue and visual regions of the spectrum. Only in the last decade have systematic efforts been made to extend our knowledge to the infra-red end. The infra-red photographic materials supplied by the Eastman Kodak Company for spectroscopic

purposes are much slower than panchromatic or orthochromatic materials. Films for the near infra-red are generally faster than films for the far infra-red. Film speed comparisons can be made by measuring the absolute sensitivity in energy absorbed per angstrom from a standard source.

Some photography has been successful as far into the infra-red as 13000 A., but only in photographing the sun. Standard materials are available that photograph as far as 12000 A. The type *I*-Z emulsion, that covers the range from 10000 to 12000 A., is well over ten magnitudes less sensitive than ordinary materials, a factor of about ten thousand-fold. The sensitivity of infra-red materials and the red sensitivity of panchromatic materials may be considerably increased by the process of hypersensitization. By bathing an infra-red emulsion in an ammonia bath, and thereafter by drying the emulsion as rapidly as possible, one can gain one or more magnitudes over the untreated emulsion.

For long exposures in the blue end of the spectrum, lasting for many hours, the plates ordinarily considered slow may overtake and even surpass the total photographic effect of plates ordinarily considered fast. For example, the Eastman Process emulsion, a slow material of high resolving power, has less reciprocity failure than the fastest blue plates. Consequently, when the two types of emulsion are exposed to the same light source for many hours, the Process plate records the greater photographic density, and in addition yields a very much higher resolving power.

The limit of faintness for any kind of astronomical observation is set by sky-fog, which ultimately causes us to stop our exposures. We cannot hope to study an object whose surface brightness is less than one-sixth or so of the sky brilliance in the particular wavelength studied (since sky + object in practice merge with sky at this level). The light from the sky background with moon and twilight absent arises mostly from a permanent aurora; the remainder comes from starlight, zodiacal light, and gegenschein. The sky-brightness may be taken as 25.6 magnitudes per square second of arc, and its color a little bluer than sunlight.

The trend in spectroscopy with the introduction of faster photographic materials, more efficient instruments and observing methods is to gain more and more spectral resolution at a given magnitude, or at a given resolution to obtain spectra of fainter stars than heretofore. We are now detecting on the stars phenomena once observed only on the sun. Astronomical spectroscopists will continue to clamor for telescopes of ever greater aperture; the completion of the 200-inch reflector will thus mark an epoch in astrophysics.

Astronomers will soon consider the anti-reflection coating of optical surfaces a routine matter (See Appendix I). Lick Observatory astronomers have already had good success in the coating of their spectrograph lenses. Astronomers can also look forward to better spectroscopic emulsions and better instruments in general. New optical materials and new techniques will make it possible to obtain long regions of the spectrum in sharp focus for spectrophotometric studies.

6

MEASURING LIGHT

WHEN ACCURATE MEASUREMENTS OF THE QUANTITY AND THE quality of star-light are available, we have the basic data which help to reveal the sizes, masses, distances, temperatures, and compositions of the stars and their atmospheres. For example, the variation in brightness of what appears to be a single star may prove it to be actually a system of two stars revolving around each other, shining side by side at the time of maximum light, but lining up so that one is eclipsing the other at the time of minimum light. When measurements of the light intensity are plotted against time we obtain the light curve of the variable, as in Figure 72. An accurate knowledge of the shape of this curve tells us much about the nature and duration of the eclipse, and, from this and a knowledge of the spectrum, we can obtain not only the sizes and shape of the orbits in which the two stars revolve around their common center of gravity, but, with the aid of the laws of dynamics, also the relative masses and even the actual sizes and shapes of the individual members of the system.

If we measure the energy radiating from a given star in different colors or wave-lengths, it becomes possible to deduce the temperature of its radiating surface. By the simple process of matching the known laboratory spectra of the elements with the lines in a stellar spectrum (Figure 73), we can discover the chemical composition and physical conditions of the star's atmosphere. More than that, from knowledge of the surface conditions com-

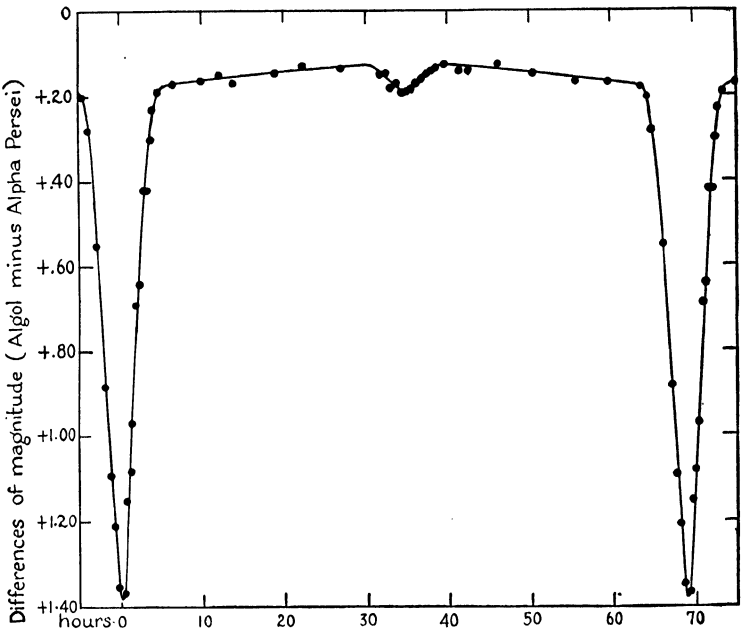


Fig. 72.—Photoelectric light curve of Algol.
Showing form of variation. (*Stebbins.*)

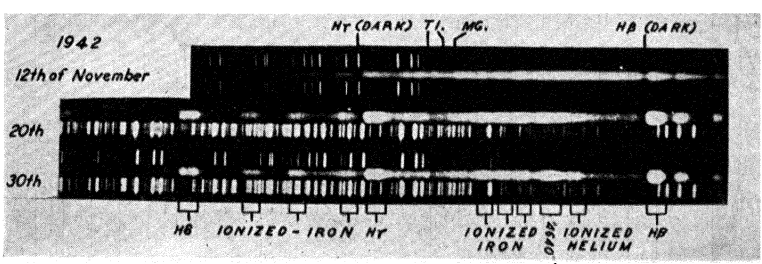
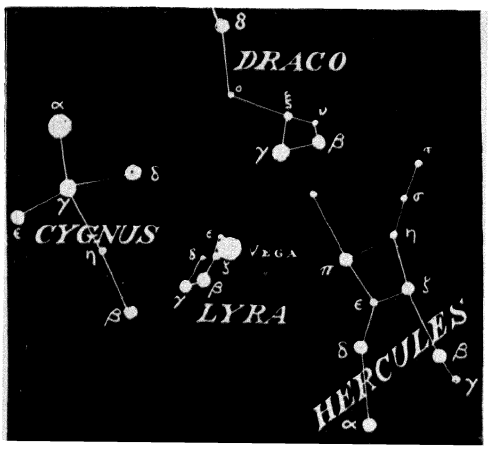


Fig. 73.—The spectrum of Nova Puppis.

The three successive spectra show changes in the star from Nov. 12th to 30th, 1942. The bright lines above and below the stellar spectra are laboratory comparison lines. (*Spectra taken at McDonald Observatory.*)

bined with some reasonable theoretical assumptions we can make some fair guesses about the physical conditions in the interior of the star. In all such cases the reliability of the final deductions hinges upon the accuracy with which we are able to measure the amount of radiation we receive from the star.



α *Cygni 1.3*
γ *Cygni 2.3*
δ *Cygni 2.8*
γ *Lyrae 3.2*
γ *Draconis 2.1*
β *Draconis 2.8*
δ *Draconis 3.0*
ξ *Draconis 3.7*
ι *Herculis 3.8*
ν *Draconis 4.2*
ο *Draconis 4.6*

Fig. 74.—Constellation groups around Lyra with stars designated by the Bayer system. The magnitudes range from 1.3 to 4.6 among the stars listed.

The measurement of starlight, known as stellar photometry, undoubtedly began with the first attempt to chart the skies. The ancient philosophers, Hipparchus and Ptolemy, arbitrarily graded the naked eye stars in six classes or "magnitudes," beginning with the brightest as first magnitude and going down to the faintest that the eye can see, which were classified as of the sixth magnitude. Since 1603 astronomers have used Bayer's system of nomenclature, in which the stars are grouped according to con-

stellations and designated by letters of the Greek alphabet, roughly in descending order of brightness. Thus (Figure 74), we find the brightest star in a constellation usually labelled with the Greek letter alpha (α), the next brightest, beta (β), and so on.

Later, when it was discovered that many stars do not remain always of the same brightness, a new impetus was given to the determination of more accurate magnitudes. Still later, the study of color provided the means for the determination of stellar temperatures.* Finally there came spectrophotometry, the detailed analysis of the quantity of light in individual colors or wavelengths, and thus it became possible to study physical conditions of celestial objects on the basis of the theories of atomic structure. At each step new instruments and more refined methods were introduced in an effort to measure more accurately the quantity as well as the quality of the light received from the celestial objects.

The Magnitude Scale

The rough gradations of brightness adopted by Hipparchus and Ptolemy served as the basis for the magnitude notation, but the scale of magnitudes now in use was suggested much more recently. In 1830 Sir John Herschel found that a star of the first magnitude as classified by Hipparchus and Ptolemy was about one hundred times as bright as a star of the sixth magnitude; furthermore, that a constant ratio of brightness was fairly well maintained on the accepted arbitrary scale, i.e., a first magnitude star was 2.5 times as bright as a star of the second magnitude, a second magnitude star 2.5 times as bright as one of the third magnitude, and so on. This constant ratio was not an accident; it has been explained on the basis of Fechner's law of sensation which states that differences in intensities which

* The color of a body which emits light is connected with the temperature of the radiating surface. For example, as we heat a piece of iron we observe progressively a dull red glow, then bright red, yellow and so on, until finally we reach blue-white heat.

correspond to the same fractional part of the whole, are perceptible to the senses equally as well, whether the original intensity is large or small. For example, it would be just as easy for the eye to detect a 10% variation in the light from a firefly as it would be to detect a 10% variation in the intensity of the light from the sun.

Pogson proposed in 1850 that the "light-ratio" between magnitudes should be 2.5119, the fifth root of one hundred, and that the magnitude scale should be so adjusted that the adopted standard intensity of a sixth-magnitude star should correspond to that of sixth-magnitude stars given in the best catalogs of the time.* The magnitude scale is now extended to cover stars or planets brighter than the first magnitude and fainter than the sixth. Thus, Venus when at the minus fourth magnitude is one hundred times as bright as a first magnitude star; a twenty-first magnitude star is one millionth as bright as one of the sixth magnitude.

Visual Photometry

The human eye is a versatile instrument. It has the ability to accommodate itself to various degrees of light intensity over an extremely wide range, and to detect minute variations in brightness equally well at all intensity levels. It was natural, therefore, that the eye (see also Chapter 2) should be the earliest instrument used in stellar photometry. Without the aid of a telescope and under the best sky conditions, away from city lights, haze and smoke, a very good eye can see stars fainter even than the sixth magnitude. With the aid of the largest telescope we can see stars down to the eighteenth magnitude. This is indeed a noteworthy

* The fundamental relationship now employed is

$$\text{Log } L = -0.4m$$

where L is the ratio of luminosity of two stars, m is the difference in their magnitudes, and the minus sign indicates that the intensity diminishes as the magnitude difference increases. Thus for a star which is 40 times as bright as a

achievement when we consider that the light from even the brighter stars is very weak. The light that we receive from a star of the first magnitude corresponds to that of a standard candle placed more than half a mile away (3594 ft), while that from a sixth magnitude star corresponds to the same candle at a distance of almost seven miles. Such stars are considered relatively

star of the sixth magnitude, we have

$$\text{Log } 40 = -0.4m,$$

from which follows:

$$m = -4.00;$$

that is, the star is of the second magnitude, four magnitudes brighter than the sixth.

Similarly, if two stars A and B differ in brightness by half a magnitude, we find for the ratio of their luminosities the following:

$$\text{Log } L = -0.4 \times (0.5),$$

or,

$$L = 1.5849.$$

This means that one star is 58.49 % brighter than the other.

Since the addition of magnitude differences corresponds to the multiplication of intensity ratios, we can write:

A difference of one magnitude corresponds to a change in brightness of 2.5 (2.5119).

A difference of two magnitudes corresponds to a change in brightness of 6.3 (6.3076).

A difference of three magnitudes corresponds to a change in brightness of 16. (15.849).

A difference of four magnitudes corresponds to a change in brightness of 40. (39.81).

A difference of five magnitudes corresponds to a change in brightness of 100. (100.00).

If now we have a star which increases in brightness, say 13 magnitudes (from a faint 12th magnitude star to one of the minus first magnitude), we have

add	5 mag = 100 times change	multiply
↓	5 mag = 100 times change	↓
	3 mag = 16 times change	
	13 mag = 160,000 times change in brightness.	

bright. The stars on the astronomer's research program are usually many times fainter. A twenty-first magnitude star, which is about the photographic limit within reach of the 100-inch telescope, corresponds in intensity to the light from a standard candle placed at a distance of 6813 miles. As a matter of contrast, the sun, which to us is the brightest star, has a magnitude of minus twenty-seven (−27). The observable range in stellar brightness, then, is of the order of 48 magnitudes, which corresponds to a ratio of one to sixteen million, million, million, (16,000,000,000,000,000,000), or a range of intensity obtained in moving a point source of light from one yard to more than two million miles away from the observer. This tremendous difference in brightness between our sun and the faintest observable stars is due mainly to the difference in distance.

The sun appears brighter than the stars because it is so near, while stars many times brighter than the sun but far away from us are not even visible to the naked eye. Likewise, two stars may appear of equal brightness merely because the intrinsically brighter star is farther away than the other. To determine the relative intrinsic brightness of stars we must reduce the observed apparent brightnesses to what they would be if all the stars were at the same distance. When this is done, we obtain what are known as *absolute magnitudes.**

Measurements of apparent magnitude are among the most basic and fundamental in the entire field of astronomy. The simplest method is to determine the relative magnitude by direct

* The astronomical absolute magnitude of an object is defined as the magnitude it would have if it were situated at a distance of ten parsecs. The word parsec is the name of the distance corresponding to a parallax of one second of arc. At a distance of ten parsecs the parallax (Figure 75) would be one tenth of a second of arc; in miles this distance is nearly two hundred million million (200,000,000,000,000). A parsec equals 206,265 astronomical units or 3.258 light years. An astronomical unit is the average distance from the earth to the sun (93,000,000 miles). The light year (5,880,000,000,000 miles) is the distance that a quantum of light will travel in the course of one year going at the rate of 186,000 miles per second.

visual comparison with a given standard star. With a little practice it is not difficult to notice differences in brightness between two stars as small as 0.1 magnitude. Many observers in the United States and other parts of the world, especially the members of the American Association of Variable Star Observers and the British Astronomical Association, carry on extensive visual observations of the variations in the light intensities of the variable stars.*

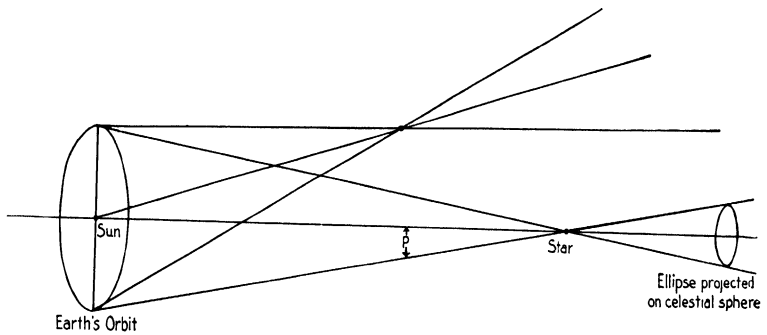


Fig. 75.—Stellar parallax.

As the earth moves in its orbit around the sun, the stars describe similar projected orbits in apparent motion on the celestial sphere. The maximum shift for a given star is a measure of the distance of that star.

The accuracy of such observations is greatly increased if the eye estimates are aided by one of the many adaptations of an instrument known as a *photometer*. In its laboratory form (Figure 76), this instrument measures the amount of light falling upon a surface placed perpendicular to the light beam. The optical arrangement differs somewhat from instrument to instrument, but the fundamental principle is the same. In the accompanying figure the light from the standard candle on one side, and the source whose intensity is to be measured on the other, is allowed to fall on the surfaces *A* and *B* respectively. The two surfaces

* See "*The Story of Variable Stars*" by Leon Campbell and Luigi Jacchia, The Blakiston Company, 1941.

are viewed simultaneously by means of the reflecting mirrors M and N and the specially prepared cube of glass. This cube consists of two pieces of glass cemented at the center so that the light from mirror N' passes through the cemented surface and into the viewing telescope. The light from mirror M' enters the telescope after having been reflected by the non-cemented portions of the left-hand half of the cube. Hence the eye sees in the telescope a field in which the center part is illuminated by the source at the right of the photometer, and the outer por-

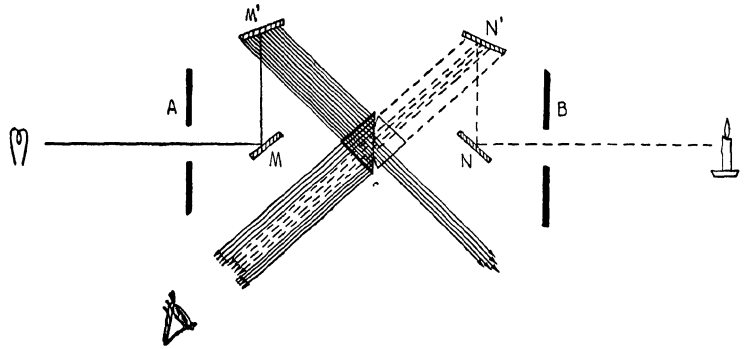


Fig. 76.—The photometer.

tions are illuminated by the source on the left hand side of the photometer. When the illumination of the two sources is exactly the same, the sharp boundary between the two images disappears. In the laboratory the light from the standard source, the candle in this case, can be kept constant by keeping the source at a fixed distance, while the distance from the source whose intensity is to be measured can be varied until both parts of the field are of the same intensity. If we now measure the relative distances from A and B to the corresponding light sources, we can compute the relative intensities, since the light intensity varies inversely as the square of the distance from the source.*

* If a point-source of light is placed at the center of a hollow sphere, the inside surface of the sphere will be illuminated with light of an intensity depending

In stellar photometry the method must be modified so that the comparison is made between the direct image of the star formed at the focal plane of the telescope objective, and the image of an artificial star, usually a small opening which is illuminated by a standard source. Such a comparison is more difficult than in the case of the surface photometer described above, because it is hard to match the intensity of two point-sources, and because the image of the artificial star never looks quite like the star image formed by the telescope. In ordinary astronomical work, it is frequently unnecessary to compare the magnitude of a star with that of a standard source of light; instead it may be sufficient to compare one star with a nearby star whose magnitude has been ascertained previously, thus determining the relative magnitude. This type of relative photometry is, from a practical point of view, much simpler, since it does not introduce errors arising from possible variations in the intensity of the standard lamp, and because it eliminates the eventual necessity of inter-comparing the standard source of one observer with that of another. To a certain extent it eliminates the effects of absorption in the earth's atmosphere.

If the two stars to be compared are not so close together in the sky that they can be seen simultaneously in the field of the telescope, their light can be reflected into the field of the same telescope by suitably placed mirrors. Since we cannot vary the distance of the source as in the laboratory photometer, we must equalize the two images by inserting in the beam of one star a calibrated wedge, whose density varies either continuously or in steps from complete transparency to total absorption. The wedge can be a piece of dark glass actually ground in the form of a wedge

upon the source and radius of the sphere. If the source remains the same and we double the radius of the sphere, the same amount of light is spread over a surface four times the area since the surface of the sphere varies as the square of the radius; therefore, the amount of light per unit area varies inversely as the square of the distance from the source.

so that at one end it will transmit a maximum amount of light and at the other be nearly 100% opaque. It may consist of a piece of glass over which some metal has been evaporated or sputtered in a manner which gives the desired variation in opacity. In all cases, however, the wedge should be strictly neutral; i.e., it must change the intensity without in any way changing the color of the star image as we go from the thin to the thick end. This requirement is not easily satisfied.

If such a wedge has been previously calibrated, it is possible to obtain the relative intensity of one source in terms of the other merely by advancing the wedge in the path of the brighter source of light until equality of illumination is reached.

Another method of equalizing the light from two stars is by the use of some sort of polarizing device. (See Chapter 1.) The light from one star is allowed to pass through a polarizing unit so that the transmitted light has only one plane of vibration. If a second polarizing unit is placed in the path of this polarized beam, the amount of light that will be transmitted through the second unit, called the analyzer, will vary from zero to maximum as we rotate one polarizing unit relative to the other. The amount of transmitted light can be calibrated in terms of the relative angle of rotation.

In cases where the difference in brightness between the standard and the star whose magnitude we wish to determine is large, it is convenient to use an intermediate device for the reduction of brightness by a considerable fixed amount. We can reduce the aperture of the telescope objective when the brighter object is observed; or we may interpose a rotating sector in the cone of light near the focus of the telescope. Placing a diaphragm with a reduced aperture over the telescope objective decreases the effective light-gathering power of the telescope, while the rotating sector reduces the amount of light that comes to eye or photometer by intermittent blocking-off of the light in the ratio of the sector opening to 360 degrees. Having thus brought the intensities to near equality, we can use the wedge or

other devices to obtain final equality. Such intermediate methods, which affect the light from only one of the objects being compared, should be used with the greatest of caution; for whatever the advantages of the additional device, we should hesitate to destroy the great advantage of having the light beams from both standard and unknown source pass through the same or at least similar paths.

The Pickering meridian photometer and the photometer "*T*" are examples of the embodiment of the "similar path for both beams" principle.

In the meridian photometer the light from any star near the meridian is brought, by means of a mirror, into one of two objectives of equal aperture and focal-length. Another mirror feeds the light from the north pole star into the second objective. Both beams pass through a polarizing prism, the eyepiece, and a Nicol prism which serves as an analyzer. When the analyzer is rotated, the ordinary ray from one star and the extraordinary from the other are brought into equality, and the ratio of brightness is determined by measuring the angle between two settings of equality. By this method more than 45,000 bright stars* all over the sky were compared with the Pole Star, and constitute now a net of standards with which other fainter stars may be compared.

For stars that are less than half a degree apart, a modification known at Harvard as "Photometer T" has proved very satisfactory. The light from two stars, after passing through the objective of a large telescope, is bent farther and brought together by means of two achromatic prisms (Figure 77, OPO). The two pencils of light pass next through the double-image prism, *G*, forming two images for each of the two stars, one the ordinary, the other the extraordinary image. As in the case of the meridian photometer the ordinary image of one star is now compared with the extraordinary image of the other. The analyzing prism *B* is rotated until the two images are equalized; the angle

* The Revised Harvard Photometry.

through which the analyzer is rotated then indicates the relative brightness of the two stars. As a check we can compare the other pair of images, and then repeat the whole process after having reversed the telescope. Also the relative positions of the two star

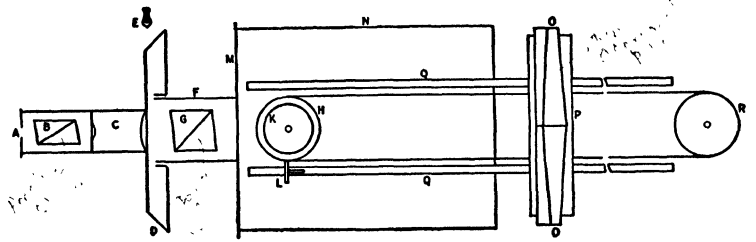


Fig. 77.—Photometer T of the Harvard Observatory.

The prisms *OPO* are moved along the optical axis by an endless chain over *H* and *R*. In this way stars 3′ apart to 40′ apart can be compared. (*From Harvard Annals 69.*)

images being compared can be interchanged in order to eliminate the tendency of the eye to see the image to the left or right consistently brighter.

Photographic Photometry

We have already seen in Chapter 3 that the density of the photographic image depends primarily upon the time of exposure and the intensity of the light which falls upon a given photographic plate. It is possible therefore to determine relative stellar magnitudes by measuring the densities of corresponding photographic images. If only the relative magnitudes are needed, one may simply compare the blackness, the size, or the general appearance of the image of the star in question with a number of comparison star images located on the same plate. The estimate is made visually and the "observer" can, after a little practice, estimate to one-tenth of the magnitude difference between two star images. If we know the magnitudes of the standard stars, the magnitude of the star in question can be computed easily from the estimated differences in the images on the photographic plate. When the two stars we wish to compare

are some distance apart on the photographic plate, it is more convenient to use an auxiliary *step-scale* or *fly-spanker*. In this case the image of one star is matched with one of the images of the step-scale. Then the step-scale is carried over to the second star image and a similar match obtained for the second star image. Thus the comparison is made between images which are always side by side. The fly-spanker is prepared by making a series of successive exposures on a plate; the exposure times vary by a chosen ratio, and the plate is moved slightly between exposures. If the images of the fly-spanker are calibrated (Figure 79) against a sequence of stars of known magnitude, any unknown magnitude can be read directly from the calibration curve. It is desirable that the fly-spanker be made on the same type of emulsion and with the same telescope as the photographs under investigation in order that the *quality* of all images be the same.

The fundamental sequence of stars to which all magnitudes are generally referred is located near the north pole of the sky and is known as the North Polar Sequence. This region is favorably situated throughout the year for observers in the northern hemisphere. The establishment of the magnitudes for the North Polar Sequence stars involved a long and laborious process of intercomparisons, mostly carried out at the Harvard and Mount Wilson observatories. The magnitudes established for this group of stars have been adopted by international agreement as the standards of reference to which the magnitudes of all stars are referred.

For convenience many secondary sequences have been established. They are found in what are known as the Selected Areas and the Harvard Standard Regions. These fields are conveniently distributed all over the sky and there is always one near any region in which new magnitudes are to be determined.

The usual procedure of setting up standardized magnitudes in a particular field is as follows. A photographic plate is taken of the region; immediately after or before, the north polar region of the sky is photographed on the same plate. Thus we

have side by side the stars whose magnitudes we wish to determine and the standard stars of the North Polar Sequence. If the region under consideration is not too rich in stars, it is possible to distinguish easily the North Polar stars from the others.

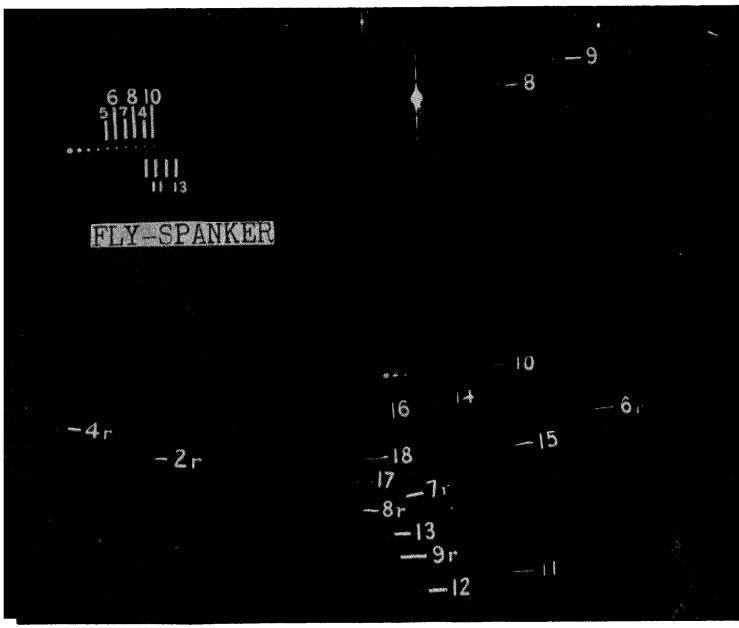


Fig. 78.—The fly-spanker step scale is placed directly on the photographic plate.

An estimate is then made of the position of the star of unknown magnitude in the step scale. Calibration of the step scale is made by comparison with stars of known magnitude, like the numbered stars of the North Polar Sequence in the figure.

Occasionally it is more convenient to make two successive exposures on the Pole, or on the field. This procedure helps to disentangle the stars of the two regions, since one set will show double images. The photographing of both fields on one plate assures absolutely identical treatment during the dark-room processing of plates.

This procedure would be entirely satisfactory if the night sky were really black. Such is not the case, however, and the photographic effects of pre-exposure and post-exposure to the night sky introduce additional errors. For when sets of images from two regions are put consecutively on the same plate, the faint sky light is superimposed during the second exposure upon the stellar images of the region photographed during the first exposure. The increase in density of the stellar images is not the same as the increase in density of the background. This is called the effect of after-exposure. On the other hand, the images of the second region build up on the general sky background of the first exposure, and are thus affected by pre-exposure. To avoid the errors thus introduced, it is generally more satisfactory to make the exposures of the region and of the Pole on two separate plates, especially when the region is very rich in stars. When such polar-comparisons are made, all the plates should be taken from the same plate box, and exposed in the same instrument on the same night, preferably with the second exposure immediately following the first.* The plates must be processed in the dark room as a unit and the densities should be measured in exactly the same manner. Even then it is necessary to take into consideration the changing effects of seeing, the meteorological conditions at the time of exposure of the plates, such as temperature, humidity, wind, (see Chapters 3 and 4), and especially the scattering and absorption of light in the atmosphere. This last we call the *extinction*, and it should next come into our discussion of photometry.

The Atmospheric Extinction

The outstanding uncontrollable factor in photometry, both relative and absolute, is the effect of the earth's atmosphere.

* The assumption is made that plates from one box are made from the same batch of emulsion and have been coated, treated, and packed under exactly similar conditions.

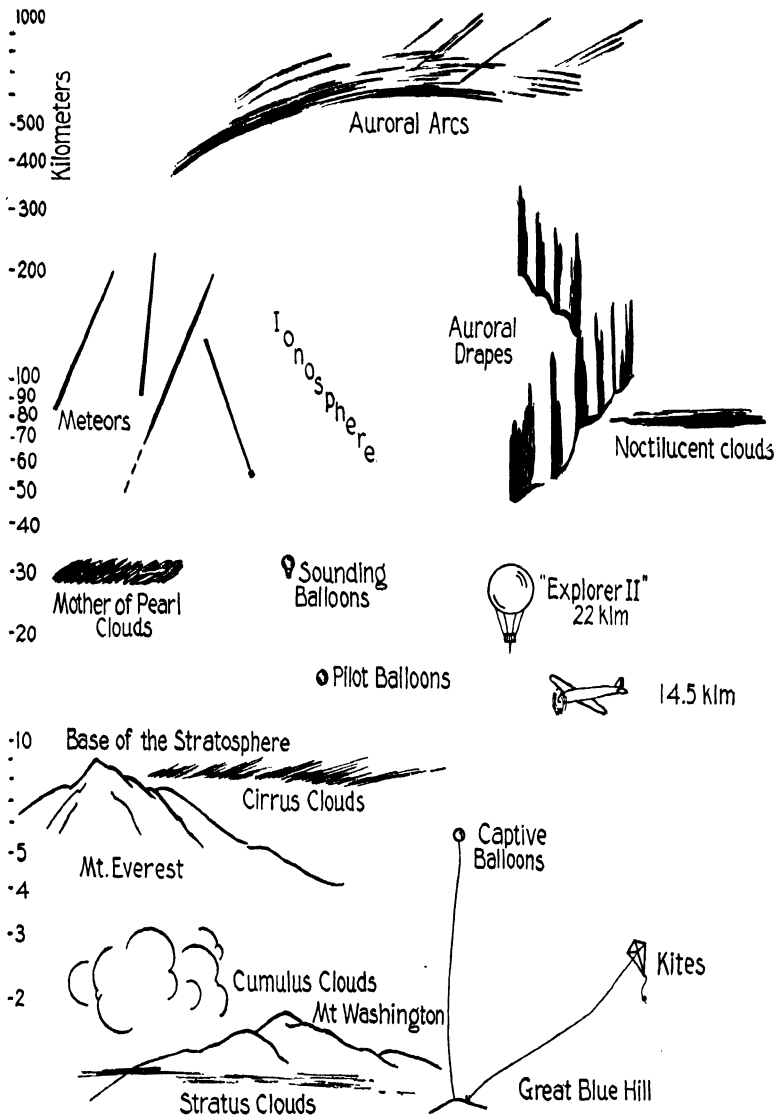


Fig. 79.—The Earth's atmosphere.



Fig. 80.—The Aurora Borealis.

The curtains of light are generally green, but occasionally contain patches of bright red.

The astronomer who lives and works at the base of an atmosphere of varying dust and water content is obliged to make his observations through this turbulent envelope which is constantly varying in effective thickness as the stars rise toward the meridian or sink toward the horizon. The effective height of this atmospheric envelope is a matter of definition. We know that 99% of the total mass lies within twelve miles of the earth's surface, in the region known as the troposphere; yet the tenuous fringes of the upper atmosphere or stratosphere reveal their existence in

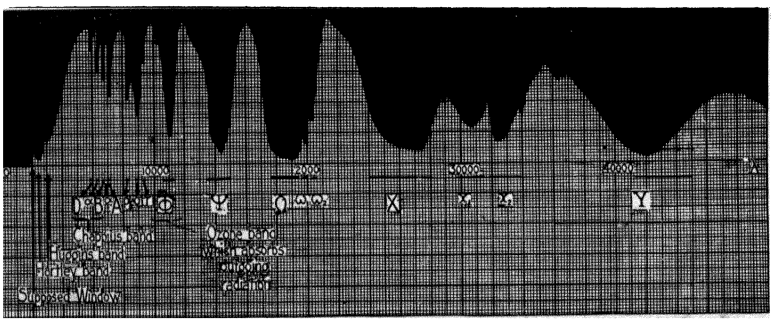


Fig. 81.—Absorption by the earth's atmosphere.

the presence of aurorae (Figure 80), which have been observed to heights of over six hundred miles. Even when visible clouds do not interfere, the light from the celestial bodies is scattered or absorbed by the constituents of the atmosphere which cut out not only narrow bands or telluric lines, but whole sections of the spectrum (Figure 81). Many of these absorption bands are produced by molecules scattered throughout the entire thickness of the atmosphere, while others arise in very definite and often very thin layers. The sum total of all the absorption and scattering of starlight, as it passes through the entire thickness of the atmosphere, is known as atmospheric extinction.

To a first approximation the amount of the atmospheric extinction varies as the secant of the angular distance from the zenith. For example, if we begin observations on a star at the

zenith, where the thickness of the atmosphere is taken as unity, the light travels increasingly longer and longer paths as the star approaches the horizon, where the effective thickness of the atmosphere is twenty times as great as it is at the zenith.

In order to study the extinction more precisely, we measure the brightness of the star by comparing it from time to time with that of an artificial comparison star of constant brightness. We expect from theoretical considerations that the dimming expressed in magnitudes should be proportional to the length of the path through the atmosphere traversed by the star's light rays. This is indeed borne out by actual observations. It is customary to represent the results of a series of observations for extinction in a diagram in which the star's measured apparent magnitude is plotted against the length of the path of the light rays through the earth's atmosphere. It can be shown without difficulty that the length of this path is proportional to the secant of the zenith distance of the star. The observations fall generally along a straight line; the slope of the straight line represents the *coefficient of extinction.*

With the aid of the observed relation we can adjust any series of magnitudes, derived without regard to extinction, by the application of a correction depending on the difference in zenith distance between the star field and the standard comparison field. In this way we can eliminate most of the extinction effect, provided of course that the transparency does not vary markedly from mean values at the time of exposure.

The coefficient of extinction differs considerably from one part of the spectrum to another (Figure 82). The value of the coefficient for photographic light is almost twice as large as the corresponding quantity for visual rays. Since the ordinary photographic plate is sensitive to a broad region of the spectrum it is not strictly correct to apply the same correction for stars o. different temperatures. Unfortunately, it is not practicable tc apply a different correction depending upon the energy distribution of each particular spectrum. In precision photometry the

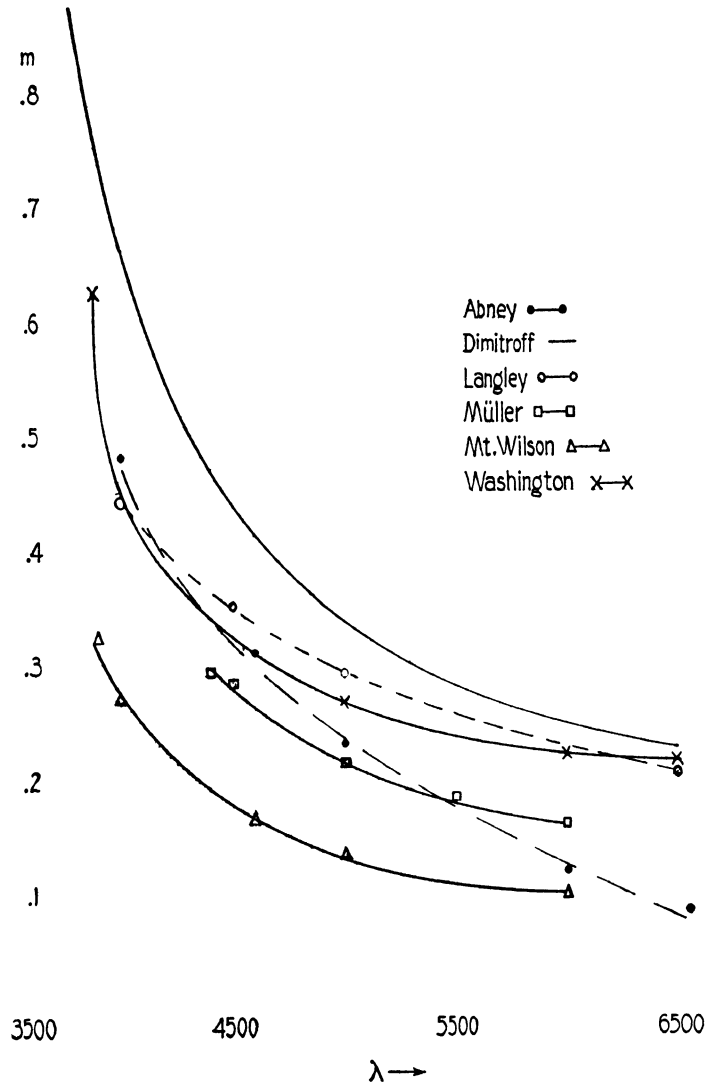


Fig. 82.—The variation of extinction with wave-length.
Results of various observers at different observatories are given.

difficulty is overcome by using, through a proper choice of plate emulsion and light filters, only a very narrow portion of the spectrum.

After the extinction correction has been applied, there still remains the difficult problem of eliminating the effects of the photographic processing and of the reciprocity failure of the photographic emulsion. From the moment the light rays first impinge upon a photographic plate, the temperature, humidity, etc., become important factors in determining the final density on the plate. The age of the emulsion, the developing, fixing, washing, and drying are as important in controlling the density of the final photographic image as is the chemistry of the developer.

The actual measurement of the density brings into play numerous measuring machines which are akin to the photometer, but when applied to the measurement of density on the photographic plate have been given the name of *densitometer*. Since many of these employ a photoelectric device, we shall postpone their description until we have discussed photoelectric photometry.

Photoelectric Photometry

The limiting accuracy with which we can measure light intensities photographically is determined by the inherent properties of the photographic plate; it is generally of the order of a few hundredths of a magnitude. Also in the photography of faint objects, a certain amount of time is necessary for the light to rise above the threshold and make an impression upon the emulsion.

The photographic process does not yield the very high degree of accuracy required in certain kinds of photometric studies. The *photoelectric cell* is now widely used for precision stellar photometry and for observation of rapid fluctuations in the brightness of variable stars. The response of the photoelectric cell is immedi-

ate, and its accuracy in recording small differences in magnitude is much higher than that of the photographic plate.

What is the principle of the photoelectric cell? When light is absorbed by certain substances, especially the alkali metals, electrical changes take place inside the atoms, as a result of which electrons are separated from the parent atoms. The electrons thus made free, escape and generate a minute current. The strength of this generated current is proportional to the number of light quanta which strike the sensitive surface, or, in other words, the resulting current is proportional to the light intensity. (See Chapter 1.)

A common type of photoelectric cell consists of an evacuated glass tube whose interior wall is coated with an alkali metal. The bulb contains an auxiliary electrode connected to the positive terminal of a battery. The negative electrode of the battery is connected to the alkali metal. Illumination of the metal surface produces a cloud of ejected electrons, which are attracted to the positive electrode and picked up by it, thus completing the circuit. The resultant current can then be measured in various ways. This type of cell is called the *vacuum photocell*. For some purposes gas-filled photocells have been found more useful.

Two other types of photocells have found some application. In the *selenium cell* the photoelectric effect is manifested as a change in conductivity. The *photronic cell*, best known for its use in illumination meters, consists of a layer of metal and a semi-transparent partial conductor. One of the advantages of this type of cell is that the electric current flows without the aid of an external battery.

In astronomical work, where light intensities are very small, the current output of a photoelectric cell is very minute. For example, the energy received from a star of the sixth magnitude corresponds to about 9000 light quanta per square centimeter per second. Assuming that each quantum yields one electron we will have for a photoelectric surface of one square centimeter a current of 10^{-15} amperes. A good galvanometer can measure

currents as small as 10^{-12}, which is a thousand times larger than the current from the sixth magnitude star. But with an electrometer we can measure currents as small as 10^{-18} amperes.

It is evident that a telescope must be used to collect the light for the photoelectric cell. A precision telescope, however, is not required for this purpose. Suppose that we are working with a poor mirror. At the focus the light rays of a star will pass through a circle of confusion of perhaps considerable size. The photoelectric cell will work satisfactorily as long as the average illumination over the circle of confusion, for the faintest star to be measured, does not fall below sky brightness.

Galvanometers and electrometers of greatest sensitivity can be handled only under special laboratory conditions. For field work at the telescope it is necessary to have a very sturdy instrument, or a current output large enough so that errors of measurement can be reduced to a minimum. Certain types of electrometers are of more rugged design and can be used at the principal focus of a telescope. In such a case one electrode of the photoelectric cell is connected to a pair of quadrants of the electrometer, while the other is connected to the ground through the battery. If the grounding key is disconnected, the indicator of the electrometer will move with a rate which is proportional to the current from the photoelectric cell.

An arrangement more convenient than the electrometer makes use of a vacuum-tube amplifier. This kind of amplifier is limited by the inherent irregularities of radio tubes and by the fact that fluctuations in the original photocell current, owing to *pick-up* or static, are also amplified together with the current we wish to measure. Another difficulty in the amplifier method is the inability of obtaining accurate and constant resistances.

Figure 83 illustrates the general method of amplification. The battery B_1 heats the filament f of the vacuum tube, producing a cloud of electrons in the space around the filament. These electrons are attracted toward the positively charged plate connected to the positive terminal of battery B_2, producing a

flow of current, the plate current, measured by the galvanometer *G*. If the photoelectric cell *C* is dark, that is, shielded from light, this current can be balanced out by the auxiliary battery B_3 and the resistance r_3, so that the galvanometer reads zero. When light falls on the photocell, the photoelectric current produced is impressed on the resistance *R*, and the potential drop across this resistance is in turn impressed on the grid *g* which produces a change in the plate current. Because of the effectiveness of the grid in its close proximity to the filament, a small change

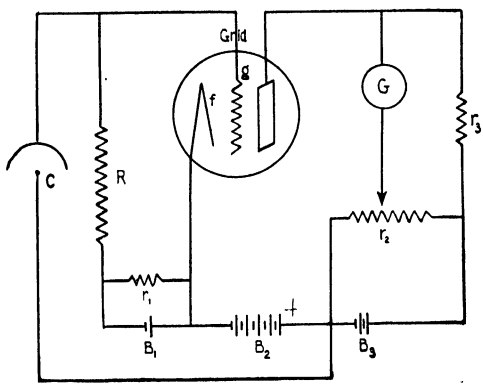


Fig. 83.—Photo cell amplifier.

in grid potential corresponds to a very large change in the plate current. Since the grid potential depends upon the light falling on the photocell, the plate current is a measure of the light intensity on the photocell. The sensitivity of the circuit depends on the sensitivity of the galvanometer and on the value of the resistance *R*.

High resistance *grid leaks* are made commercially up to 10^8 ohms, but the value of resistance *R* is limited by the filament-to-grid resistance of the vacuum tube, which in special type tubes, e.g., the FP-54, is as high as 10^{15} ohms. Wire resistors are unstable and the best available resistances are prepared by sputtering metallic film on quartz, by drawing fine India ink or

pencil lines on paper, or by the use of conducting glasses, or even liquids, such as xylol-alcohol mixtures. The most critical requirements of such resistances are: an ability to remain constant over a long period; an absence of polarization; a low temperature coefficient; and no departure from Ohm's law. If such resistances were available with values of $R = 10^{15}$ ohms, it would be possible with the amplifier to measure currents as small as those measured with the finest electrometers, 10^{-18} amperes.

In order to measure small currents, one must eliminate all possible fluctuations in the batteries and guard against stray

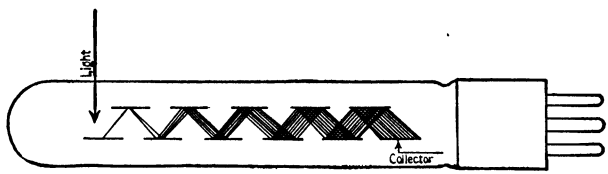


Fig. 84.—Schematic representation of an electron multiplier tube.

The electrons released by the light of the first photosensitive surface are focused by means of electric and magnetic fields and are accelerated from one surface to the next so that the final output is several million times the initial current set off by the photoelectric action of the light beam.

pick-up in the photocell circuit. It is a practice in stellar photometry to shield the connections between the photocell and the grid of the amplifier tube, and to evacuate the space inside this shield. Even such precautions are often insufficient and the vacuum-tube amplifier leaves something to be desired.

A step toward eliminating stray pick-up is found in the development of the electron multiplier, Figure 84. The primary electrons released from the sensitive surface, owing to the action of light, are focused by means of an electric and magnetic field, on a second surface especially sensitized for secondary emission. The primary electrons impinging upon the second surface release secondary electrons and the original current is increased from a fraction to ten times the original value. After leaving the

second surface the electrons are again focused on the third, where the number of electrons is again multiplied, and so on. At the end of ten or more such consecutive operations, the electrons pass to the collector giving a current greatly amplified. The greatest advantage of this arrangement is the possibility of a more nearly perfect shielding, because the entire ten stages may be enclosed in a high vacuum jacket. The simplicity and size of the apparatus is slightly offset by the fact that this particular type of sensitive surface has a very high coefficient of thermal emission so that a small change in temperature is accompanied by large changes in the background or spontaneous emission, even when the tube is not exposed to light. This difficulty is partially overcome by keeping the entire apparatus at a very low temperature.

A multiplier tube at Harvard has a sensitive surface composed of a layer of caesium over an oxidized layer of caesium with silver at the base. This Cs-CsO-Ag surface has a maximum secondary emission or multiplier ratio per stage of from eight to ten, which occurs at a bombardment voltage of from 400 to 600 volts, and requires that the electrodes or plates be connected to successively higher positive potentials.

While an exhaustive treatment of photosensitive surfaces is beyond the scope of this chapter, it should be noted that the preparation of a fine photosensitive surface is something of an art, and its success depends on the composition of the metal film, the thickness, and the sensitizing of the film by a glow discharge in the presence of hydrogen or other vapors. The spectral sensitivity, for example, varies with the alkali metals, beginning in the ultra-violet for lithium and shifting to the yellow region for caesium (Figure 85). At the same time that the maximum emission is shifted, the maximum sensitivity is shifted, the yield at the maximum is lowered, and the overall sensitivity broadens over an increasingly larger band of the spectrum. In the composite surfaces the sensitivity increases in comparison with the pure metal, and the spectral range increases until in some cases

it covers not only the visible, but extends into the infra-red region of the spectrum.

In recent years the photoelectric cell has become a very popular instrument in astronomy. It is, however, not the only type of receiver capable of yielding photometric results of very high accuracy. Extremely sensitive *thermocouple* receivers have been used in the focal planes of large reflectors to measure the radiation of the stars and planets. A properly constructed thermocouple records all the energy emitted in all wave-lengths transmitted by the atmosphere.

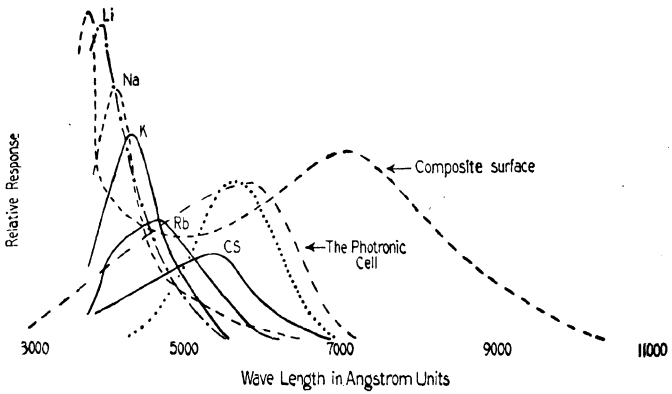


Fig. 85.—Sensitivities of various photocells.

The magnitudes measured with the aid of a thermocouple arrangement are called *radiometric magnitudes*. They are of considerable importance as basic data for the study of stellar interiors. In comparison, the photoelectric cell confines itself to a more restricted portion of the stellar spectrum.

Photometers and Densitometers

The astronomer frequently wishes to measure accurately in the laboratory the relative magnitudes of star images recorded on his stellar photographs. Or, he may have instead an adequately calibrated stellar spectrum from which he desires to

obtain with the highest attainable accuracy the distribution of light intensity. An artificial scale of star images or a wedge photometer will give only approximate results. For really accurate work he will again turn to the photoelectric cell or the thermocouple. Both have been used with conspicuous success in measurements on photographic plates. We shall describe here some typical instruments in which the photoelectric cell is featured. It will be clear, however, that a thermocouple may be substituted for the photocell, without thereby basically altering the general plan of the apparatus.

First we consider a kind of photometer that is especially adapted to the measurement of star images on a photographic plate. An electric lamp, fed by a storage battery, sends its light rays through a small circular aperture into a microscope objective. The latter is used to focus the image of the aperture sharply on the photographic plate. The transmitted light is collected by a second microscope objective and directed to the light-sensitive surface of a photoelectric cell. The photoelectric current which is generated is amplified and then measured by a sensitive galvanometer.

The plate fog or sky background will transmit a certain amount of light and a corresponding galvanometer deflection will be registered. If we move the plate so that a star image will be in the light beam, superposed on the regular sky background, then the silver grains of the star image will absorb and scatter as well, and a considerably larger fraction of the incident light than before will be cut out. As the star image enters the light-beam, the galvanometer deflection registers a decreased photocurrent. Obviously, the change in light intensity in the beam and the corresponding galvanometer reading will depend on the size and density of the stellar image, which in turn depends upon the magnitude of the star.

The difference between the galvanometer reading for the average background fog of the plate and the reading for the star image will be a measure of the amount of absorption caused

by the presence of the star image. In practice the galvanometer deflections for a number of star images of known magnitude are recorded and used for the making of a calibration, very much in the same way as stars of known magnitude are used to calibrate a series of fly-spanker images.

Without proper auxiliary apparatus, it is very difficult to measure objectively differences in light intensity with accuracy.

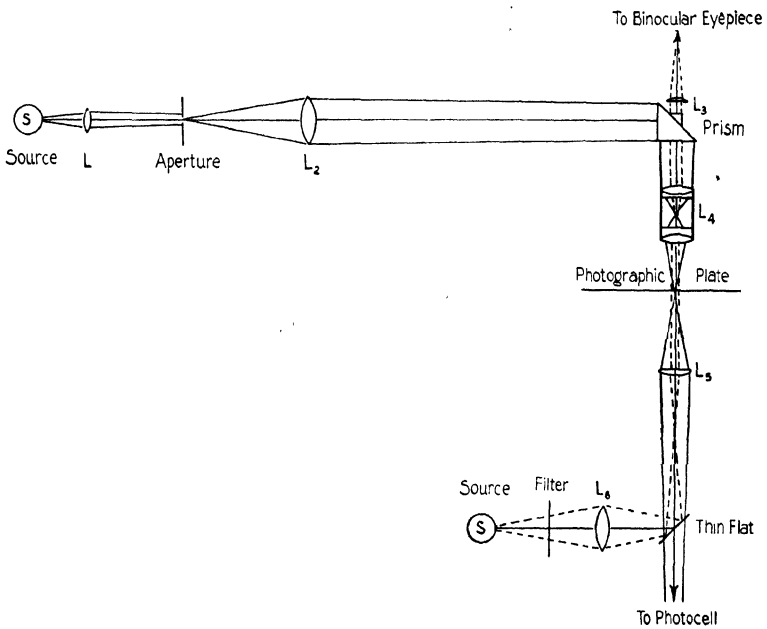


Fig. 86.—The optical system of the automatic star counting machine.

By translating intensities into electric currents we have reduced our problem to the simpler one of measuring small differences in electric currents accurately. Such an apparatus is well illustrated in the McCuskey-Scott star-counting machine (Figure 86), which is almost wholly automatic. In this machine the photographic plate is moved slowly in a systematic fashion, so that every part of the plate will in turn pass through the scanning

beam. The light of the illuminated spot on the plate subsequently strikes the photoelectric cell. The output of this photoelectric cell is fed into an amplifier, so that the different impulses produced by stars of different magnitudes will trip only the corresponding valve of the amplifier. Each time the valve trips, the action is recorded upon a counter. Thus, the number of star images between set limits of magnitude is automatically recorded as the plate is moved across the beam.

We mentioned earlier in this section that the photoelectric cell or the thermocouple may be used as well for the registration of variations in intensity with wave-length of the photographed

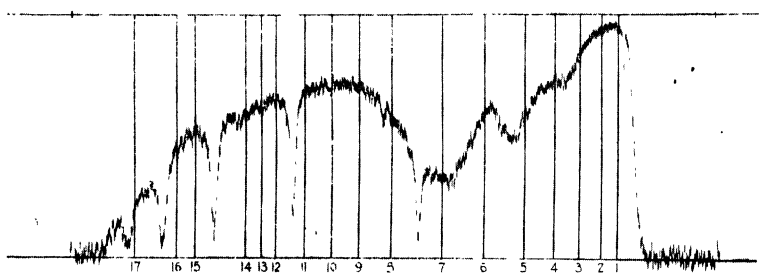


Fig. 87.—A microdensitometer tracing of a stellar spectrum.

spectrum. The instrument that is used for this purpose is called a microdensitometer or microphotometer. In this instrument the photographic plate upon which the stellar spectrum is recorded is carried across a narrow scanning slit of light by an accurate screw. Geared to this screw is a drum, or a roller covered with sensitive photographic paper, so that with each movement of the plate the drum rotates through a proportional arc. As the spectrum plate moves, the intensity of the transmitted light varies with the density of the portion of the spectrum directly beneath the slit image. Accordingly, the output of the receiving photocell varies in proportion. Again by the use of an amplifier the minute currents from the photocell are amplified and are fed into a galvanometer whose deflections indicate the corresponding

variations in the spectral density. As the galvanometer mirror swings, an auxiliary light beam is reflected from it and is focused upon the sensitive photographic paper of the rotating drum. Thus, the continual variations of the densities of the spectrum are recorded as shown in Figure 87. It is possible by changing

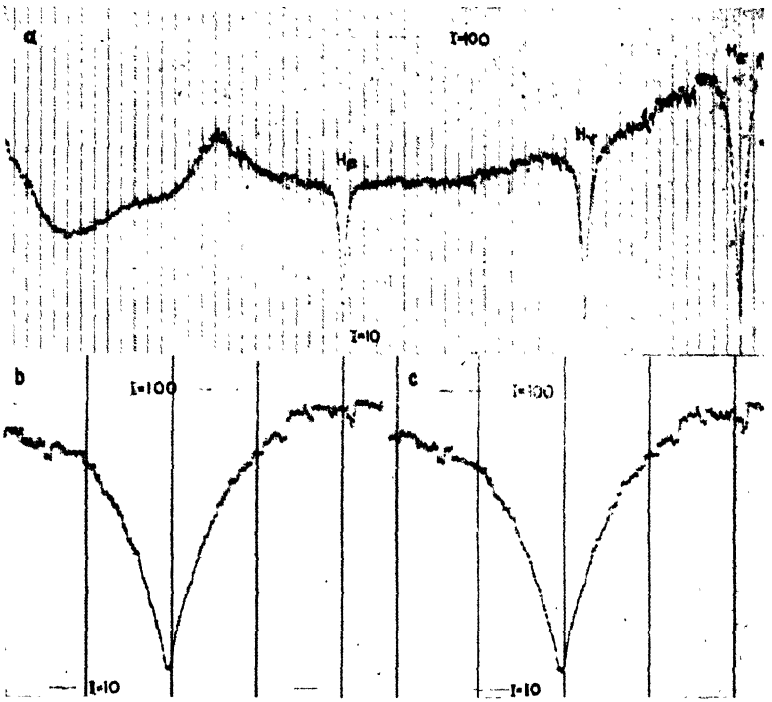


Fig. 88.—Tracings made with direct-intensity microphotometer.

the gear ratio between the screw which moves the photographic plate, and the drum on which the sensitive photographic paper is carried, to increase the length of the tracing for a given spectrum to any desired amount. By a suitable choice of magnification, minute variations in the density of a spectrum, or the exact intensity distribution in a spectrum line, may be studied in great detail.

While the photoelectric cell and the thermocouple have both been used successfully, it must be mentioned that on the whole the photoelectric cell holds more promise for the future. The slower response of the thermocouple prevents rapid scanning along the spectrum.

Once a microdensitometer tracing has been obtained, there still remains the arduous task of reducing all variations in photocurrent to variations in light intensity. This involves careful plate standardization, a variety of characteristic curves and considerable labor. A desirable form of microdensitometer, now in operation at the University of Michigan, employs a balanced circuit between a scanning slit on the spectrum and a second scanning slit on a standardizing photographic wedge. The transverse motion of the wedge locates the moving point of light on the tracing, and records the intensity variations on the paper (Figure 88). The spectrum thus tells its story of astrophysical significance without further reduction.

7

INSTRUMENTS FOR SOLAR RESEARCH

THE STUDY OF THE SUN IS OF SUCH IMPORTANCE IN ASTROPHYSICS that many efforts have been made to construct the most effective instruments for solar research. The developments are of sufficient interest for us to devote this entire chapter to methods for studying the surface and atmosphere of the sun. A complete treatment of the subject is out of place here,* but we shall gain, from a brief survey, some insight into the special techniques used in solar research.

The continuous study of specific solar phenomena is sometimes the exclusive field of research for an entire observatory. Abbot of the Smithsonian Institution has for years studied the total radiation of the sun from various sites in this country and abroad. Special solar observatories are in operation at the McMath-Hulbert Observatory of the University of Michigan, at Meudon, France, Pic du Midi in the Pyrenees, Kodaikanal, India, and Canberra, Australia. Solar research constitutes a major part of the investigations at Mount Wilson, Greenwich, Potsdam, Utrecht, Harvard, and elsewhere. The sun is therefore under almost continual observation.

The sun can be observed directly with any visual or photographic telescope after common-sense precautions have been

* A forthcoming volume in this series by D. H. Menzel will be devoted wholly to the sun.

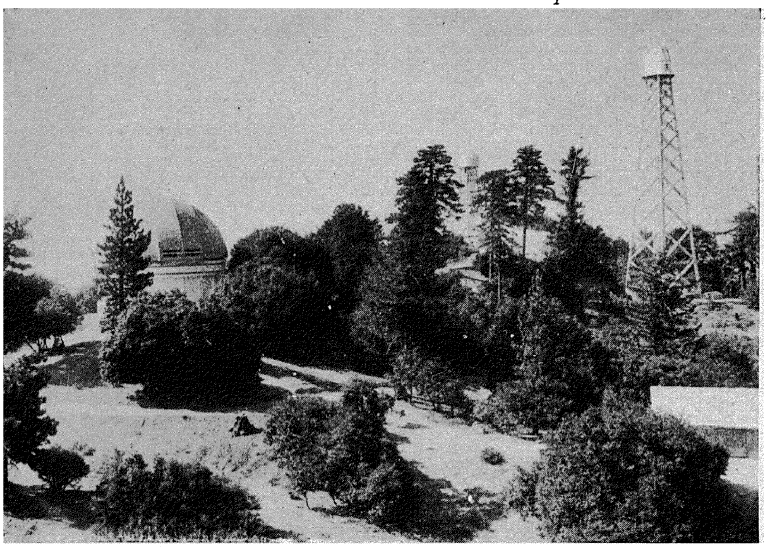


Fig. 89.—The 60 foot and 150 foot tower telescopes at Mount Wilson.

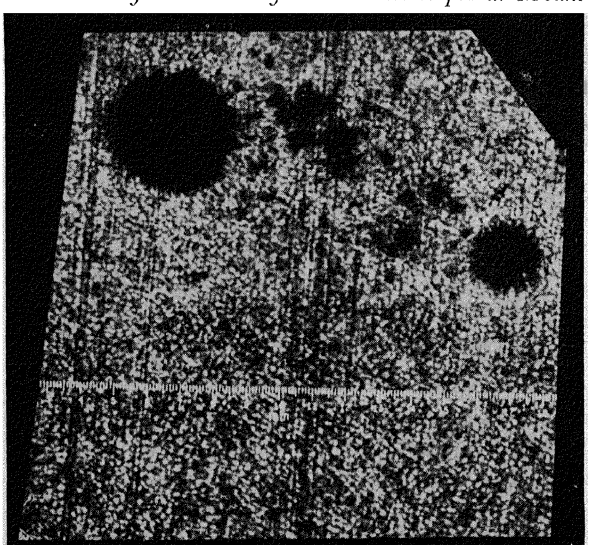


Fig. 90.—A close-up view of the solar surface near a group of sun-spots.
Taken on Kodalith emulsion at high contrast. (*Yerkes Observatory.*)

taken. One should never attempt to observe the sun visually without using one of the several types of solar eyepieces. The image of the sun formed, for example, by a 12-inch mirror of 100-inch focal-length is approximately one inch in diameter. The field-lens of a one-inch eyepiece collects most of this energy and, with the aid of the eye-lens, concentrates it on an exit pupil about one-eighth of an inch in diameter. A piece of wood held in the exit pupil will burn readily.

Excellent photographs of the sun can be made by using the eyepiece as a projection lens. One gains thereby the two-fold advantage of enlargement of the image and lengthening of exposure time. Professional photographs are often made in this way for the systematic recording of sunspots. Occasionally, direct photographs are made in the focal plane of a mirror or lens of very long focal-length. The large *f*-number of the objective renders the exposure time on fine-grain plates reasonable.

The Spectroheliograph

The spectroheliograph has served to provide solar physics with detailed observations of the sun in the monochromatic light of various radiations of hydrogen, calcium; and lately, of helium. The gases in the upper solar atmosphere are cooler than the solar surface or photosphere; but even so, they are intensely hot by terrestrial standards. These gases can be photographed by their own light. The instrumental problem is simply one of providing a way of reducing the light of the photosphere drastically without reducing markedly the light of the solar atmosphere. For an attack on this problem it must first be recognized that the radiation from the sun's upper atmosphere consists essentially of monochromatic emission lines spaced here and there throughout the spectrum. For example, the light from a solar prominence is given off in wave-lengths 6563 (*H-α*, or Fraunhofer "*C*"), 4861 (*H-β*, or Fraunhofer "*F*"), 4340 A. (*H-γ*, or Fraunhofer "*G*"), calcium H and K, etc.

The photosphere of the sun, on the other hand, emits a continuous spectrum. Consequently, the intensity of emission of a hydrogen mass suspended above the solar surface is tremendously increased, relative to the photosphere, simply by allowing

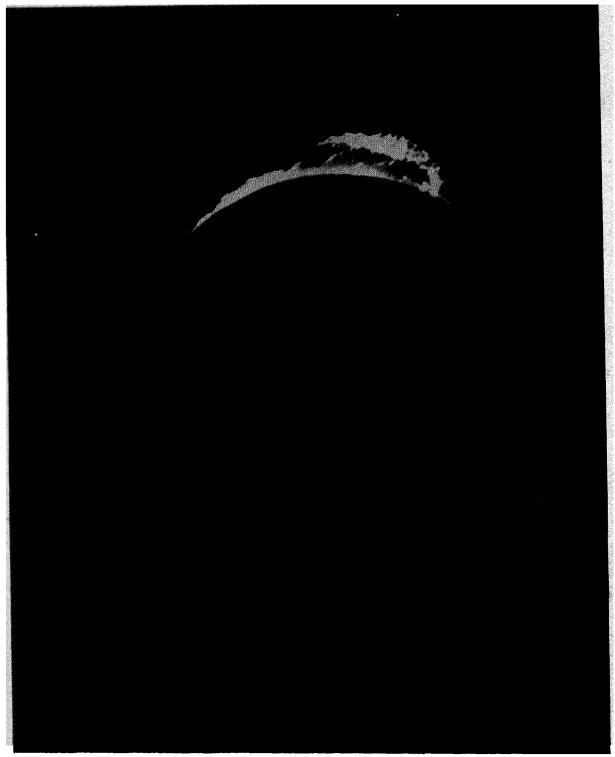


Fig. 91.—A prominence photographed during a total solar eclipse.

only the wave-lengths in the close vicinity of one of the stronger hydrogen lines access to the photographic plate.

Such selection can be obtained by forming a spectrum of a part of the sun's surface and transmitting through a second slit the few angstroms desired. Only a narrow strip of the sun's surface can be seen in this way. The problem then remains one of

obtaining a complete photograph of the solar disc in the light of the selected small section of the spectrum. This problem was solved independently by Hale and Deslandres in 1890 through the spectroheliograph.

By means of a coelostat and lens, light from the sun is brought to a focus on a slit lying across the circular image of the sun.

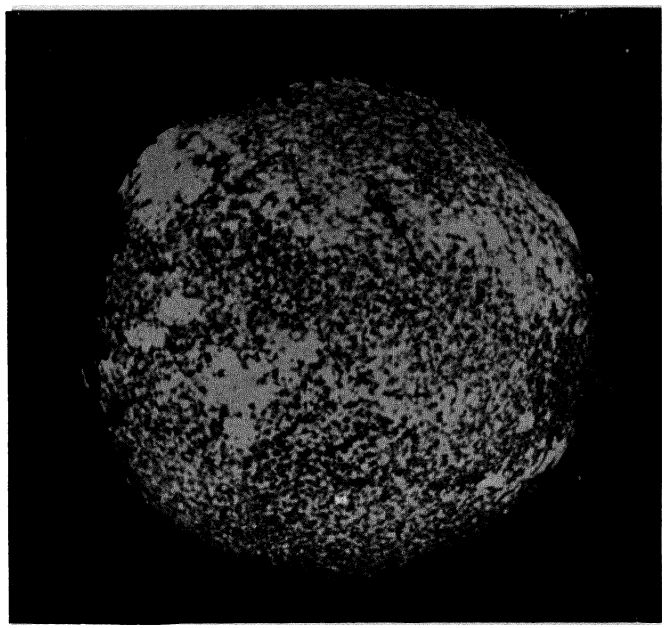


Fig. 92.—The sun in calcium light.

Consequently, only a narrow portion of the sun's surface is admitted at any one time to the rest of the instrument. The light from the slit is collimated by a first concave mirror and passes to a reflection grating. Light from the reflection grating, striking a second mirror, is focused into a spectrum on the face of a second slit. The grating is so tilted as to bring a given color upon the second slit. The light transmitted by the second slit is simply an image of the original portion of the solar surface

confined within a very narrow color region of the spectrum.

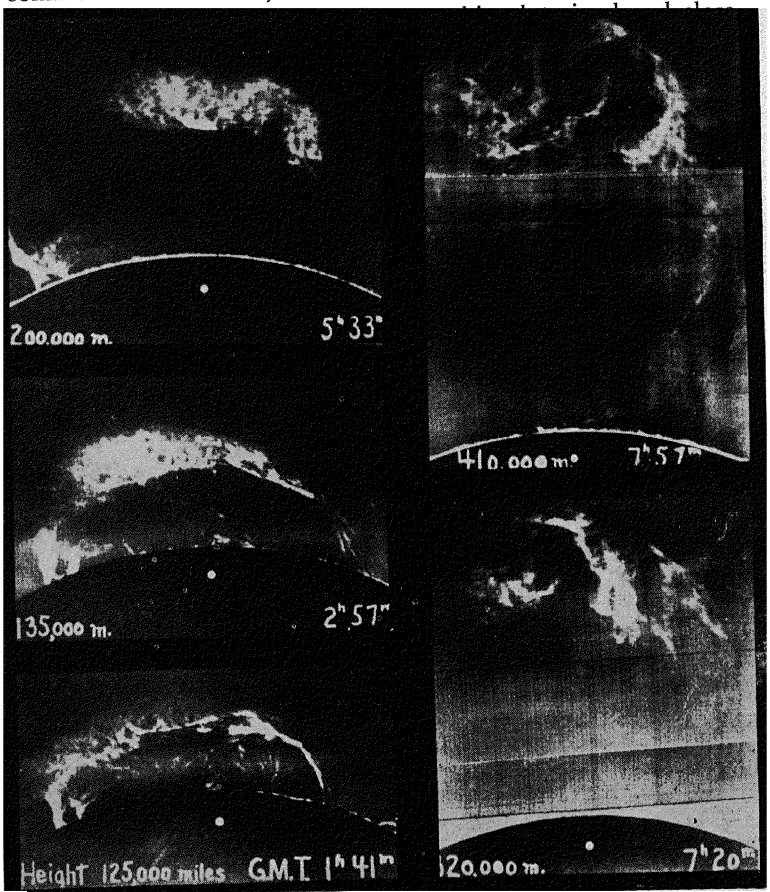


Fig. 93.—An eruptive prominence shown at intervals in its rise from the solar surface.

The dot shows the relative size of the earth. (*Courtesy Yerkes Observatory.*)

behind the second slit, usually only a few thousandths of an inch wide, where it records the strip image of the sun. In order to build up the entire circular image of the sun, in a modern form

of spectroheliograph the first slit and second slit are driven across the solar image. On a stationary photograph the series of strips overlap and integrate to form a complete image of the sun in the monochromatic wave-length chosen. By occulting the solar image with a black disc, one can obtain photographs of the relatively faint prominences off the solar limb.

None of the Fraunhofer absorption lines of the solar spectrum is completely black. Even the darkest part of an absorption line is simply dark in comparison with the nearby continuous spectrum. Consequently, one might suppose that spectroheliograms can be taken in monochromatic radiation of any element. In ordinary practice only the hydrogen and calcium lines seem to be broad enough and bright enough to yield satisfactory results. In the last few years, however, successful photographs have been made by D'Azambuja at Meudon in a far infra-red line of helium.

Many of the solar prominences are in violent motion as judged by terrestrial standards. Some solar activity is concluded in a matter of minutes. Other prominences are extremely quiescent. The gaseous masses in violent motion, either toward or away from us, produce a Doppler shift in the spectroheliograph spectrum. (See Appendix II.) Consequently, if the second slit is adjusted for the center of the hydrogen red line, for example, some gaseous masses are moving so fast as to be shifted off the slit and thus become invisible.

The Spectrohelioscope

In 1924 George Ellery Hale devised a way of obtaining visual observations of the prominences and large portions of the solar surface by means of the *spectrohelioscope* (Figure 94). In place of the photographic plate the observer uses an eyepiece. An observer can scarcely form a mental photograph of the sun's surface merely by watching a strip image drift slowly across the field of view. It is, however, well known that if twenty or more flashes of light are delivered to the eye each second, it is no longer

possible to distinguish flicker. This so-called principle of persistence of vision is used in the spectrohelioscope. The first and second slits are oscillated rapidly back and forth. The observer then sees in the eyepiece a built-up picture of the solar surface, and can watch the solar activity directly.

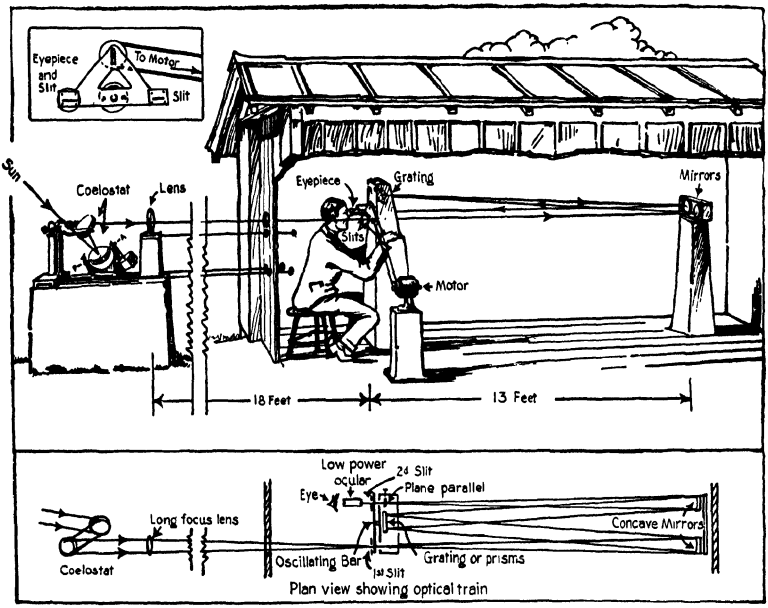


Fig. 94.—A type of spectrohelioscope.

(*From "Amateur Telescope Making," Courtesy Munn and Company, Inc.*)

In the type of spectrohelioscope recommended by Hale, use is made of Anderson prisms. The light is made to pass through square prisms of optical glass placed behind each slit. When the prisms rotate rapidly, the image of the sun and the spectrohelioscope image oscillate back and forth. Thus, rotation is substituted for oscillation. A simple variable speed motor can be used to operate the prisms.

The spectrohelioscope makes it possible for an observer to measure the radial motions of prominences with convenience and

precision. The second slit of the instrument in its position relative to the first slit marks a wave-length setting. If the second slit is given a fine adjustment by means of a graduated head, or moved optically by an interposed glass plate subject to rotation on a vertical axis, the observer can calibrate the head in angstroms, or better, in kilometers per second. In making an observation of a prominence the observer brings a gaseous filament of hydrogen into the most prominent possible view by rotating the graduated head. Readings of the radial velocity then can be taken off the dial. Plots of successive measures lead directly to the motion of the gas with time.

The McMath-Hulbert Observatory

The principle of the spectroheliograph has been most extensively and elaborately applied at the McMath-Hulbert Observatory of the University of Michigan. The Observatory, which was designed and constructed by Dr. Robert R. McMath, consists of three main structures, which are shown in Figure 95. The small dome in the foreground, which was built in 1929 and originally contained a 10.5-inch equatorial reflector, pioneered the application of motion-picture technique to the study of the sun, moon and planets. When adapted to the equatorial reflector for motion picture work, the spectroheliograph was called the *spectroheliokinematograph*. Motion pictures obtained with this instrument revealed many spectacular solar phenomena not previously suspected by astronomers. It soon became evident that a new and important tool for solar research had been fashioned, which could best be exploited by a larger observatory. It is not our intention to dwell on the effort that went into the building of the observatory. The first of two new solar telescopes, seventh of the tower telescopes of the world, was for the most part constructed in the period from July, 1935 to July, 1936—a remarkably short time for an ambitious instrument.

The 50-foot tower telescope was designed to record the motions of prominences and disc features in any color of light.

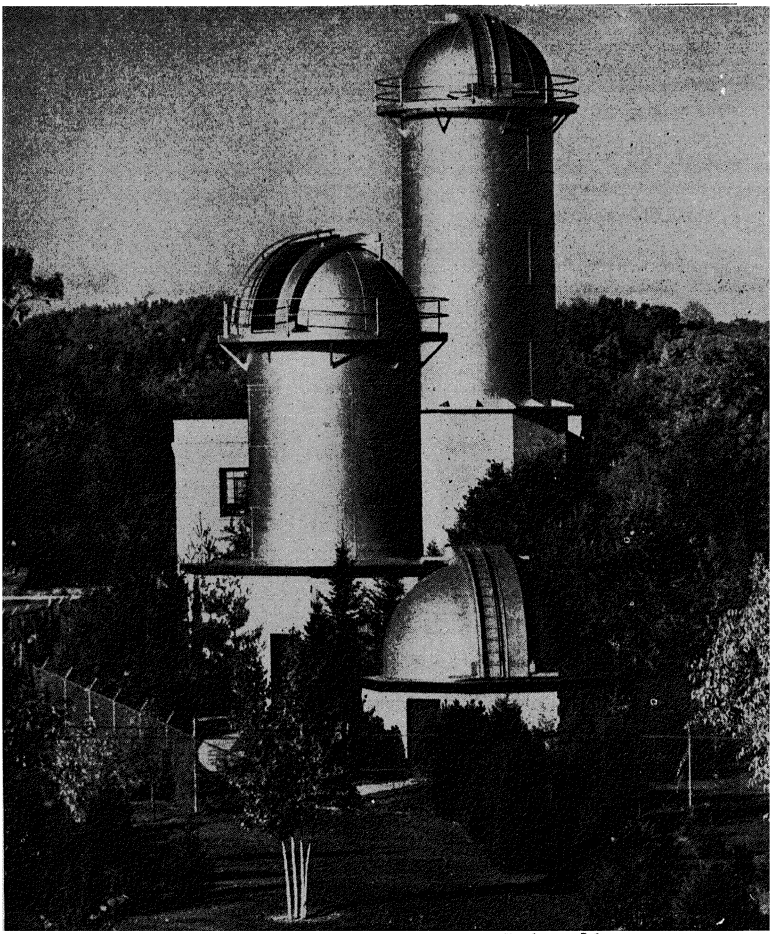


Fig. 95.—General view of the McMath-Hulbert Observatory.
(*From a photograph by Colonel Sidney D. Waldon.*)

Photographs of the sun projected against the celestial sphere show, of course, only two coordinates of the motion. The first year of observing with the tower telescope indicated that two-dimensional photography was inadequate, and that the absence of the radial-velocity or line of sight component of the motion

tended to mask the true character of prominence motions. Accordingly, in 1937, experiments were undertaken to devise an instrument that would automatically and continuously register movements along the line of sight. This instrument, the Stone Radial Velocity Spectroheliograph, was installed in the 50-foot tower in 1939. Its concurrent operation with the main spectroheliograph leads to the determination of the space motions of solar gases. In 1940, the 10.5-inch equatorial reflector was replaced by a 24-inch Cassegrainian reflector by Perkin-Elmer designed for motion picture photography of the moon and planets.

Studies of the motions of its surface gases tell only part of the story of conditions on the sun. In the last analysis astronomers are seeking to learn why and how the motions take place, and this aim is likely to be realized as a result of observations of radiant energy given off by the prominences, sunspots, etc. For this reason the McMath-Hulbert Observatory added a third building, the 70-foot McGregor Tower, in 1940. Simultaneous operation of the two towers permits a complete study to be made of the physical behavior of prominences and eruptions during their careers.

Both towers are composed of outer and inner frames. The outer serves to protect the delicate optical instruments in the inner frame from wind, weather and heat, and also carries the dome. The inner tower is very sturdily built to hold the optical parts in their proper alignment at all times.

The diagram in Figure 96*b* shows the plan of the instrument. A coelostat at the top of the tower sends the parallel sun-rays down to an off-axis parabolic mirror, which in turn sends a beam upwards to a flat mirror and down again to a focus on the bed of the spectroheliograph turntable. Alternately, the beam from the coelostat may pass through an objective lens, swung in the place of the third flat, from which lens it passes to a focus on the spectroheliograph slit. Two off-axis parabolic mirrors are available, the first 16 inches in diameter yielding a focus

of 40 feet or about a 4.5-inch solar image, the second 12 inches in diameter, yielding a focus of 20 feet. The seeing at Lake Angelus near Pontiac, the site of the tower telescope, is so good that most of the time the 40-foot focus provides a sharp, quiet solar image.

The remaining parts of the apparatus follow the spectroheliograph design with many ingenious improvements for fast

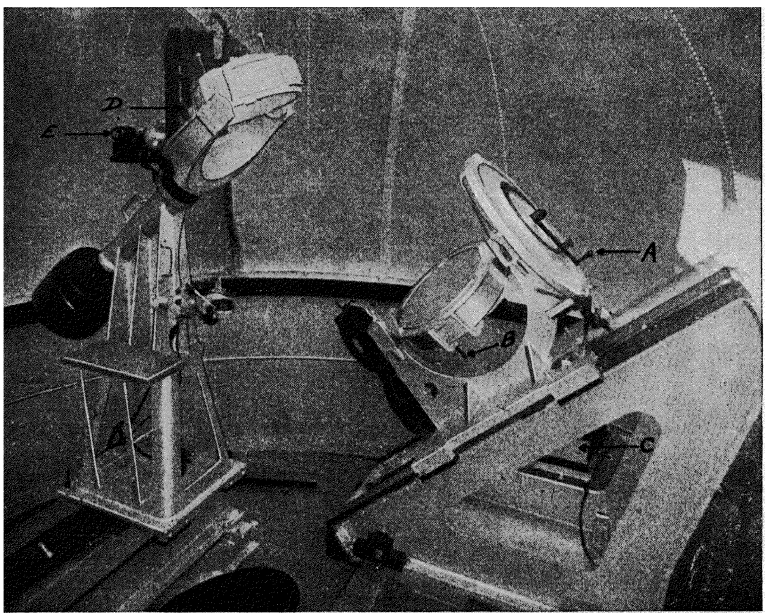


Fig. 96a.—The Coelostat of the McMath-Hulbert tower.

operation and convenience. The spectrum is provided by a grating yielding a dispersion of 3.5 A./mm. Facilities are provided for various other dispersions.

The two slits of the instrument on the spectroheliograph head move in parallel grooves rather than at the ends of an oscillating bar. Highly precise mechanics are required to achieve the best performance. The McMath-Hulbert Observatory has in this respect reached the optimum. Because of the extremely low coefficient of thermal expansion of invar, much of the construc-

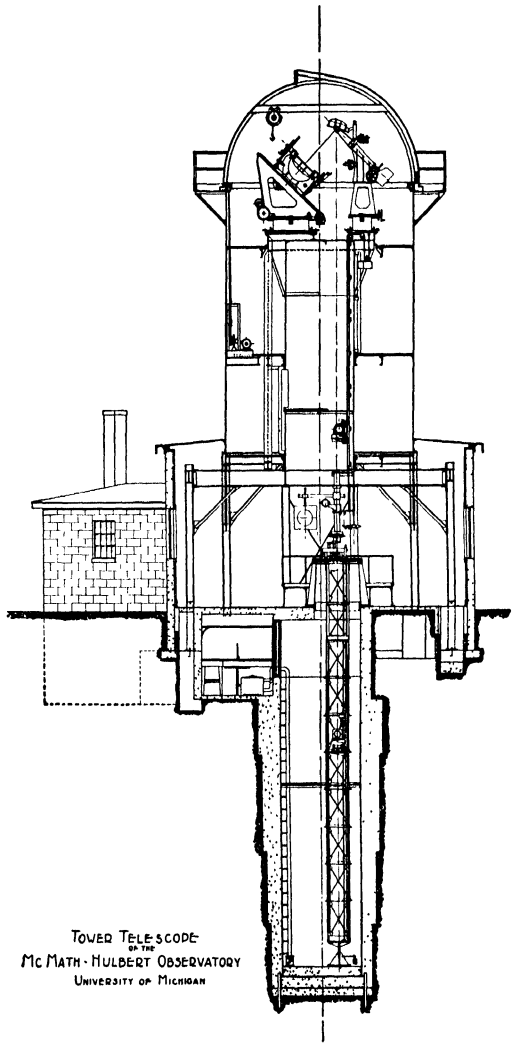


Fig. 96b.—Cross-section diagram of the tower and the spectroheliograph well.

(Drawing by John Brodie and G. Malesky.)

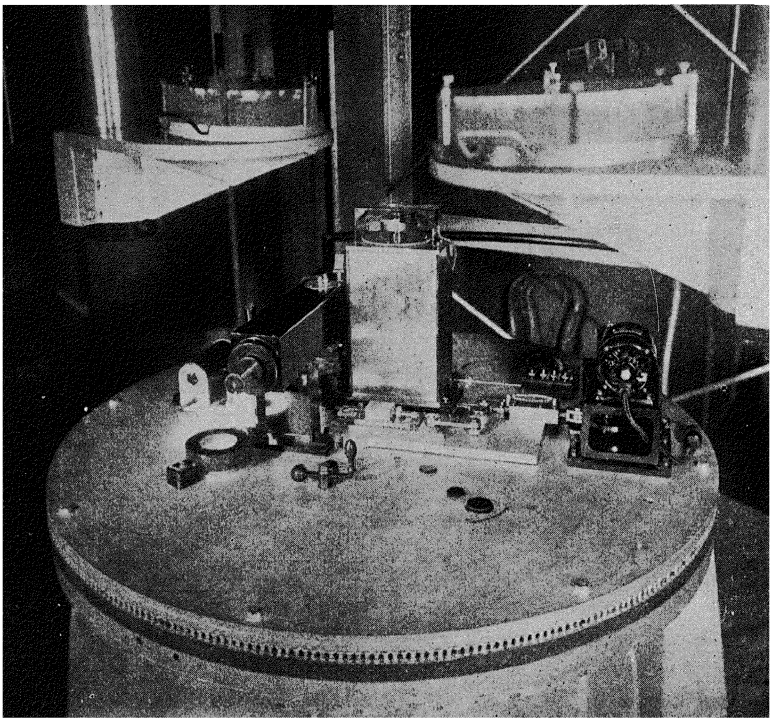


Fig. 96c.—The spectroheliograph head, with camera in place.

The grating lies in the well below the head. (*From the McMath-Hulbert Observatory, of the University of Michigan.*)

tion uses this alloy. The slit jaws are made of carboloy for the sake of extreme hardness and durability. Behind the second slit of the spectroheliograph head a specially adapted motion-picture film mechanism records the spectroheliograms at desired and mechanically set intervals. The slits move back and forth at the rate of once a second. Consequently, during an exposure lasting a number of seconds, the slits scan the solar image a corresponding number of times in each direction.

The motion-picture camera operates on any desired wavelength, usually the $H\alpha$-line of hydrogen, or the K-line of calcium.

The instrument is so constructed that the camera remains fixed in position. Some of the films contain thousands of separate exposures. Because of the long time required to obtain such a film, some means is necessary for making sure that the exact wave-length region desired is maintained on the slit of the instrument. A third slit oscillating in synchronization with the first two and set to operate on the *H* line of calcium meets the requirements. A "scout camera", using photographic plates, records the *H* line and enables the observer to obtain checks from time to time on the performance of the instrument and to ensure perfect work on the *K* line. The photographs made with the scout camera are developed immediately after their exposure to serve as guides throughout the day's work.

The *H* and *K* lines of the solar spectrum lie beyond the ordinary visible range. An auxiliary device is required to set the desired part of these lines on their respective slits. In some spectroheliographs visible lines of the solar spectrum may be used as reference standards of wave-lengths. In the McMath-Hulbert instrument the reference wave-length is provided through two auxiliary slits in the spectroheliograph head. Light from a mercury tube for observations of *K*, and from a neon tube for *Hα*, passes through these slits, which are in line with the second scanning slit. The resulting spectrum is observed through a microscope containing a reference cross-wire in line with the first slit. After the instrument is once adjusted the observer simply needs to set the 5790 line of mercury on the cross-wire to ensure that the desired portion of the *K* line be on the second slit of the instrument. Since the mercury spectrum is stationary while the primary slits are oscillating, it is possible to check the adjustment of the instrument, even during exposures.

The Radial Velocity Spectroheliograph is of the horizontal type and is fed by a separate optical system within the 50-foot tower. Light from the coelostat passes through a 10-inch achromatic lens and thence to a flat mirror, which deviates the solar beam by 90° and directs it on the first slit of the spectrohelio-

graph. A sample motion picture frame taken with the radial velocity instrument is shown in Figure 97 together with a simul-

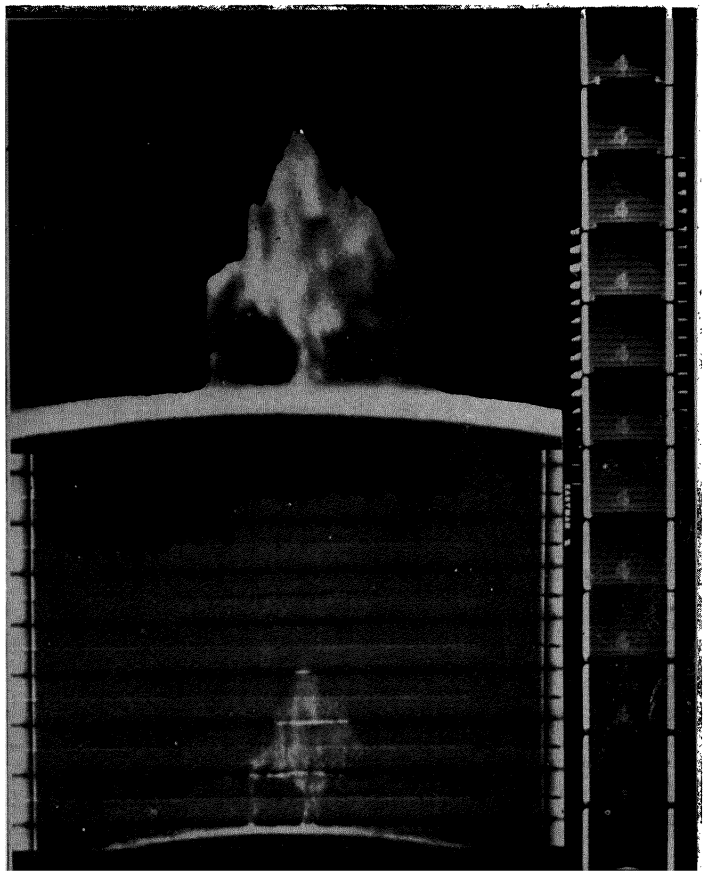


Fig. 97.—A sample photographic sequence from the Stone Radial Velocity Spectroheliograph of the McMath-Hulbert Observatory of the University of Michigan.

taneous frame from the main spectroheliograph. The spectroheliograph slits move intermittently across the face of the prominence, yielding nine separate photographs of the dark line

of hydrogen in the spectrum of the sky. Each dark line image is flanked by a narrow strip of continuous spectrum. Superposed on the dark line spectrum are the bright lines of hydrogen emitted by various portions of the prominence. The displacements of the bright from the dark lines are proportional to the radial speeds of the gases, in accordance with the Doppler effect. A carefully selected pattern of exposures ensures complete coverage of the prominence. The return stroke of the slits is continuous rather than intermittent, and produces a faint superposed image of the prominence, which helps to identify the location of the bright lines with respect to the prominence.

The 70-foot McGregor Tower telescope represents the utmost in simplicity of solar tower design, due to the almost exclusive use of aluminum castings in the coelostat mountings. The first and second flats are 18 inches and 16 inches in diameter, respectively. Since the first flat is made of quartz, the influence of temperature changes is minimized. A quartz mirror had also been planned for the second flat, but the mirror blank was lost at sea in a torpedoed vessel while enroute from England, and was replaced by a ribbed pyrex mirror.

The focusing elements consist of a pair of separated positive and negative achromats, 10 inches and 7.5 inches in diameter, with a combined equivalent focal-length of 100 feet. A focal-length of 50 feet may be obtained with the positive lens alone. An auxiliary third flat quartz mirror, mounted on a pedestal at the foot of the tower, deflects the solar image 90° on to the slit of a horizontal spectrograph. The face plate of the spectrograph is shown in Figure 98. Approximately 25 feet behind the slit is a collimating lens and plane reflection grating, which returns a spectrum with a dispersion of about 2 A./mm in the first order. The face plate is carried on two precision bearings, is easily rotatable, and may, with the aid of a vernier scale, be accurately positioned at any desired angle. The lens and grating assembly is housed in a cylindrical cage, and may be rotated from the head end of the spectrograph by a crank which is linked to the cage by

a rigid connecting rod. A second vernier scale permits matching of the slit and grating position angles. The grating lens is focused with the aid of a similar crank and connecting rod arrangement. A selsyn repeating system, also operated from the front of the

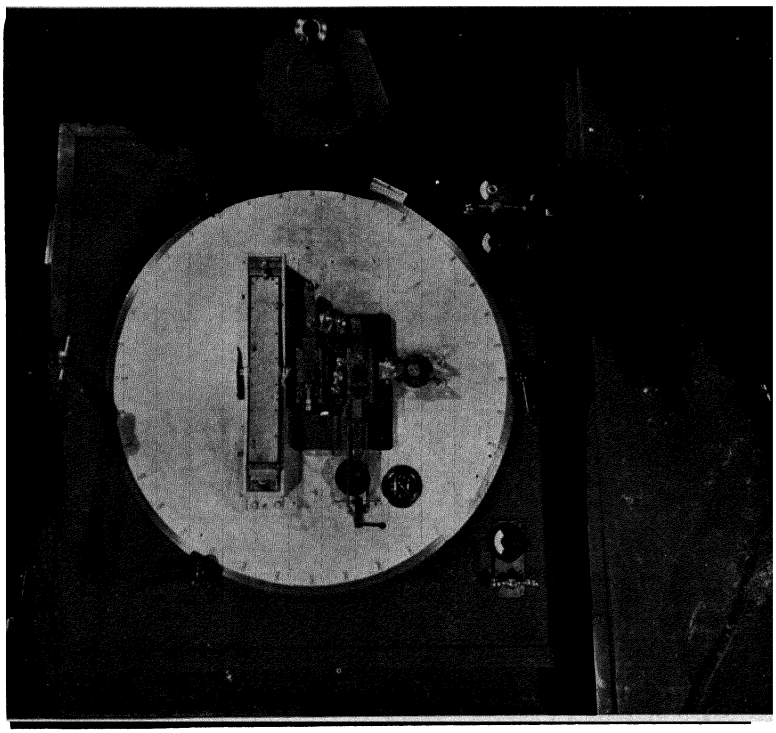


Fig. 98.—The face plate of the spectrograph of the McGregor Tower telescope of the McMath-Hulbert Observatory.

spectrograph, is used to tilt the grating and thus bring into view any desired region of the spectrum.

The spectrograph may be employed either for direct photography of the spectrum or for two-dimensional scanning, in monochromatic light, of disc and prominences. When the spectrum of

a prominence is to be photographed, the grating is tilted so as to direct the spectrum to a plate-holder located above the slit. The plate-holder may be tilted to any desired angle, and is equipped with curved templates, which ensure sharp focus over the entire length of the spectrum.

In principle the scanning mechanism is similar to that employed with the spectroheliograph in the 50-foot tower. In place of the motion-picture film is a sensitive energy receiver, by means of which the energy absorbed is converted into an electric current, which is then amplified and automatically recorded. Since the energy receiver covers only a tiny area, two-dimensional scanning is necessary. The horizontal component of the scan is continuous and is accomplished similarly to that in the 50-foot tower spectroheliograph. At the end of every half-cycle of the continuous stroke the slit and receiver move vertically by an amount equal to the width of the receiver. Because of the inversion of the spectrum by the reflecting surface of the grating, the slit and receiver must move in opposite directions during both the horizontal and vertical strokes.

Also available in the McGregor Tower is a motion picture camera of novel design which is used for direct photography of sunspots, faculae and of the elusive surface structure known as granulation. The phenomenon of granulation, which has often been likened in appearance to that of rice grains floating in a bowl of soup, is difficult to photograph with clarity, except under conditions of nearly perfect seeing. In order to minimize the effects of at least the long-period seeing disturbances, the exposure time of the camera has been made as short as possible—$\frac{1}{1000}$th of a second. Care has also been taken to eliminate camera vibrations, especially those induced by the motion of the shutter.

When the direct photography camera is to be used, the third flat is rotated until the desired region of the sun falls on the aperture of the camera (shown at the extreme right of Figure 98). The shutter is contained within the cylindrical housing, and con-

sists of three rapidly rotating discs. Near the outer periphery of each disc is a slot which is approximately the size of a 35 mm motion picture frame. The shutters rotate at different speeds and are synchronized in such a way that the disc openings coincide at the camera aperture for $\frac{1}{1000}$th of a second. The interval between coincidences may be chosen between $\frac{5}{6}$th of a second and 15 seconds, depending upon the selection of proper pairs of change gears. Behind the shutter housing is a DeVry 35 mm motion picture camera. The entire camera assembly is mounted on a heavy steel base plate, which is bolted securely to the steel supporting frame of the spectrograph head.

Lyot Coronagraph

The great developmental work at the McMath-Hulbert Observatory has brought the observation of solar activity down to an every-day affair. There remain, however, some solar phenomena still beyond the observational powers of the spectroheliograph.

Astronomers have traveled all over the world in order to make use of the precious moments of observation afforded by a total solar eclipse. Until recently, the solar corona, the outer envelope of the sun extending many hundreds of thousands of miles above the solar surface, was observable only during infrequent moments of total eclipse. This coronal appendage is altogether only about a millionth as bright as the sun itself.

Most of the light of the corona in the visible region comes from the coronal continuous spectrum; however, in very short portions of the spectrum, the coronal continuum is not so bright as the coronal emission lines, which occur somewhat at random throughout the spectrum, and which are nearly monochromatic The interpretation of these coronal emission lines until very recently had defied the efforts of solar physicists. Although the nature of this radiation is not fully understood, we have good reason to believe now that the coronal emission lines arise from definite processes under conditions of extreme excitation by solar radiation in the far ultra-violet.

One of the great handicaps in the solution of the coronal mysteries is the lack of sufficiently accurate and sufficiently varied observations. Astronomers have long striven to solve the problem of observing the corona outside of eclipse. The major difficulty lies in trying to observe, against the background of the sun, emission lines that are only one hundredth as bright as the full moon. This problem has been attacked with very marked success during the past few years by Lyot of the Paris Observatory.

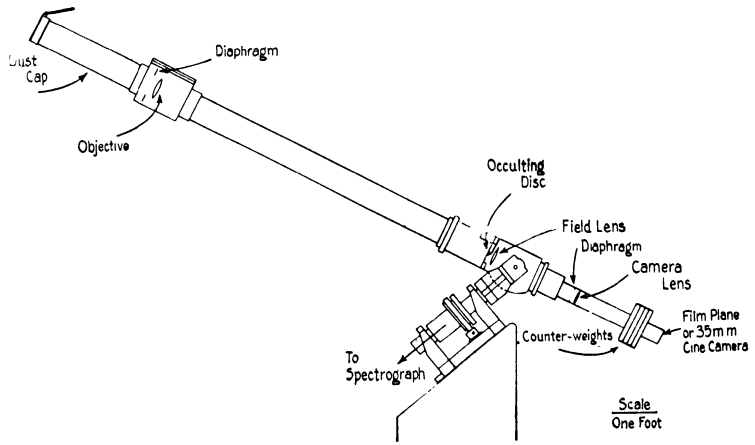


Fig. 99.—The Lyot coronagraph in schematic cross-section.

For observations of solar prominences and coronal lines outside of eclipse, almost perfect optical instruments and atmospheric conditions are required. If there were no observing site on earth with clear enough atmosphere to permit coronal light to exceed atmospheric light near the sun's limb, there would be no point in designing instruments for observing the sun outside of eclipse. However, rather elementary calculations based on observations of the absolute brightness of coronal lines during eclipse indicate that coronal light is brighter than sky light per angstrom of spectrum in dust-free air of mountain rarity.

The instrument most suitable for solar observations of this character was not only designed by Lyot of the Paris Observatory

and Pic du Midi, but was brought by him to a state of optical perfection never achieved before in practice. The arrangement of the Lyot coronagraph is shown in the diagram. The objective lens images the sun on the occulting disc. The lens must be perfection itself. Optical glass absolutely free of bubbles and striae must be worked into a lens with surfaces that are completely free of sleeks, scratches, and abrasive pits.

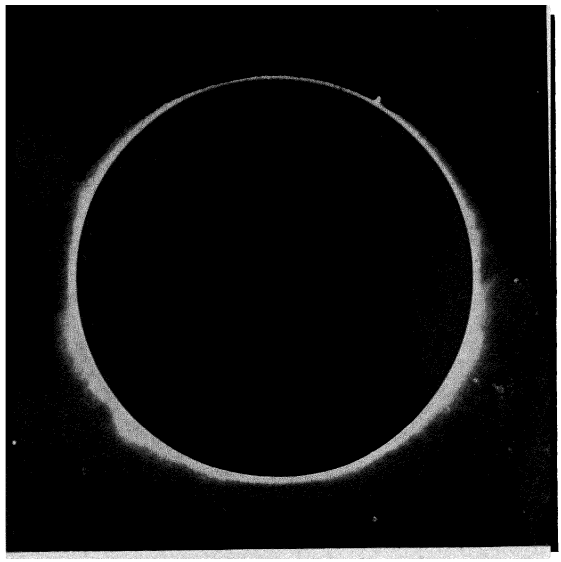


Fig. 100.—An artificial eclipse.
(*Lyot.*)

The sun is about 19 magnitudes brighter than the brightest coronal emission line. In terms of light intensity this magnitude difference amounts to a factor of 40,000,000. A minute bubble in the glass may scatter into the instrument light equivalent to a coronal line. It is a part of the design of the instrument that any such scattered light not otherwise eliminated be trapped and prevented from reaching the plate.

The opaque or occulting disc coincident with the sun's image produces an artificial eclipse within the instrument. A tilted



Fig. 101.—The corona in the light of λ6374 (Iron, nine times ionized). (*Lyot.*)

flat mirror on the front of the disc reflects most of the blocked sunlight off to one side where it is completely trapped. A field lens behind the disc images the objective lens onto a camera lens of slightly smaller diameter than the objective image. The diffraction at the edge of the objective is thereby cut out. The camera lens images the focused image of the sun and disc on the photographic plate. Circular diaphragms are placed in other places best suited to trap scattered light. The important parts of the optical system are the objective, the disc, and the arrangement to trap the scattered light. The camera device introduces no essential difficulties.

Spectrographic equipment can be placed in the usual way in place of the photographic plate. Either the slit or slitless type of spectrograph may be employed.

A properly made and properly located coronagraph operates so well that only the earth's atmosphere prevents it from photographing the corona clearly. Using the coronagraph as a visual telescope, an observer may see thousands of brilliant dancing specks. These specks are dust particles in the atmosphere, snow

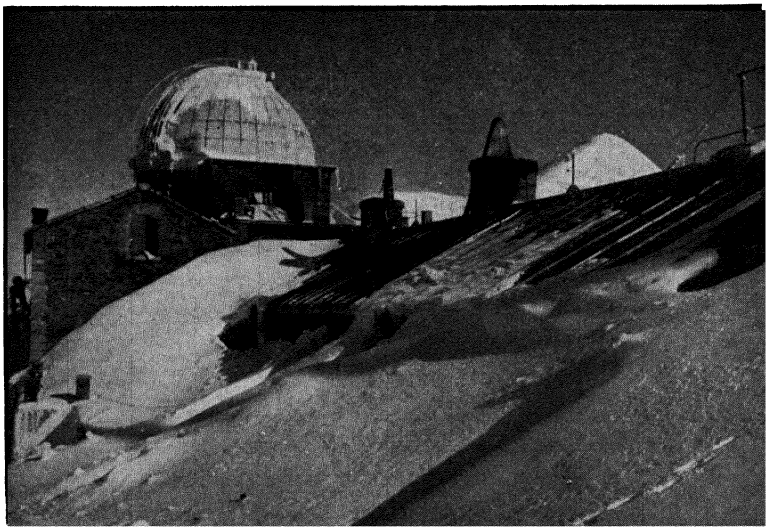


Fig. 102.—The observatory at Pic du Midi.



Fig. 103.—The Harvard Station at Climax, Colorado.

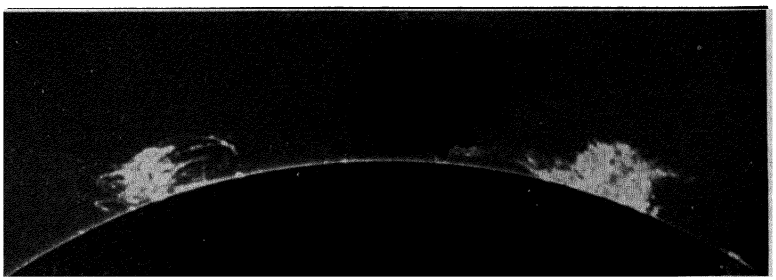


Fig. 104.—A pair of prominences photographed through the Harvard coronagraph.
(Roberts.)

crystals, or perhaps seeds from plants like milkweed. Since the specks are a long way off, and are moving relatively slowly, they often appear in focus on coronagraph pictures as bright streaks. There is nothing one can do about the problem directly, since such particles are at higher elevations than most mountains. It is of considerable interest that in spite of such obstacles Waldmeier at Arosa has succeeded in observing Regulus (alpha Leonis) within 12.4 minutes of arc of the sun's limb.

In addition to the Lyot coronagraphic station, Pic du Midi, two other coronagraphs are in operation at the present time: one at Arosa, Switzerland, and the other at the Climax, Colorado, station of the Harvard Observatory. The American observatory is at an altitude of 11,500 feet and endures an annual snowfall of 20 feet. Because of the heavy snow, the observatory roof is conical. Both direct coronal photography and spectrographic studies of prominences and corona are in progress at Climax. (See Figure 104.)

The Quartz Monochromator

In a few special types of work a filter that transmits a very narrow band of wave-lengths is exceedingly useful. Glass and gelatin filters alone or in combination do not satisfy such requirements. A band of 50 angstroms width is about the narrowest one

can obtain efficiently with filters. In solar work, involving the study of monochromatic emissions of prominences or corona, it is desirable to isolate the particular wave-length under examination and to eliminate the glare of solar light of other wave-lengths scattered by atmosphere and instrument. A recent advance in filter technique is of great importance. A filter has been perfected capable of isolating about five angstroms at a time in any part of the spectrum; we shall describe it here briefly.

In the first chapter we found that since light vibrates in a transverse direction, polarization is possible. A ray of unpolarized light passing through any one of many kinds of crystals is divided into two rays called the *ordinary* and the *extraordinary*, respectively, and these two rays are of opposite polarization. The crystal has one index of refraction for the ordinary ray, and another for the extraordinary ray. The existence of the two indices accounts for the splitting of the light into two beams, a process called *double refraction.*

Quartz possesses this property. Its indices for the D_2 sodium line are 1.5537 for the extraordinary and 1.5446 for the ordinary ray at 23°C. A quartz crystal is known as a single or uniaxial crystal. The *crystal axis* is identified by the coincidence of the ordinary and extraordinary rays.

If a plane polarized beam passes into the crystal parallel to the crystal axis, the ordinary and extraordinary rays continue to travel in the same direction and are each *circularly* polarized in opposite directions. The wave-front of the right-handed circular polarization draws away from the wave-front of the left-handed circular polarization, that is, of the wave-fronts that left the source together. The observational effect is that the beam of light being transmitted through the crystal has its plane of polarization slowly rotated with distance along the crystal axis.*

* The constant of proportionality of angular rotation to distance along the crystal axis is called the *specific rotation.* Many liquids, and solids in solution have extremely high variation of specific rotation with color, and perhaps might be converted into some useful kind of filter.

The amount of rotation depends markedly on the wave-length, (approximately as $1/\lambda^2$) inasmuch as the two indices of refraction of the crystal depend as well on the wave-length.

After the light goes through some thickness of the crystal, and passes into air, the orientation of the plane of polarization depends upon color. A polaroid sheet interposed in the beam will let through those wave-lengths of proper polarization and will absorb wave-lengths of opposite polarization. Intermediate wave-lengths are variously absorbed and transmitted with inten-

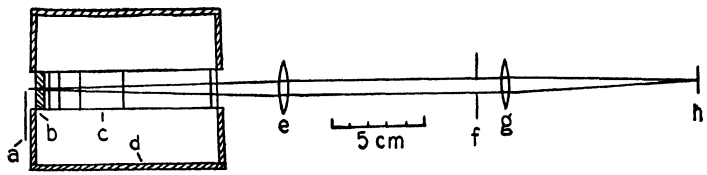


Fig. 105.—The optical system of the quartz monochromator.

A metal disc at *a* occults the sun. Light from the solar limb passes through a glass filter at *b* and then through the six quartz elements at *c*. The chamber *d* maintains the quartz at a constant temperature. The lens *e* collimates the light and *g* focuses the light again on the plate at *h*. The diaphragm *f*, as in the coronagraph, lies at the real image of the telescope objective and traps scattered light and cuts off the diffraction edge of the objective. (*From J. W. Evans, Chabot Observatory.*)

sity varying as the square of the cosine of the angle of orientation. The various transparent regions for a 25 millimeter thickness are about 50 angstroms broad. By combining this optical system with ordinary filters, we can isolate without difficulty bands about 50 angstroms broad in any part of the spectrum. Such filter resolution, however, falls far short of requirements for solar work.

If a plane polarized beam of light entering the crystal passes through at *right angles* to the crystal axis, the extraordinary and ordinary rays travel in ellipsoidal and spherical wave-fronts, respectively. If the beam is now observed after passing through some thickness, it will be found that the polarization passes from plane to elliptical to circular and back again. The thickness of

quartz required for one complete cycle is again a function of color; in a thickness of 25 millimeters, a certain wave-length will go through about 350 full cycles and at the surface be again plane polarized. Adjacent wave-lengths of maxima will have gone through 349 on one side, and 351 cycles on the other, and so on. Intermediate wave-lengths will be circularly or elliptically polarized. A 25 millimeter thickness gives a spacing of about 19 A. in the wave-crests.

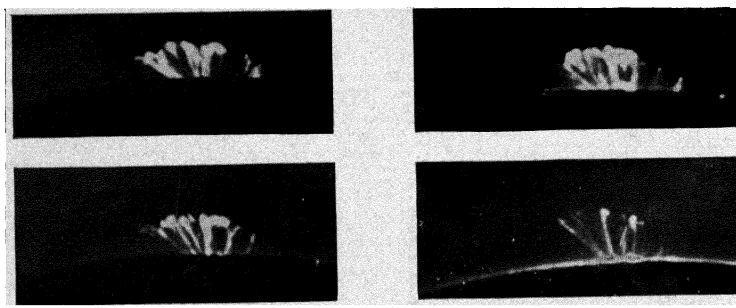


Fig. 106.—Prominences photographed through the quartz monochromator at the Chabot Observatory.

(By J. W. Evans.)

Since there exist so many closely packed maxima, it is undesirable to stop at this point. Therefore, we next let the beam pass through a 12.5 millimeter thickness, and the wave-crests will yield maxima spaced 38 A. apart. The two thicknesses of quartz combined, with a sheet of polaroid between them and behind them, will transmit maxima 38 A. apart, but as narrow as described in the preceding paragraph. A succession of filters ordered in thickness 1, ½, ¼, ⅛, etc. will isolate a particular wave-length the value of which depends on the thickness assigned to the unit at some temperature.*

* Öhman's filter has four crystals and five polaroid sheets. Evans uses six crystals and seven sheets. This type of filter was first proposed by R. W. Wood in 1914; Wood employed a single quartz crystal and two Nicol prisms for isolating either of the sodium doublet lines.

The over-all thickness of a crystal filter for $H\alpha$ (6563) with an effective resolution of five angstroms is about 90 millimeters. The diameter of the circular slabs should be large enough to accommodate a useful field. Very excellent photographs of solar prominences have been taken through such a filter by J. W. Evans. See Figure 106.

8

BUILDING A TELESCOPE

THE ACCURACY WITH WHICH THE OPTICIAN MUST POLISH AND figure an optical surface transcends the reach of all mechanical devices with which we ordinarily measure length, thickness, or curvature. In the making of a telescope lens or mirror it becomes necessary to employ the properties of light, already described in Chapter 1, for detecting variations from the desired *figure*—variations that are often less than one millionth of an inch. Such perfection is hard to attain, even on a surface of a few square inches, and the task becomes increasingly difficult in the case of modern large telescopes where this accuracy must be maintained on surfaces with an area as large as two hundred square feet. Yet in the building of a telescope, optical excellence is but the first step. However high the optical accuracy, it cannot be serviceable to the astronomer unless it is combined with a carefully designed supporting mechanism, a sturdy tube, strong mounting, a fine drive and a good shelter.

All too often we think of a telescope as a combination of optical parts whose excellence inspires well-deserved admiration, but we forget that every inch of the mechanical assembly from the foundation to the roof requires mechanical skill, pioneer engineering, and sometimes a daring of design found in only a few other fields of research. A telescope is more than a machine; it is an enterprise around which clusters the life of an institution. It is in a sense a never ending development, born of the vision of the scientist who conceives it and the technical knowledge of

the engineer who designs it; it assumes form in the hands of the builders, the mechanics, and the many workers whose ability and skill contribute to the construction; and finally it is nursed by the observer, not altogether without affection, through many nights and years of service, continuously altered or improved as the years bring new technical developments or as new ways are found of using it more efficiently.

Perhaps it is appropriate that one should first ask: Why build more telescopes? The building of a telescope comes usually as the climax of a long and patient effort to solve a difficult problem with existing instruments, which are either inadequate or overcrowded. There are really only a few hundred persons in the world actively engaged in astronomical research. It might seem strange that everyone of them should not be able, with a little effort, to find an adequate telescope somewhere at one of the many observatories.* Yet it often happens that there are no telescopes available for the solution of a particular problem, and the desirability of knowing the answer to that problem may become so insistent that it results in a private or institutional grant for the new enterprise. Sometimes plans are made, details worked out, and even the beginning of construction is started, backed up only by some small initial grant, or an individual's skill, enthusiasm, or faith, many years before the public is aware that something new and big is going on in the astronomical world.

Oftentimes it happens that a benefactor leaves a sum for the establishment of an observatory. Then detailed plans for the research of the institution must be worked out before the instruments best suited for that type of research can be decided upon. Invariably, however, there are unavoidable limitations of location, seeing conditions, and latitude, as well as previously begun research or tradition. It is the exception rather than the rule to find a telescope that has not been affected in one or more ways

* See list of telescopes and observatories in Appendix.

by some of these many considerations, not the least of which is the astronomer. After all, a telescope must be manned by astronomers whose training, specialty, or interest decide the policy and work of the observatory.

The amateur telescope maker is, however, generally not bound by such restrictions. His motive, unlike that of the pro-

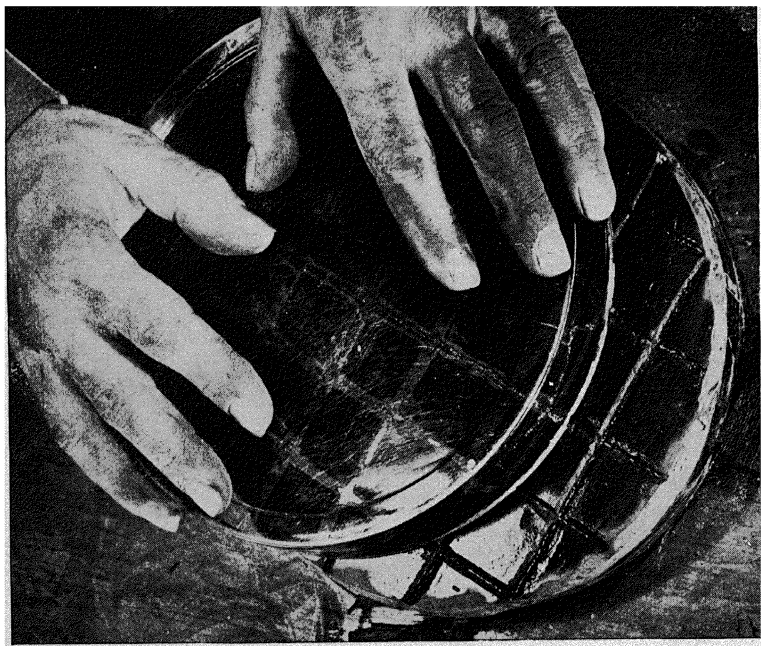


Fig. 107.—Polishing an 8-inch mirror.
(Courtesy, The Franklin Technical Institute, Boston.)

fessional astronomer or telescope builder, is to create for the sake of creating, and to satisfy the desire to possess a telescope of great excellence and of his own making. His is a healthy ambition and one to which the astronomers as well as the professional opticians have given their whole-hearted support, for the amateur telescope makers are an enthusiastic group, tucked away in

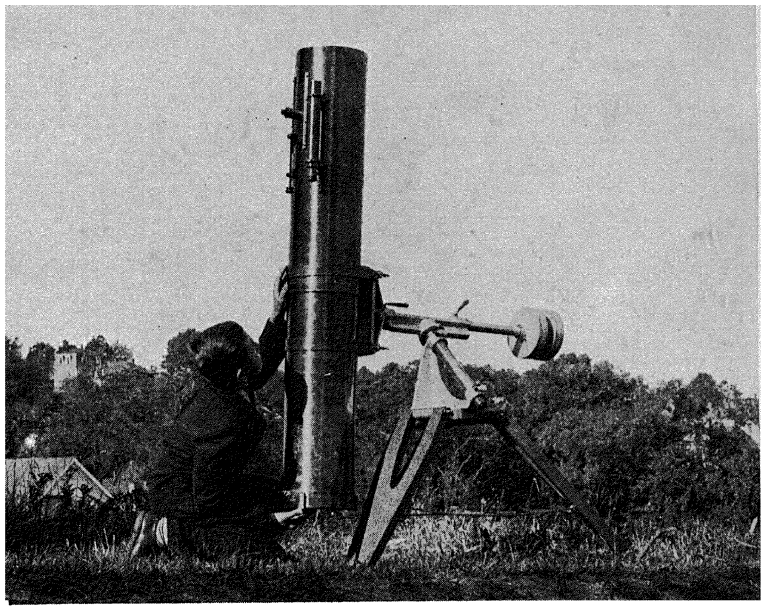


Fig. 108.—An amateur and his telescope.

Young and old alike have mastered the fine art of telescope making.

cellars, attics, barns, and other out of the way places. They know no defeat and, in the true spirit of the amateur, unhampered by professional reputation, by contracts, or time limits, they patiently polish away (Figure 107) on their surfaces toward the desired optical perfection. Nor have their efforts been in vain. They have produced not only conventional surfaces of great excellence, but they have tackled with equal enthusiasm and success the odd and the unusual. We recall the Schmidt type of telescope as one of many examples where the amateurs for several years led the field in the development of methods for making unusual surfaces.

Not only have the amateurs produced small telescopes (Figure 108), but from their ranks have come men who have been associated with some of the largest astronomical enterprises in the world. Were not the Clarks, Brashear, Warner, Swasey, and

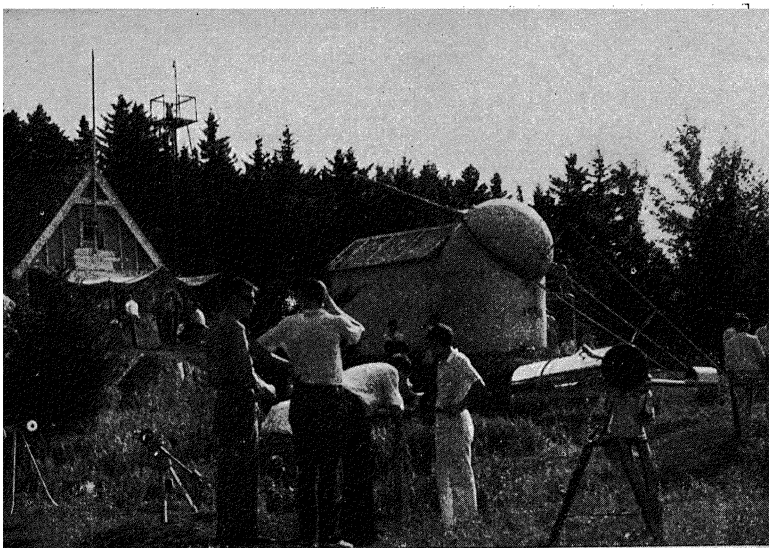


Fig. 109.—A view at Stellafane, Springfield, Vermont.

Porter amateurs at the start? There are others less known, yet equally skilled and enthusiastic, who carry on the amateur tradition. One finds such individuals in the most unexpected places. They work individually or in groups, in cities and in the country, all over the world. One of these groups is the well-known Springfield, Vermont association. Started more than two decades ago, it has done much to spur the efforts of the amateur telescope makers in the United States. Stellafane (Figure 109), the clubhouse of the Springfield group, has appropriately become the Mecca of all amateur telescope makers.

The space of a paragraph, even of a chapter, is much too small to tell the fascinating story of the rise of the amateur telescope movement, but it is of interest to note that as early as 1925 Albert G. Ingalls of the Scientific American found that the hobby of telescope making was thriving well in Windsor County, Vermont, some five years after the Springfield group was organized. At that time the literature on mirror making was scattered and frag-

mentary, but the example of the Springfield group and Ingalls' own interest in mirror making led him to the compilation of the books on *Amateur Telescope Making*, which are to-day the handbooks of the beginner as well as the advanced amateur.

The Choice of Optical Parts

The choice of practical optical arrangement depends entirely upon local conditions and the use for which the instrument is intended. We have already seen in preceding chapters that each type of telescope is best suited to a particular sort of work. A visual refractor can be adapted to photographic work by employing "yellow" plates and proper filters that transmit only the yellow-green light for which a visual telescope is corrected. Yet the visual refractor is usually made of long focal-ratio ($f/15$) which renders the telescope too slow for photographic work. This condition is aggravated by the fact that yellow-sensitive plates are much slower than plates sensitive to blue and violet light. On the other hand, no matter how large the reflector, we cannot use it efficiently for survey work in the place of a refractor or Schmidt-type combination, for without the use of additional correcting lenses the field of the reflector is limited to a fraction of a degree. A large mirror is best suited for spectrographic work as a light-gathering auxiliary, and for the photography of individual objects, close groups of stars, nebulae, and clusters. Compare for example a 200-inch reflector and a 20-inch Schmidt of equivalent focal-ratios. The 200-inch reflector would gather about 100 times more light so that it would photograph a stellar object in a small fraction of the exposure time needed by the 20-inch Schmidt; but the Schmidt combination would be able to cover the entire sky in less than 1000 photographs while the 200-inch reflector would require more than 400,000 exposures. This illustration is not intended to show the relative advantages and disadvantages, but rather to emphasize the fact that these two types of telescopes are complementary. There are many important criteria which must be taken into consideration

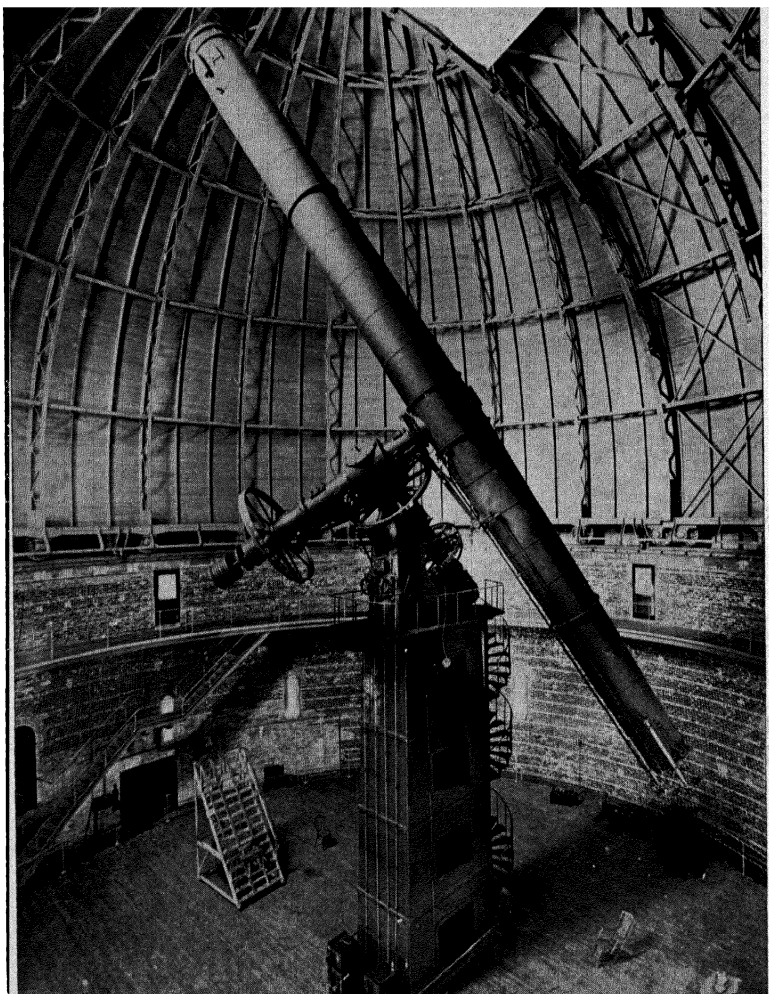


Fig. 110.—The 40-inch refracting telescope of the Yerkes Observatory.

before a satisfactory evaluation of the merits of any two telescopes can be made.

The size of the telescope is limited mainly by the size of the glass discs that can be obtained. The largest refracting telescope

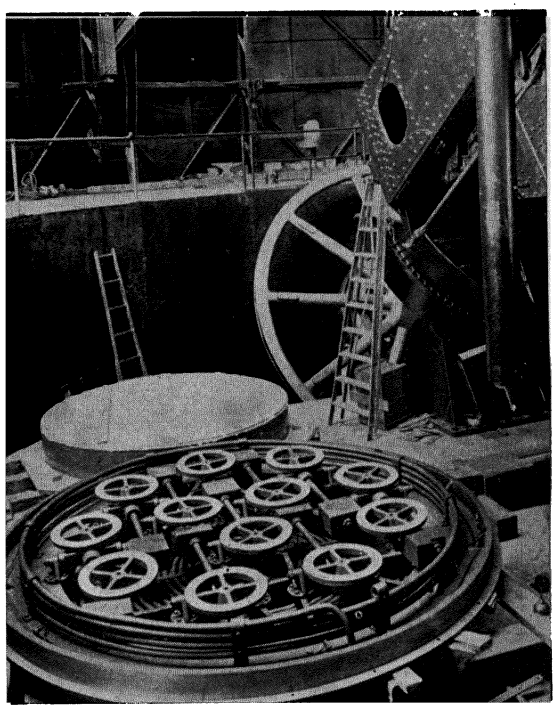


Fig. 111.—Cell of the 100-inch telescope at Mount Wilson, California. (*Courtesy Mount Wilson Observatory.*)

is the 40-inch visual of the Yerkes Observatory (Figure 110). To obtain optically pure glass disks larger than forty inches in diameter is in itself a big requirement, but even if it were possible to manufacture larger pieces of clear glass, we would hardly figure such a lens since the limit of rigidity has already been reached. A lens of glass forty inches in diameter and several

inches thick sags when supported only at the edge, and its figure will be distorted. A mirror, on the other hand, can be made of ordinary plate glass or pyrex well annealed since the glass serves only to support the reflecting surface of silver or

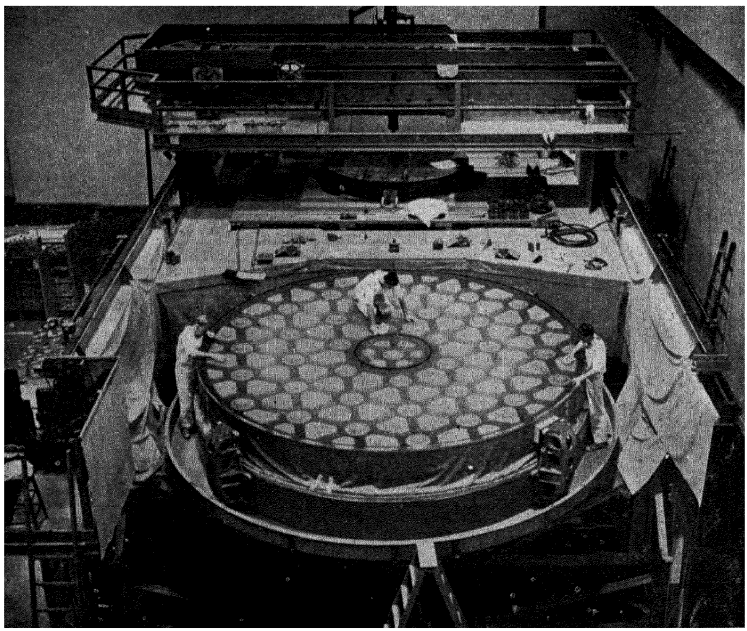


Fig. 112.—Cleaning the 200-inch mirror disc for inspection during polishing progress.
(Photo by O. K. Harter.)

aluminum. Furthermore, a mirror can be placed in a cell so designed that it will support the mirror uniformly from the back. But the effects of flexure are serious even in this case and a specially designed supporting mechanism is required when we mount large-sized mirrors (Figure 111).

Imagine a disk of glass seventeen feet in diameter, weighing fourteen and one-half tons, hollowed out in the shape of a shallow

dish to an accuracy of one millionth of an inch. A mirror of this size must retain its figure not only when it is on the horizontal table on which it is ground and polished, but also when tilted in any position, as it will be in actual use. Such is the optical

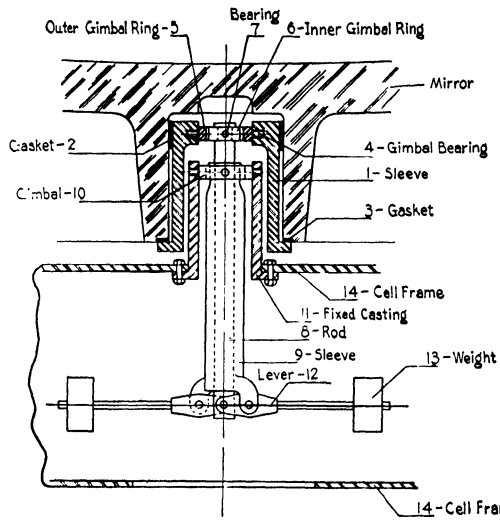


Fig. 113.—Supporting mechanism for the 200-inch mirror, Mt. Palomar, Calif.

Modifications have been made since the above diagram was published to perfect the support system. The weight of the mirror is now borne by gaskets much closer to the surface of the mirror than indicated above.

requirement of the largest telescope mirror in the world—the 200-inch of the Palomar Observatory (Figure 112). This stringent requirement becomes all the more significant when we remember that a good plate glass window pane of the same size can deviate from flatness by half an inch and may bend and buckle two or three times as much and still be serviceable.

Large size implies also great weight. The problem of reducing the weight without impairing the rigidity was solved for the 200-inch disk by ribbing the back, as shown in the

accompanying figures. The cellular form reduced the total weight of the glass to nearly one half, and at the same time, because the glass is everywhere only about five inches thick, the time necessary for the mirror to adjust itself to changes of temperature in the surrounding atmosphere is also greatly reduced. The triangular patterns shown in the figure represent the places from which the glass was omitted in order to lessen the weight, while the round holes provide locations for the ingenious and complicated system of supporting levers and counter-balancing weights, designed to keep the optical surface from buckling. (Figure 113.)

A small mirror can easily be placed in a simple cell and held down with safety by placing some soft type of material, such as blotting paper or carpeting, between the glass and the cell bottom. But when the mirror is two feet or more in diameter, a system of supporting pans is necessary and is usually designed to prevent cramping as well as buckling (Figures 111 and 113). In addition a system of side or strap supports serves for centering the mirror in its cell and leads to an even distribution of the pressure on the edges of the mirror when the telescope is tilted; the mirror so supported is said to be floating.

The cell of a lens is equally important and must be designed with great care, for in a large many-component objective, such as the 20-inch Ross astrographic (Figure 55), all components must be in extremely precise alignment with respect to the optical axis, and tolerances must be provided for the difference in radial thermal expansion of glass and cell, as well as for the change in separation of the lenses with longitudinal thermal expansion of the cell.

The "Tube"

The tube or framework is the backbone of a telescope, and serves to keep the photographic plate of the photographic telescope, or the ocular for the visual telescope, at the proper

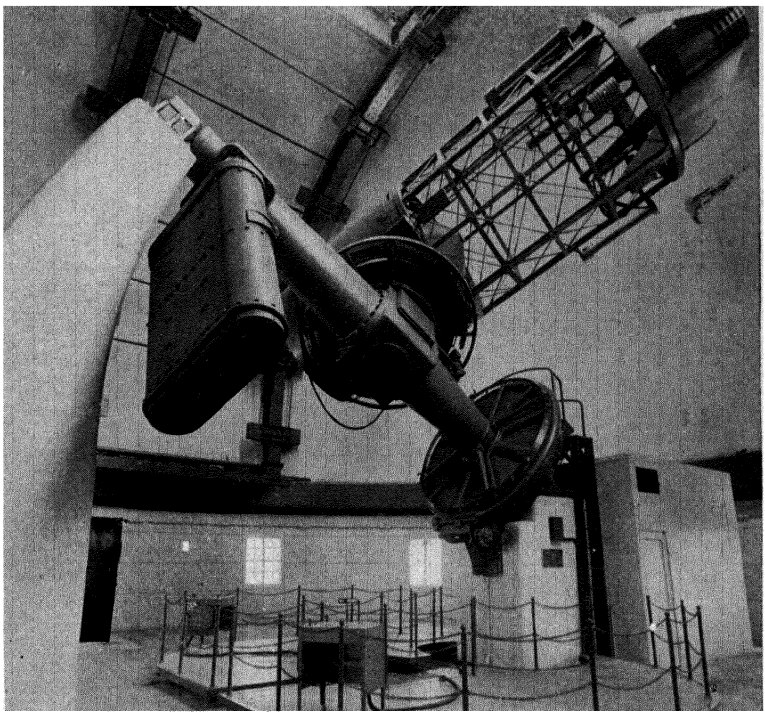


Fig. 114.—The 82-inch reflecting telescope of the McDonald Observatory, Fort Davis, Texas.

The special design at the upper end of the tube make the prime focus readily accessible.

distance from the objective. It is apparent therefore that even the slightest flexure of the tube will displace the center of the photographic plate or the eyepiece from the optical axis. Because of the ability of the human eye to follow slow changes of position of an object under observation, the tube of a visual telescope, if protected from wind and ground vibration, can usually be made of light material and can have a certain amount of flexure and twist. The problem is, however, more complicated for the photographic telescope. Here the exposures are frequently

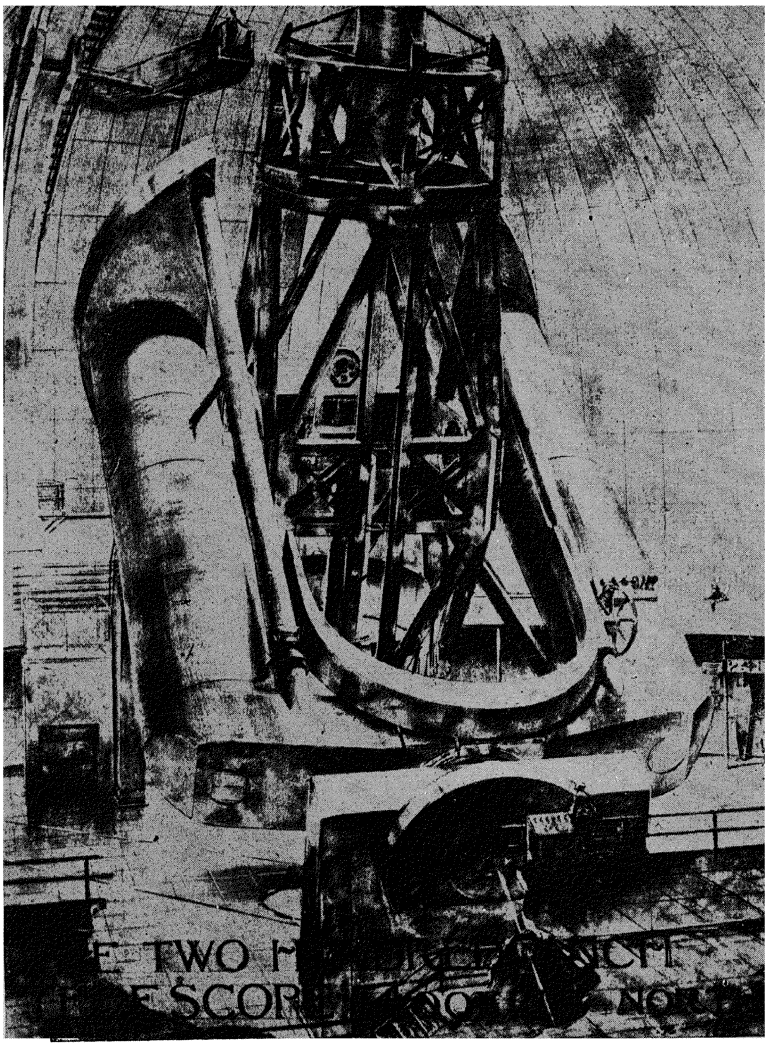


Fig. 115.—The 200-inch telescope.
(*Drawing by R. W. Porter.*)

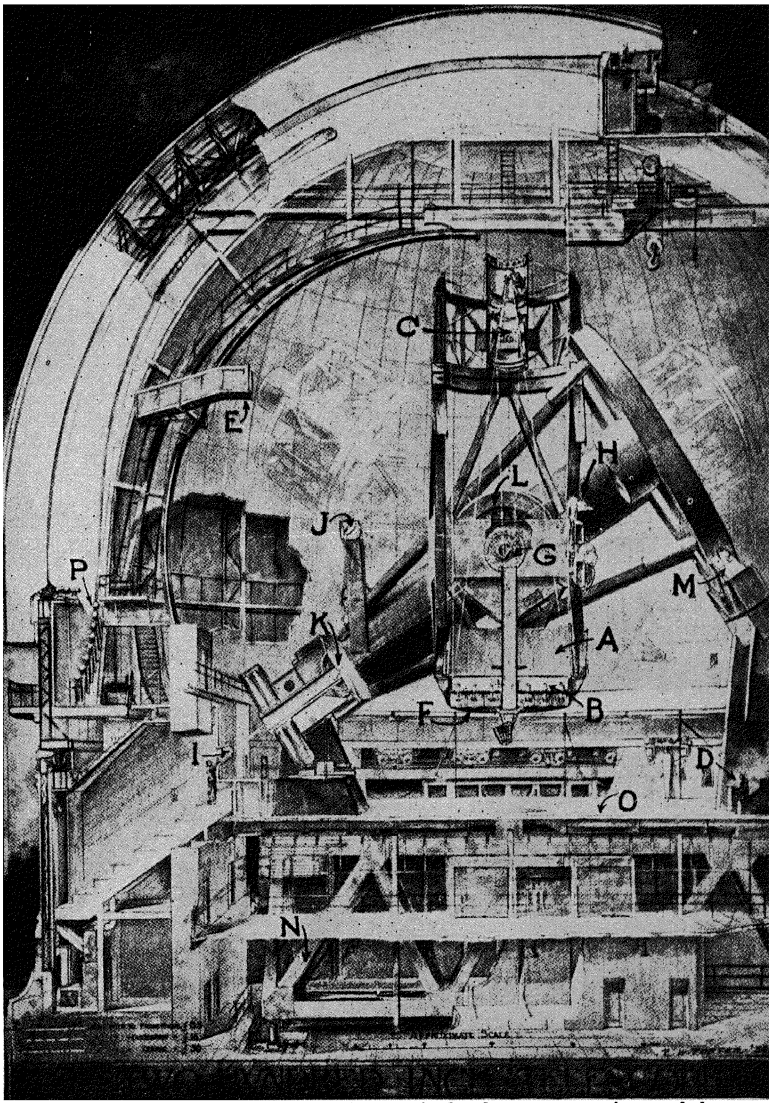


Fig. 116.—Cut out drawing of the 200-inch telescope mounting and dome.
(*Drawing by R. W. Porter.*)

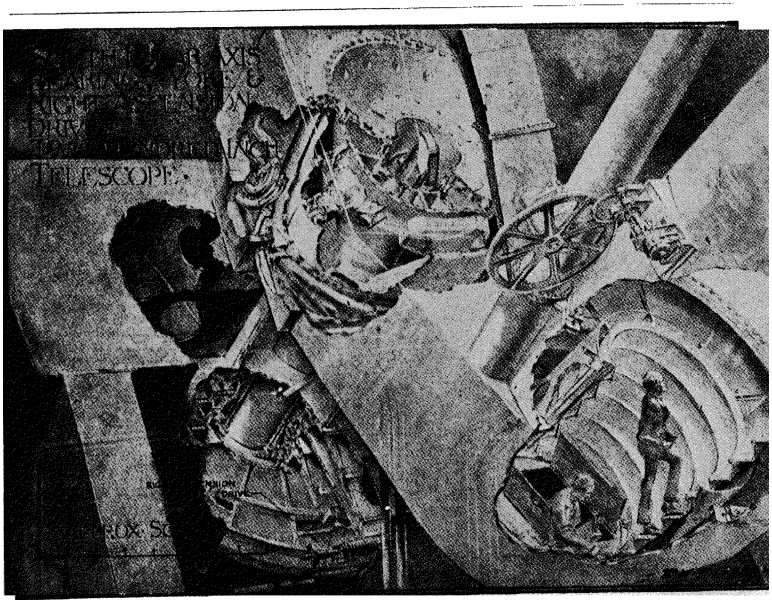


Fig. 117.—The 200-inch telescope, south polar axis and yoke.

The men are walking inside the arm of the yoke. (*Drawing by R. W. Porter.*)

long, the photographic plate is rigid and once clamped in the plate-holder does not permit any motion between the lens and the plate; hence rigidity requirements are more stringent. A slight displacement of the plate-holder from the optical axis may cause an elongated or trailed image, thus spoiling the quality of the plate. In the design of a photographic telescope the tolerances are very small and become smaller as the instrument increases in focal-length.

Most of the large reflectors are built with provision for work at the Newtonian, Cassegrainian, coudé, and in some cases the prime focus (Figures 37 and 114). The change from one form to the other is not a simple matter. The flat mirror of the Newtonian arrangement must be replaced with a convex one if the observations are to be made at the Cassegrainian focus. The

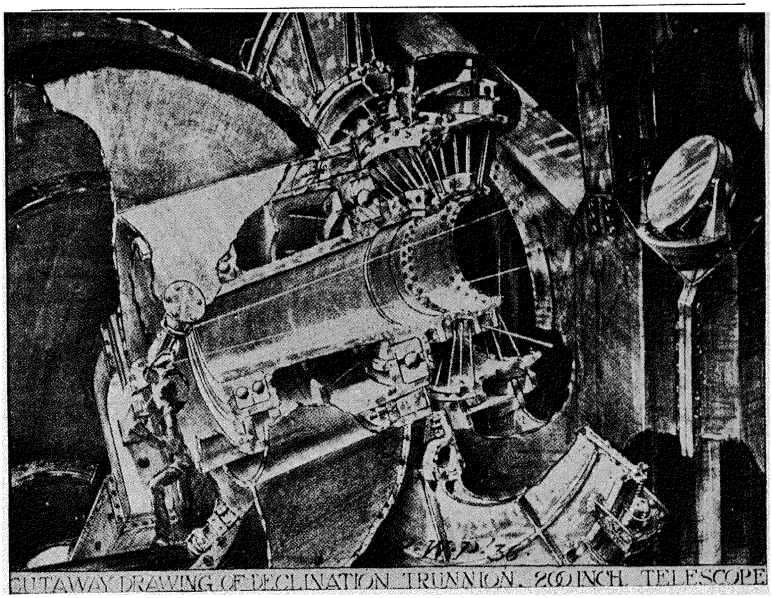


Fig. 118.—Declination trunnion of the 200-inch telescope.

Note the man working at the spectrograph inside the trunnion. (*Drawing by R. W. Porter.*)

plate-holder receiver and focusing device, usually referred to as the tail-piece, must be transferred from the upper end of the telescope to the lower, and the instrument has to be properly counterbalanced. Such a transfer consumes time. Although programs are mostly planned well in advance so that these changes are made during the day, it is occasionally desirable to change quickly from one arrangement to another during the night. This will be possible in the 200-inch telescope, where the auxiliary mirrors are so mounted within the tube that the change from one arrangement, say the prime focus, to the Cassegrainian or coudé focus can be accomplished automatically by remote control in a few minutes. To make such a change possible, thousands of pounds of auxiliary mirrors, mirror cells, motors, and levers must be balanced in all positions, and they

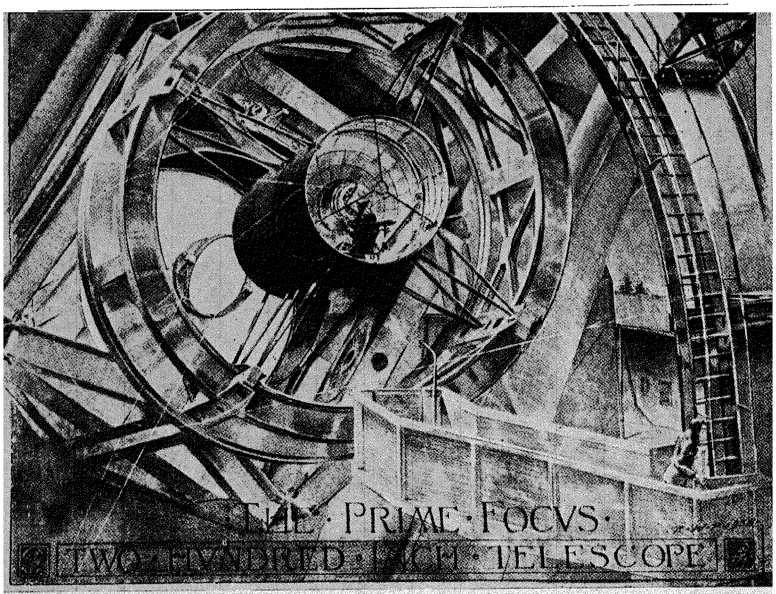


Fig. 119.—Prime focus of the 200-inch telescope with the observer inside the observer's cage.
(*Drawing by R. W. Porter.*)

must fit into their proper places with an accuracy sufficient for the requirements of fine optics.

One can form an idea of the rigid construction as well as the size of the largest of all telescopes, from the extensive cut-out figures made by Porter (Figures 115, 116, 117, 118, 119), which show the inside workings of some parts as no photograph can reveal them. The entire structure is so heavy and so rigid that one can walk inside the arms of the yoke of the mounting, in order to reach some of the spectrographic rooms located inside the declination trunnions (Figures 117, 118); the observer actually rides the telescope during the exposure (Figures 116, 119).

The tube, which in a visual telescope is constructed of material ranging from paper through wood and various metals, is

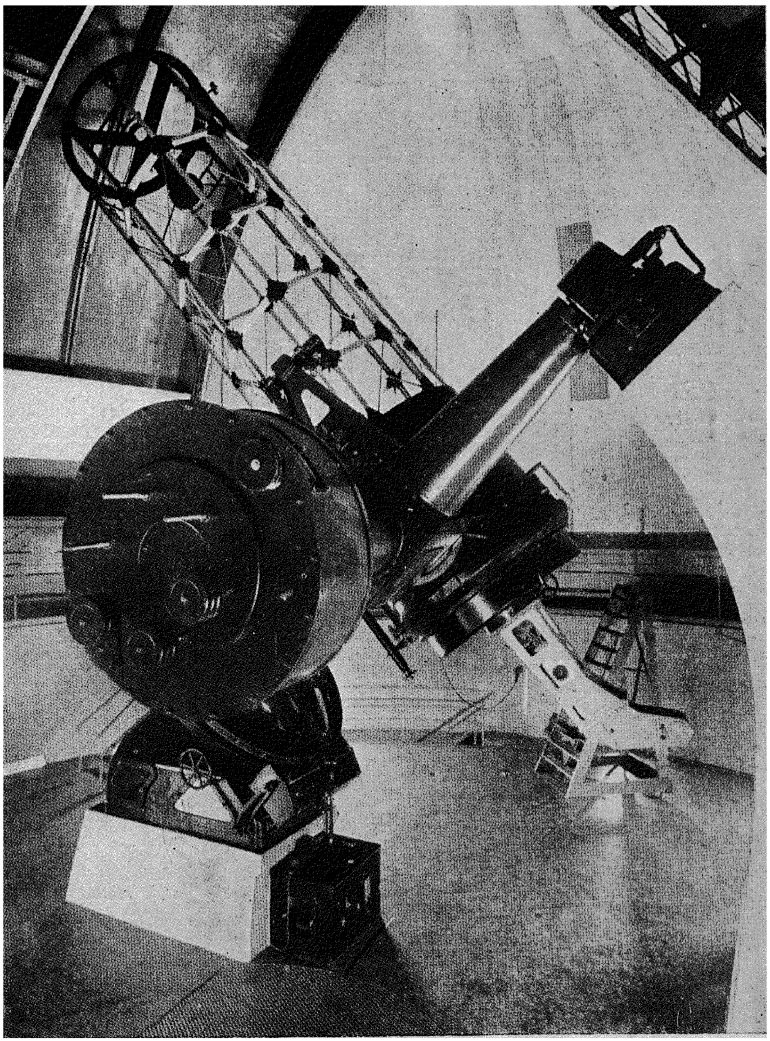


Fig. 120.—The 74-inch reflecting telescope of the David Dunlap Observatory, University of Toronto, Canada.

often made of light material such as duralumin or of the lighter magnesium alloy known as Dowmetal. The conventional round tube of uniform diameter is sometimes replaced by an open frame prismatic structure, especially in the large reflecting telescopes where light superstructure is desirable (Figure 120). In the construction of the 200-inch telescope tube we find even greater departure from the conventional cylindrical type. In the place of the uniform diameter structure, the tube consists of a cubical section in the middle, from the corners of which 20-inch *I* beams support two cylindrical sections. These two sections carry respectively the mirror cell on one end and the observer's cage for the prime focus at the other. The strict requirement of rigidity is shown by the fact that the entire tube, which together with the mirrors and the observer's cage weighs 140 tons, does not sag or deform under gravity by more than one sixteenth of an inch. An ordinary structure of comparable size, like a tower or a bridge, can sway or sag under load by several inches and still be safe.

The Mounting

Thus far we have described the parts of the telescope proper, which, however perfect, would be useless unless it were handled by an astronomer of Herculean strength. A telescope must be moved from one position to another, and set on the star or region under observation. Even in the case of the smallest visual telescope, the supporting mechanism must permit a motion which will allow the telescope to be set on any star that appears above the horizon. In addition we must have provision for moving the telescope smoothly from east to west so that the stars can be followed in their nightly motions. Since it is the rotation of the earth from west to east that gives the apparent westerly movement of the stars, the telescope is usually mounted on a polar axis that is parallel to the axis of the earth. This axis is carefully oriented on the meridian, i.e., directly on the north-south line, and is adjusted so that the north end, for northern

latitudes, will point directly toward the north pole of the sky.[1] The telescope tube is not rigidly attached to the polar axis but can rotate about an axis perpendicular to the polar axis. This second axis is called the declination axis because it allows the telescope to move in declination from the celestial pole to the equator and even below the equator to the horizon. Once set, the telescope is rigidly clamped to the polar axis. If now the polar axis rotates westward with the same angular speed as the eastward rotation of the earth, the telescope will follow any star as it describes its diurnal arc across the sky.

The actual arrangement of these two axes and the support upon the foundation give a variety of mounts, two of which are shown in Figure 121. The most common type is the *German mount* (Figures 121*a*, and 110), especially suited to the visual refractor. The short polar axis and the single pier which supports the instrument at a point near the middle of the tube permits great freedom for the observer and allows access to all portions of the sky. A variation of this mounting is found in the two-pier type *English mount* (Figures 121*b* and 122), in which the polar axis is much longer and supported on two piers. The declination axis is also extended and carries the counter-balancing weights, *W*. This type of mount is especially desirable when the telescope is of great weight and freedom from flexure and rigidity is essential. Both the German equatorial and the two-pier mounts, however, have the disadvantage that they cannot always be used conveniently in following an object across the meridian without swinging the telescope from one side of the pier to the other. Shifting the telescope across the meridian is particularly incon-

[1] The altitude of the pole varies from place to place. For example, at the north pole of the earth the pole of the sky is exactly overhead, at the zenith; while for an observer situated exactly at the equator both north and south poles will be on the horizon. For a location between the equator and the north or the south pole the respective north or south poles of the sky will be elevated by an angle equal to the latitude of the observer. Thus for Cambridge, Massachusetts, the polar axis will be elevated about 42 degrees.

venient in photographic work where long exposures are usually made as the field crosses the meridian, because this is where the ill effects of the atmosphere are at a minimum.

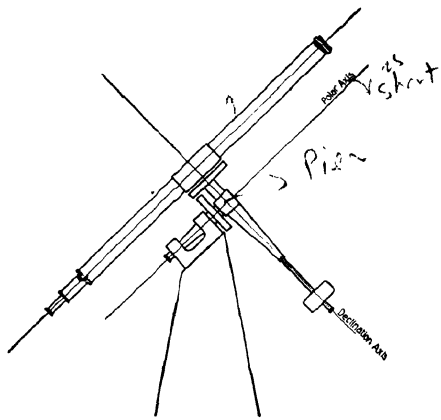


Fig. 121a.—The German equatorial mount.

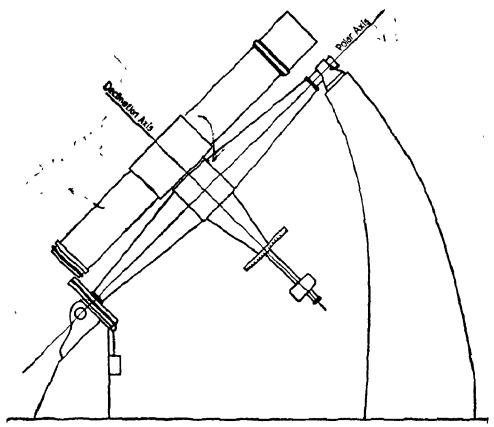


Fig. 121b.—The English equatorial mount.

A variation is found in the mounting of the 100-inch Hooker telescope (Figure 123), in which the tube, instead of being overhung on a counter-balanced cross axis, is attached by trunnions to

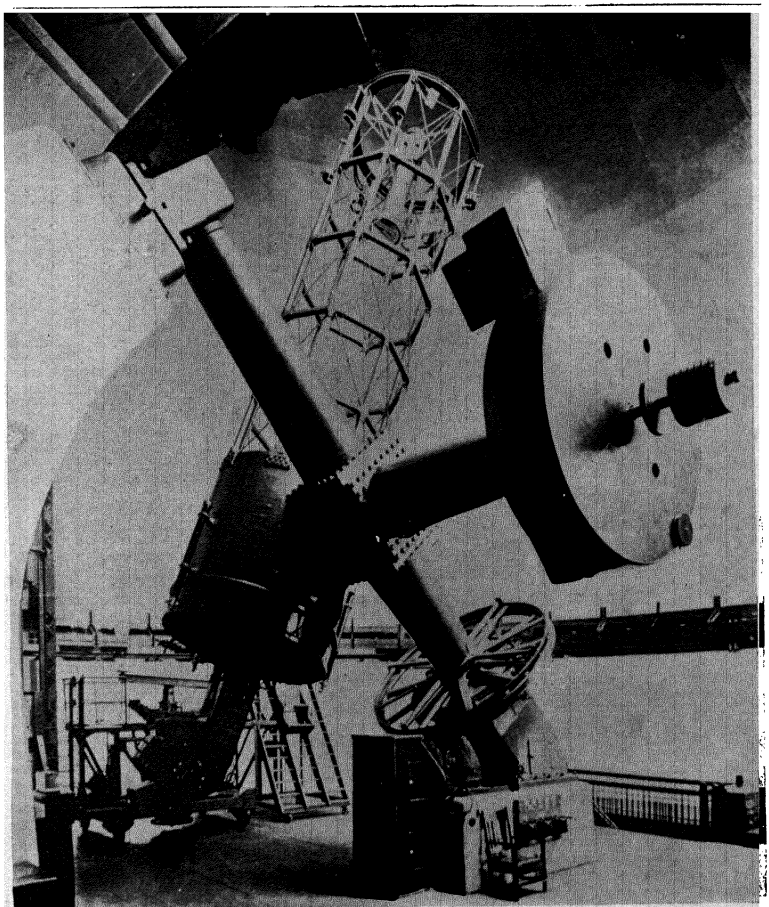


Fig. 122.—The 72-inch reflecting telescope of the Dominion Astrophysical Observatory, Victoria, B. C.

the cradle or yoke which carries at its ends the north and south polar bearings. The *yoke type* of mount obviates the shifting from east to west at the meridian and eliminates the necessity of counter-balancing the tube on the declination axis, but has the disadvantage that it is impossible to observe with it the region of the celestial pole.

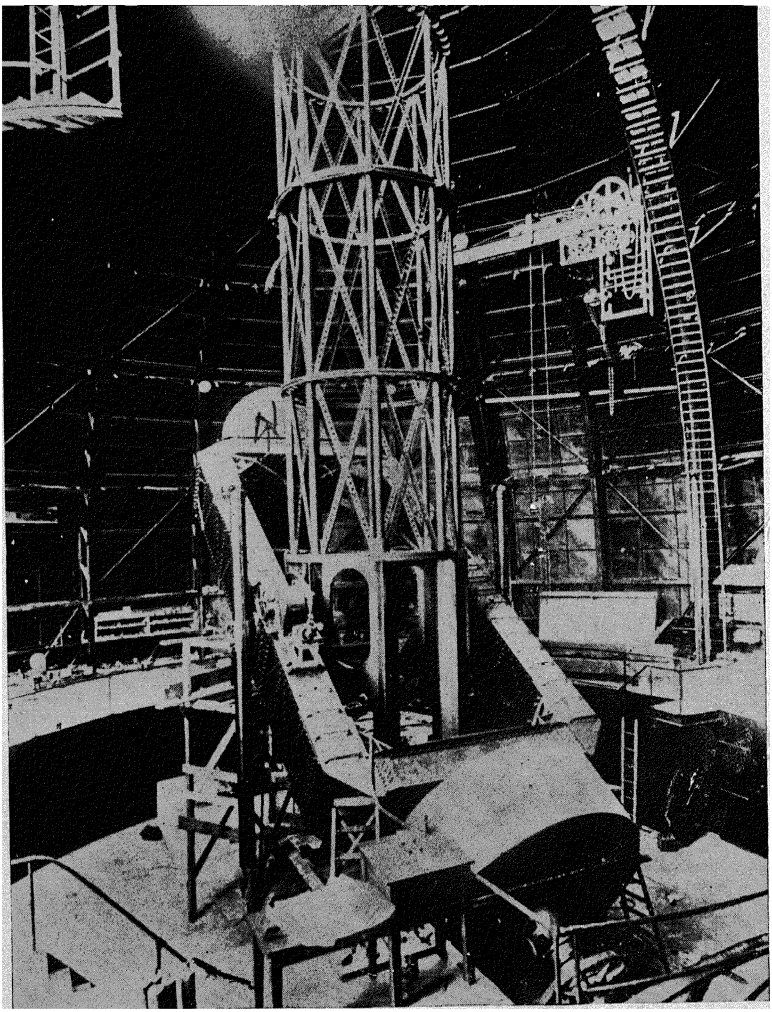


Fig. 123.—The 100-inch reflecting telescope of the Mount Wilson Observatory, California.

The *fork type* of mount (Figure 124), which is extensively used, overcomes several of the above-mentioned disadvantages. Here the declination trunnions are mounted at the tips of the two-

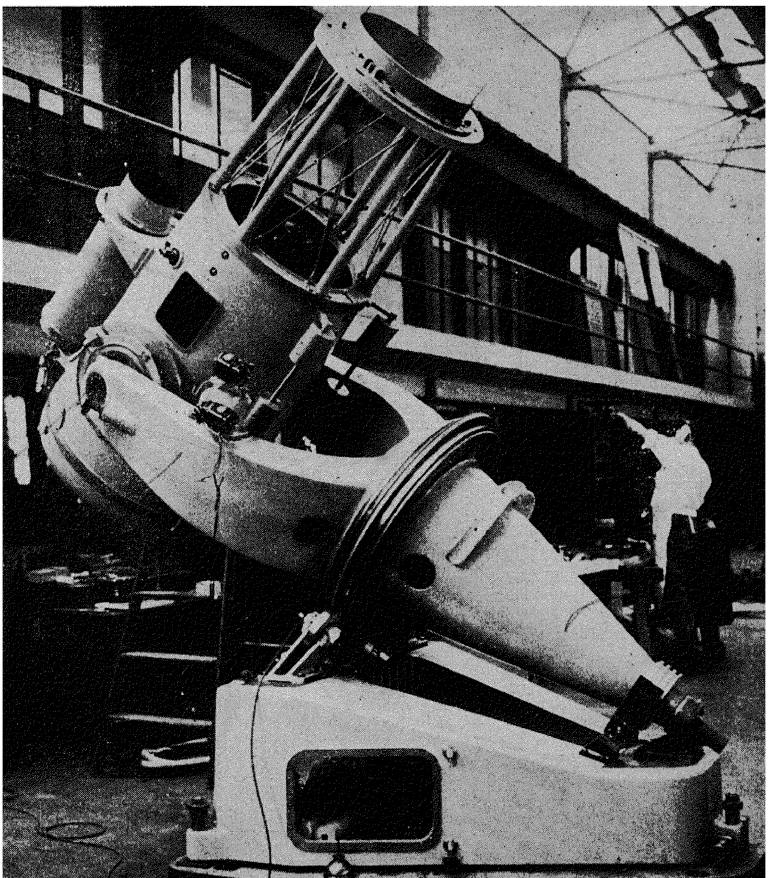


Fig. 124.—The 18-inch Schmidt telescope now on Mt. Palomar, California.

pronged fork so that the tube swings between the prongs while the handle of the fork becomes the polar axis. With this arrangement one can follow a star uninterruptedly from east to west,

without having to shift the telescope about the pier. Such a mount is adapted to the short-focus refractor, and especially to the reflector, because its tube's center of gravity is near the end of the heavy mirror and mirror cell which is counter-balanced by the long but light superstructure of the upper end. This

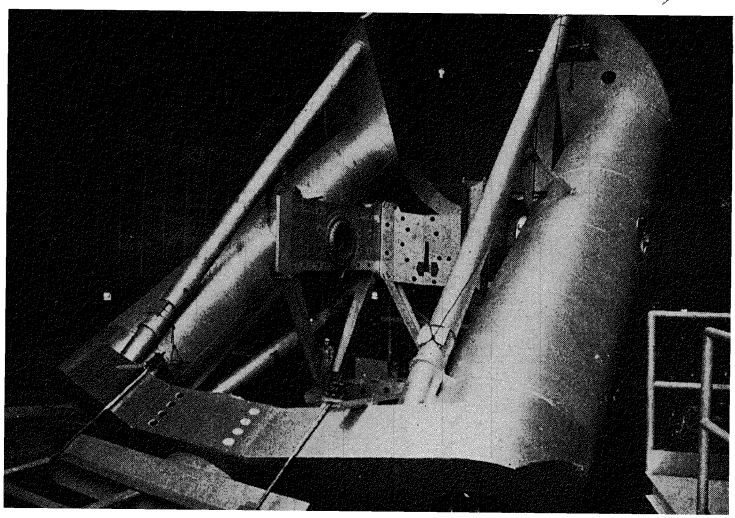


Fig. 125.—The fork end horseshoe of the 200-inch telescope on Mt. Palomar, California.

Note the man standing on the center beam.

type of mounting would, because of the great overhang, be subject to excessive flexure if used in larger telescopes.

A combination of the fork, yoke and two-pier mount is found in the mounting of the 200-inch telescope at Palomar. Here the entire axis is much like a fork whose prongs are joined with a horseshoe (Figure 125). The outer surface of this horseshoe, some 46 feet in diameter, is the north bearing of the polar axis. The horseshoe floats on thin pads of oil pumped under high pressure into the area between the metal surfaces. The telescope tube is so mounted that it can swing inside the horseshoe when

the telescope is pointed to the pole. So huge is this bearing and so heavy the load it carries, that it is not possible to keep its shape when in actual use under load. When the axis turns east or west the weight will bend the horseshoe section and will deform it. To eliminate this difficulty, the bearing surface was machined as follows: a compression member was placed at *A* (Figure 126), and a tension applied with the turnbuckle

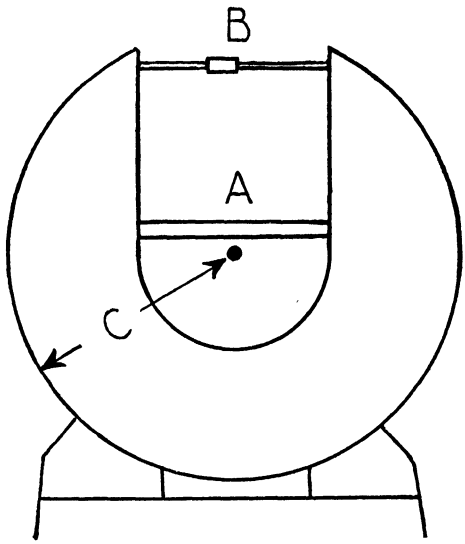


Fig. 126.—Method of deforming horseshoe of 200-inch mounting during machining of bearing surface.

at *B*. The horseshoe thus deformed was placed on the boring mill and its edges ground circular. When the bars *A* and *B* were removed, the prongs were deformed. In the instrument under load the radius *C* will remain nearly constant for all positions of the telescope.

The Drive

The apparent motion of the stars must be offset by means of a driving mechanism, usually referred to as the clock or drive,

because the original arrangement of such a drive was a weight-driven clock. The rate of a telescope clock, however, must be continuously changed in order to correct for *differential refraction.* When a star is near the horizon, its light is bent, or refracted, in passing at an angle from the less dense outer layers

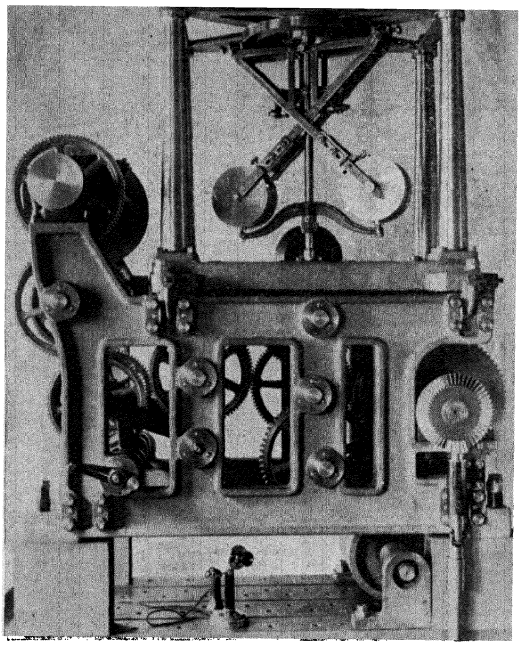


Fig. 127.—The original driving clock of the 100-inch telescope.

of the earth's atmosphere to the denser lower layers. The star appears therefore slightly higher in the sky than it actually is. In observing an object it is necessary to point the telescope in the direction from which the light *appears to come.* The clock must therefore run slow when driving near the eastern horizon and must be continuously speeded up as the star rises to the meridian. The clock must again be slowed down as the star sets in the west. Only on the meridian, where the diurnal motion

is horizontal and therefore parallel to the atmospheric layers, will the clock run at the true sidereal rate.

The *weight-driven clock* also called the *gravity drive* (Figure 127), is the oldest, and in some respects the simplest, because its rate can be controlled by a mechanical governor. It has the disad-

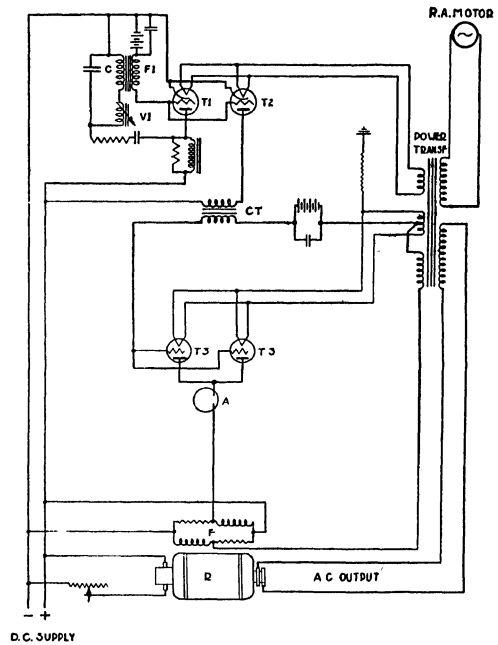


Fig. 128a.—The thermionic tube frequency control circuit.
(McMath-Hulbert Observatory.)

vantage, however, that the change in rate is not easy to control while the clock is in motion. There is the further necessity of periodically winding, which can be accomplished automatically by the use of an electric motor, and suitable contacts.

Recently the frequency-controlled synchronous motor drive perfected at the McMath-Hulbert Observatory has come into prominence (Figure 128). This type of drive is exceedingly ac-

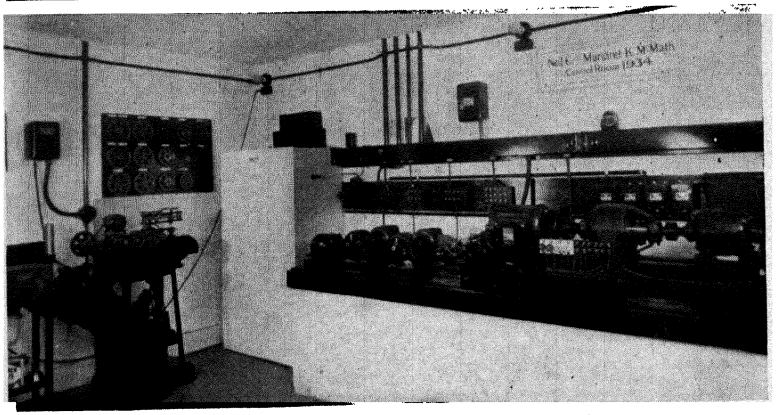


Fig. 128b.—Interior view of the main control room.
(*McMath-Hulbert Observatory.*)

curate and is based upon a design in which the frequency of the generator can be controlled accurately and altered at will by the observer. This drive has flexibility and is well adapted for observatories with a single instrument, but is not convenient where many instruments are to be driven from the same generator, for the control of the frequency as practiced at present requires a separate generator and control mechanism for each individual telescope.

In order to provide a simple and independent control for each instrument, Professor Willard P. Gerrish, of the Harvard College Observatory, as early as 1900 devised the electric drive which now bears his name. This drive was designed to take care of voltage fluctuations in the ordinary electric power supply, especially where the observatory is located far away from the central distributing station. It is equally well adapted to any electric supply for it presupposes no regulation of voltage or frequency. Figure 129 shows the form of the Gerrish drive devised by Herbert Hanson, and now in use at the Harvard College Observatory, which operates entirely from the alternating-current lighting supply. The speed of the electric motor geared to the

worm and worm wheel, to which is attached the telescope, is controlled by the pendulum of an ordinary clock. As the pendulum swings through the vertical position, the magnet *A*, which is attached to the pendulum, lifts the armature *B* and opens the contact switch *C*, breaking the ten-volt circuit. As soon as the circuit is broken, the armature *H* drops so far away from the electromagnet that it can not be pulled back, even though the ten-volt circuit is restored as soon as the pendulum swings

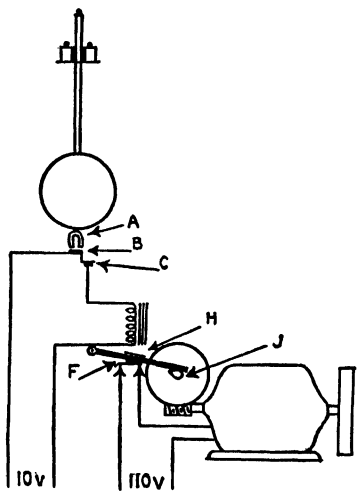


Fig. 129.—The Gerrish-Hanson drive.

past the vertical position. When the armature *H* drops, it closes the power switch *F* (a mercury or micro switch) and the driving motor starts. Geared to the motor is the cam *J* which returns the armature *H* to its original position, where it is held by the ten-volt magnet until the pendulum on the return stroke repeats the process. It is the interval between the time the pendulum reaches the vertical position and the time the cam lifts the armature that constitutes the power stroke to the drive. If the motor is going too fast, it will turn the cam faster and shut off the power soon after the pendulum releases the

armature *H*. On the other hand if the motor is driving slow, the cam will not lift the switch *F* so soon and the power stroke is lengthened. In the later design of this drive the magnet switch is replaced by a photoelectric cell so that the signals are sent as the pendulum cuts off the small beam of light shining on the photoelectric cell. The pendulum of the clock then swings absolutely free and does not do the work of lifting the armature as in the old drive.

The rate of the clock can readily be varied by increasing or decreasing the load on the pendulum, even during operation of the clock, thus effectively raising or lowering the center of gravity. The great advantage of this drive lies in the fact that it can operate on alternating as well as on direct current and requires neither frequency nor voltage control of the electrical power.

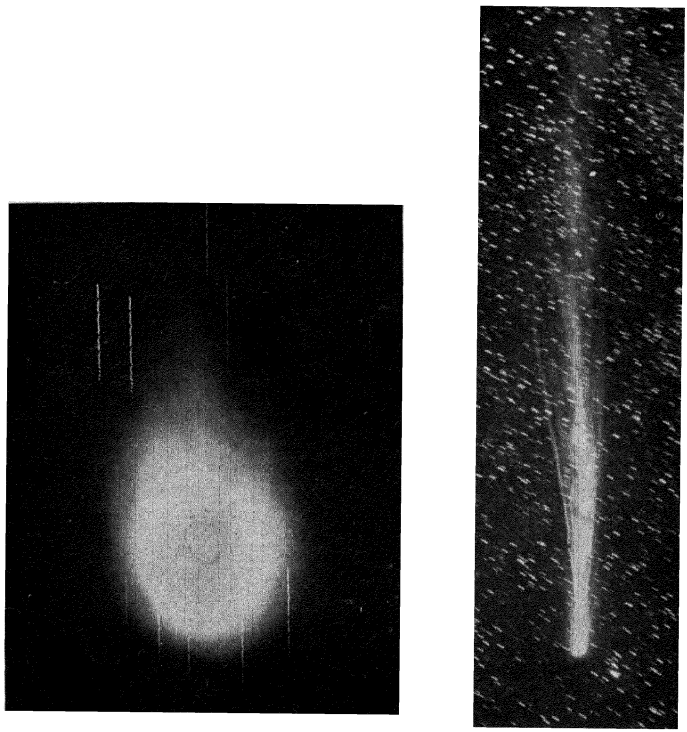
Guiding

Even when care is taken to make the drive as nearly perfect as possible, there are small residual corrections which for the present can best be eliminated by stationing at the telescope an observer who actually guides out the errors throughout the duration of the exposure.* For this purpose each photographic telescope is provided with an auxiliary visual telescope or microscope which is used for guiding. The object to be photographed, or a nearby star in the sky, is usually set on the cross-wires, which are made ordinarily from fine spider web,† and the star image is continually held bisected on the cross-wires

* The development of photoelectric automatic guiding devices has advanced very rapidly, but as yet automatic guiding has not been employed extensively in routine observing.

† Spider web is used because it has sufficient elasticity to remain tight under varying conditions of temperature and humidity. At night the cross is illuminated by a small electric light and appears as fine luminous lines against the sky background.

by means of the auxiliary slow motions usually provided for this purpose.



a *b*

Fig. 130.—Star trails produced by the motion of the telescope guided on the comet which moves with different apparent velocity from that of the stars.

(*a*) Head of Halley's Comet 1910; (*b*) Morehouse's Comet 1908.

If however the object to be photographed is moving with respect to the stars, as in the case of a comet or an asteroid, we compute the angular motion of the object, and orient the micrometer screw, which is a part of the eyepiece of a good

guiding telescope, in the desired direction of motion. The observer then turns periodically the head of the screw a fraction of a revolution, thus displacing the cross-wire in the desired direction, while he keeps the guide star on the moving intersection. In the finished picture (Figure 130), the object has been followed while the stars sometimes show irregular trails, due to the inability of the observer to bisect the star image exactly at each movement. It is not practical, except on rare occasions, to guide on a faint moving object itself, especially if it is a hazy patch like the head of a comet.

For a given aperture the greater the focal-length of the guiding telescope relative to the photographic telescope, the easier the guiding, since a small motion of the guide star in the field of the guiding telescope will correspond to a smaller motion of the image on the photographic plate, in the ratio of the focal-lengths of the two telescopes. In some cases the ratio of the apertures of the two telescopes is even more important for successful guiding. It is not advisable to use as a guiding telescope one whose aperture is less than one half of that used in the photographic telescope. Ordinarily the objects that are to be photographed are several magnitudes* fainter than the faintest star visible through a telescope of equal aperture, and unless the region to be photographed is rich in bright stars it will be difficult to find a good guide star conveniently near. The difficulty is less if the guiding telescope is relatively large in aperture.

Flexure is the greatest obstacle to good guiding, especially if the telescope is of considerable length. The elimination of flexure in the tubes of the photographic and the guiding telescopes, and in the coupling between the two, is a special problem in the design of a telescope. One way of eliminating the effects of such flexure is through the use of the moving plate-holder, Figure 131. In this arrangement a guiding microscope is attached to the plate-holder receiver, and it, with the plate-holder and microscope, can be moved as a unit along two axes perpendicular

* See Chapter 6 for a discussion of magnitudes.

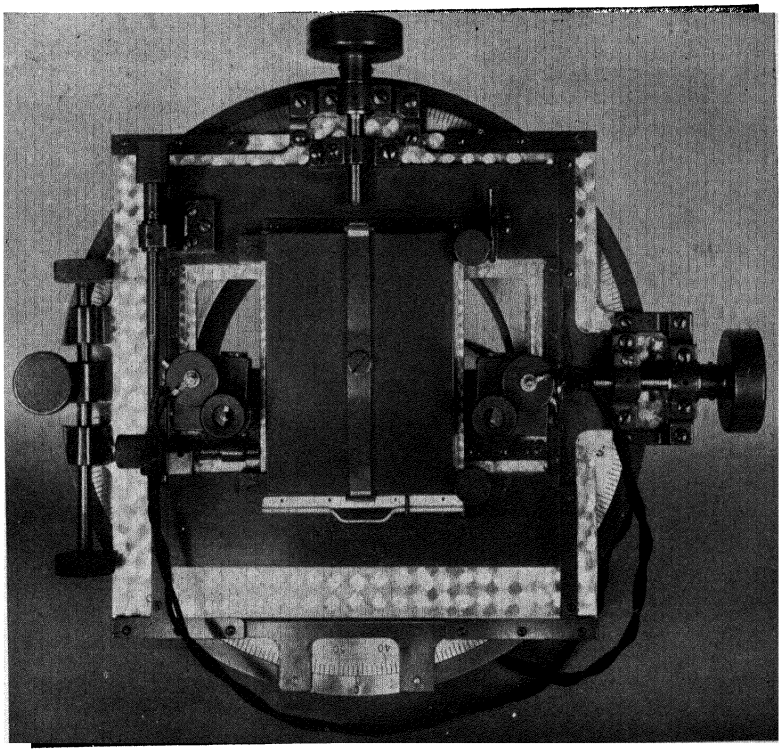


Fig. 131.—Double-slide plate-holder.
(*J. W. Fecker.*)

to each other. The motion is accomplished by means of two fine screws which move the assembly in the focal plane of the telescope. The observer now sets the microscope on a star generally at the edge of the field and then moves the plate-holder as he guides with the microscope. Because of its two motions this arrangement is known as the *double-slide* plate-holder.

Curved Plates—Dew Cap

We have already seen (Chapter 4) that the image quality varies as we go from the center to the edge of the field because

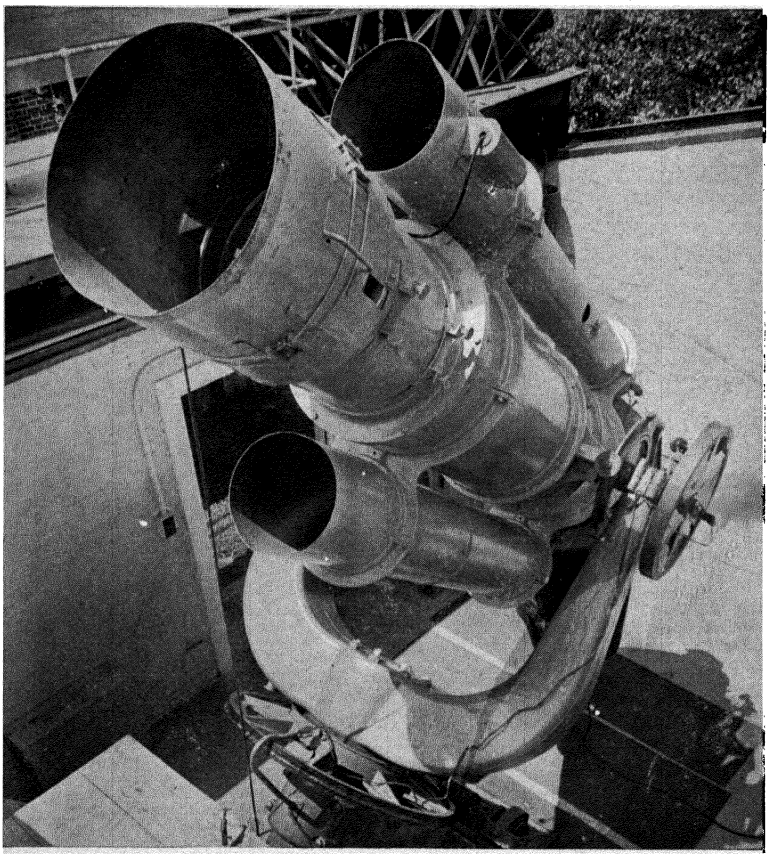


Fig. 132.—Dew caps on the 16-inch telescope at Oak Ridge.
(*Photo by Cox.*)

of the various aberrations, among which is the curvature of the field. In order to obtain a larger field the refractor may have a curved plate such as that of the 16-inch Metcalf telescope at the Oak Ridge station of the Harvard Observatory (Figure 132). The photographic plate is loaded into the curved-back plate-holder and the space between the glass plate and the curved

back of the plate-holder is evacuated. The atmospheric pressure then holds the plate against the curved back.

The Schmidt presents the opposite problem. Here the focal surface is a sphere convex toward the mirror, with a radius of curvature equal to the focal-length of the telescope. The curvature is obtained by pressing the plate into a plate-holder with a properly curved back. The disadvantage of greater curvature is partially offset by the fact that the plate is curved with the emulsion over the convex side. This fact adds to the strength of the plate by giving the glass a protective skin. If film, which often buckles in the plate-holder, is used, the plate-holder back is perforated so that suction can be applied to hold the film in contact with the curved surface. Still another way of holding the film down is to stretch it over the curved back with a retaining ring around the edge.

A dew cap is another convenient and in a damp climate a very necessary accessory to the telescope. The dew cap serves the purpose of a lens shield, and if supplied with heaters (Figure 132), it prevents condensation over the front surface of the lens. An ordinary 15-watt cartridge heater, or an electric lamp enclosed in a box and attached to the outside of the dew cap, is sufficient to keep the temperature a fraction of a degree above that of the dew point.

The Housing

One of the many problems met in the building of a telescope is the construction of an adequate housing. For temporary or simple protection from the elements a canvas thrown over the instrument is sufficient. The instrument may even be dismantled and put away, as in the case of the miniature cameras (Figure 133), which are taken off the mounting and carried to the dark room even for loading.

As the instrument increases in size, the need for a solid cover becomes more acute. A very simple shelter for moderate-sized telescopes is the sliding-roof arrangement. This type of housing

has a disadvantage in that it does not offer good wind protection during the operation of the telescope. The surface area which a large telescope presents to the wind is considerable and calls for careful design of wind screens or shutters, especially when the tube is of the closed rather than of the skeleton type. Even light winds are detrimental to good photographic results, and, in the case of instruments situated on mountain tops, strong winds

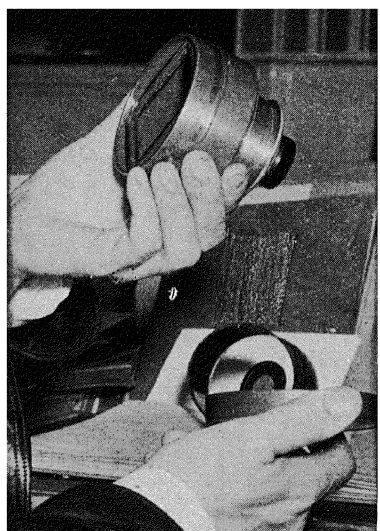


Fig. 133.—Miniature telescope, perhaps the smallest in use.
Lens ¾-inch diameter *f*/5 with plate 2.5 × 2 inches. (*Photo by Paul Southwick.*)

may present a serious problem. For large telescopes a turret or dome is indispensable, and supplementary canvas curtains or sectional shutters (Figure 134) are very useful. The turret or the dome must be capable of rotation so that the slit opening, through which the telescope is pointed toward the sky, can be oriented in any direction. Once again the problems of strength and weight are considerable and increase manyfold with each increase in the size of the telescope. The hemispherical steel dome

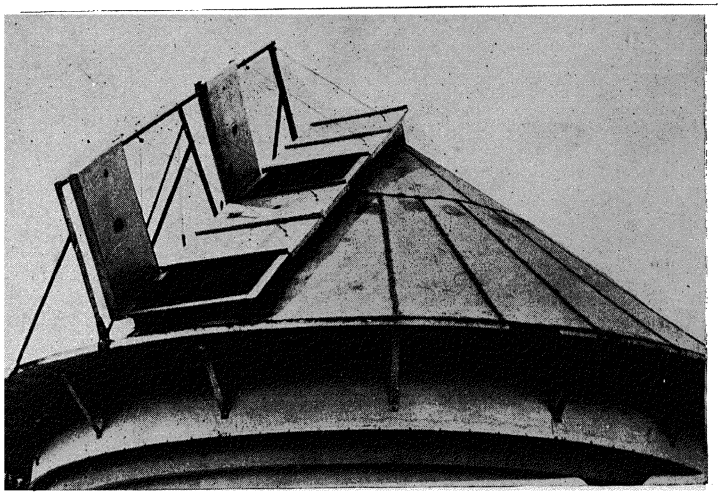


Fig. 134.—The specially designed dome for the Fremont Pass Station of Harvard College Observatory, Climax, Colorado.

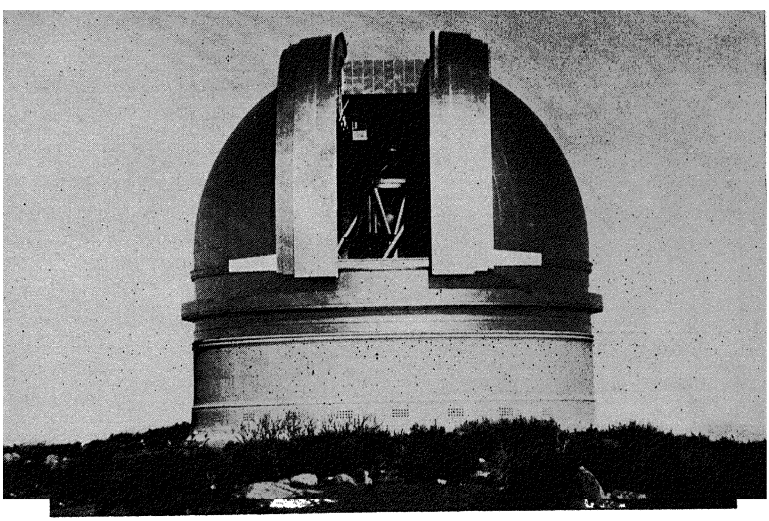


Fig. 135.—The dome of the 200-inch telescope, Mt. Palomar, California.

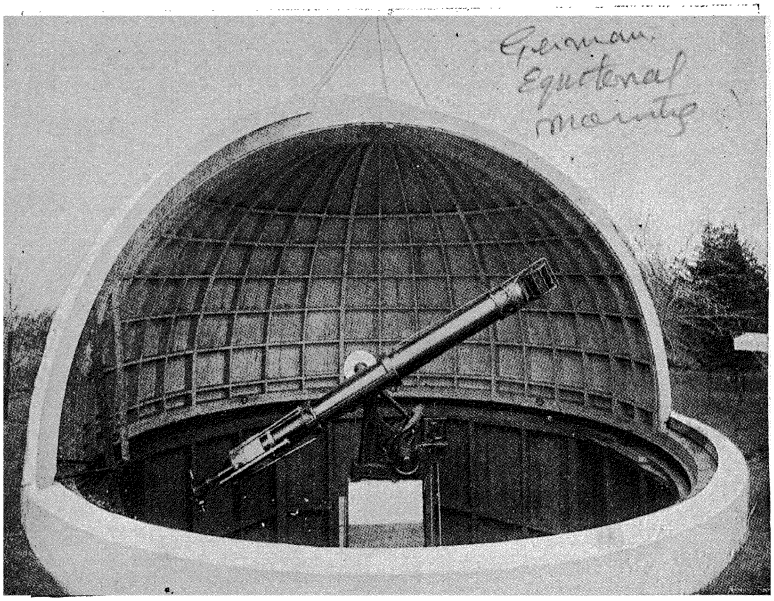


Fig. 136.—For special purposes it is sometimes necessary to construct domes of unusual character.

The above picture shows the split dome housing the 6-inch Clark refractor in the Students' Observatory of the University of Wisconsin. The lens formerly was the personal property of S. W. Burnham, who used it for many years in double star observations.

One half of the dome shown above is larger than the other half and can rotate about it. Thus, half of the sky is left open for observation.

of the 200-inch telescope, for example, is 137 feet in diameter, weighs 1000 tons and is mounted so that it can be easily and smoothly rotated (Figure 135). The construction of such a large hemisphere is particularly difficult when we consider that a movable dome cannot be anchored to the foundation, and that it is actually split from beyond the zenith to the horizon to provide the wide opening through which the telescope must be pointed during observations. This opening must have no cross bracing of any sort.

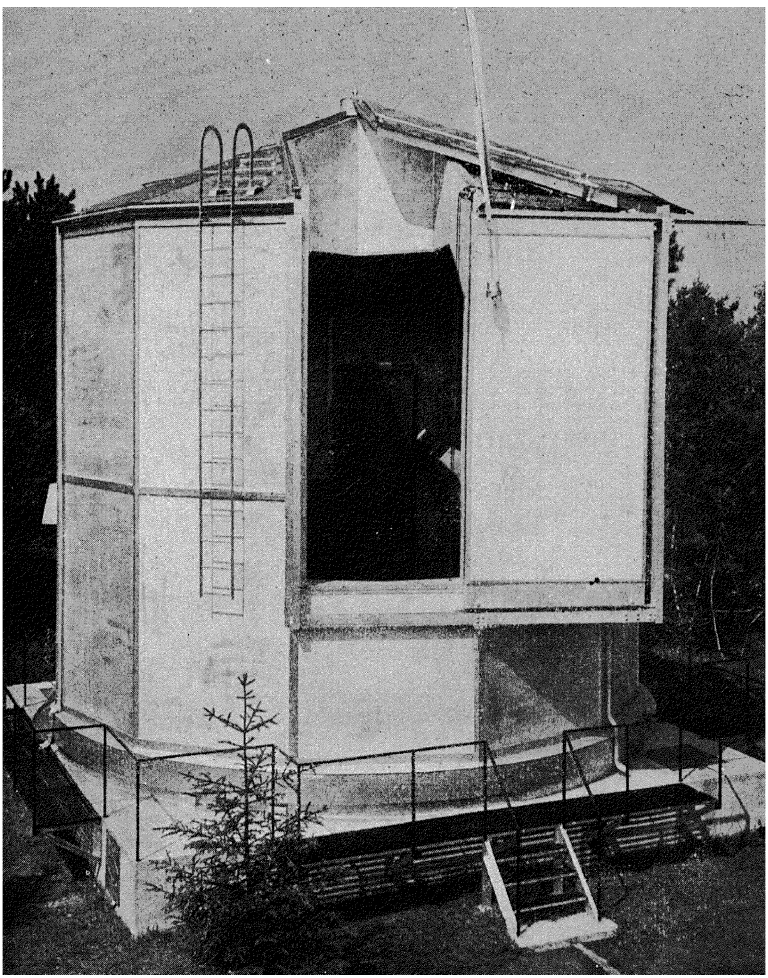


Fig. 137.—The Jewett telescope building at Oak Ridge.
(Photo by Donaldson.)

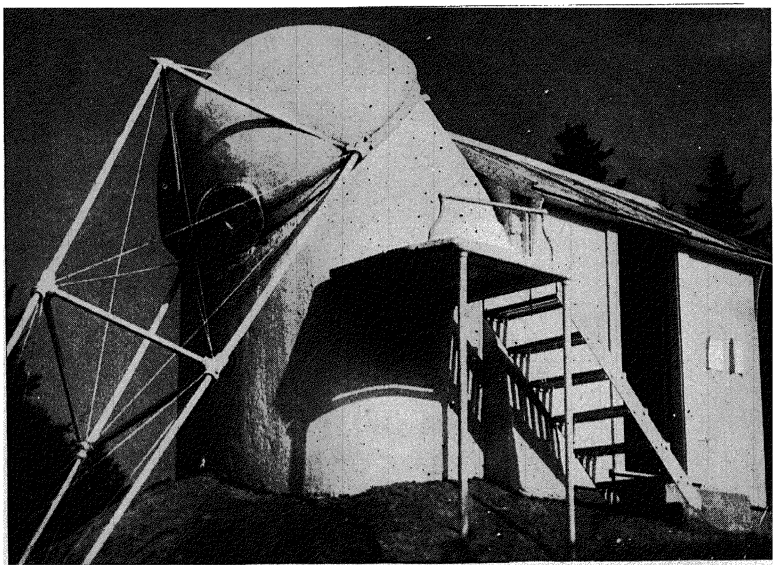


Fig. 138.—The Stellafane turret telescope.

The choice between a spherical structure and a box or turret structure is based not only on architectural or financial considerations, but on the wind intensity as well. In a hemispherical dome one component of the wind pressure is directed along the radius of the sphere so that this structure is more stable than other types. Whenever the wind problem is not serious, the turret type is equally useful and more economical.

There are many variations in housing design that are especially adapted to particular problems. The Jewett Memorial telescope building at the Oak Ridge Station of Harvard Observatory (Figure 137) is unique in that the entire structure revolves from the floor level. A typical turret-telescope combination is found in the Stellafane structure, where the dome is the polar axis and carries with it the mirror which is a part of the telescope proper (Figure 138). The polar telescope (Figure 139) is especially convenient for observers who desire to remain stationary or to work in a heated room. Figure 140 shows the telescope tube of the

Loomis instrument at the Yale Observatory, mounted parallel to the earth's axis and pointed down toward a mirror which reflects the sky. The greatest disadvantage of this arrangement is that the reflecting mirror and the objective, if a refractor, are of necessity close to the ground and in a position detrimental to good seeing, but the convenience of a stationary observing

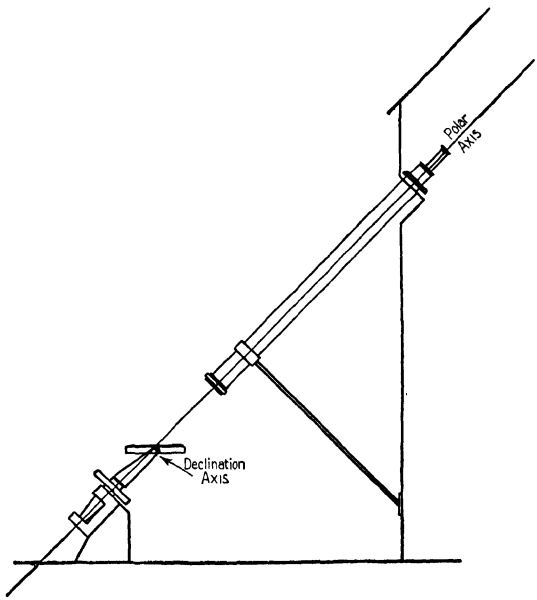


Fig. 139.—The polar telescope.

end may be desirable when delicate or bulky auxiliary apparatus is in use.

The coudé arrangement of the reflecting telescope (Chapter 5) embodies the convenience of a stationary observing point, as found in the polar telescope. It is especially well adapted to a high-dispersion spectrograph. Such apparatus is bulky and requires constant temperature conditions as well as a stationary observing point.



Fig. 140.- The Loomis Tower telescope of the Yale University Observatory.

The Dark Room

Although in routine observational programs the processing of the photographic plates can be done miles away, a dark room close at hand is advisable for the loading of plate-holders, the testing and standardizing of plates and other operations. If the dark room is also to be used for developing the negatives, careful consideration to its construction and equipment should be given, even though the instrument it serves may be very small. Shape and size of a dark room are often a matter of circumstance, but the location and equipment must be chosen with regard for the needs of the observer, and the type of work that is to be done. If there are long exposures, with plates changed only each hour or so, a short walk to the dark room will be a welcome change for the observer, especially if he has been guiding in a cramped position (Figure 141). In the case of short exposures where plates are changed perhaps every five minutes, a handy dark room saves both steps and time.

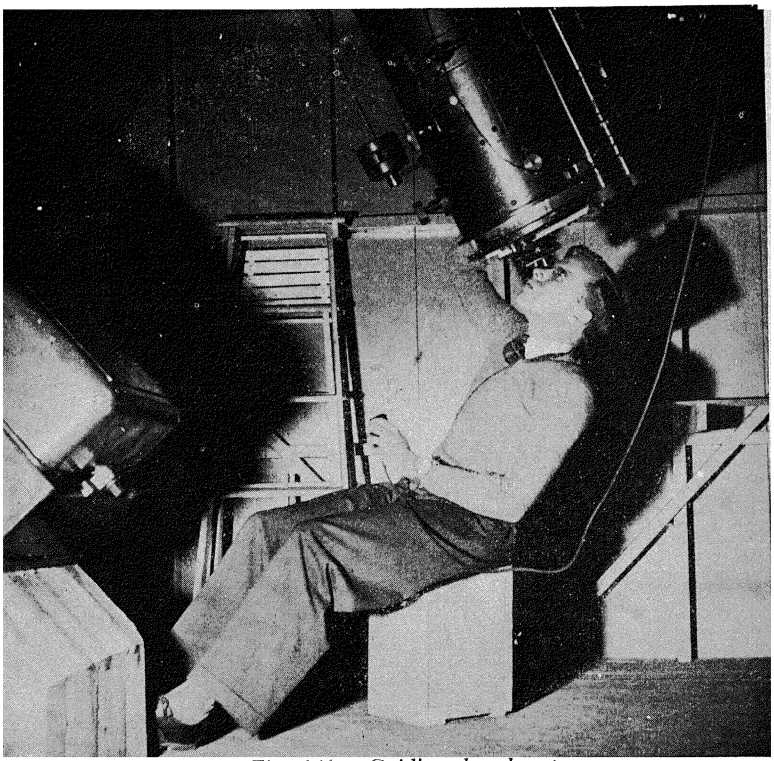


Fig. 141.—Guiding the telescope.
(*Photo by Dick Kelsey.*)

A dark room equipped with running water is convenient, although it requires a certain amount of heat protection in cold climates. Use of a heated room for unloading the cold plates just exposed in the telescope increases the danger of dewing up the plates and decreases their value for photometric purposes. In the present stage of photography, where infra-red plates are much in use, the dark room should contain the necessary drying cabinet for use in hypersensitization,* for although

* See Chapter 3.

it is possible to dry a plate by holding it in front of an ordinary fan, the danger from dust is considerable. Air conditioned, dust-free dark rooms as yet have not found much application in astronomical photographic technique. They are nevertheless advisable, for nothing that will help standardize the photographic process and eliminate uncertainties should be overlooked in astronomical work where a mere speck might suggest a galaxy, or a few added silver grains might imply the cataclysmic convulsions of a star, or the trail of a comet.

The Future

It is a far cry from the tiny tube of Galileo to the giant reflectors of to-day, but it is well to remember that the modern

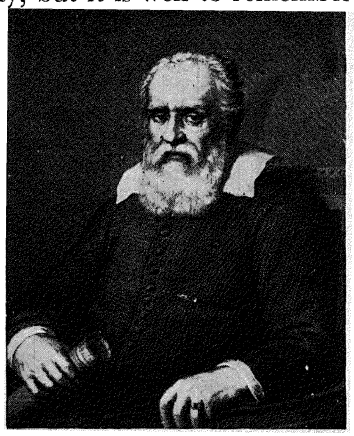


Fig. 142.—Galileo with his telescope.

telescope, with its finger touch control and smooth running mechanism, could not have existed a hundred years ago. Such telescopes became possible with the engineering advances and the electromotive power developed in the past century, as well as with improvement in the manufacture of glass and the art of grinding and polishing of optical surfaces.

Since the time of Galileo the prevailing style of telescope has shifted back and forth from lens to mirror, then back to

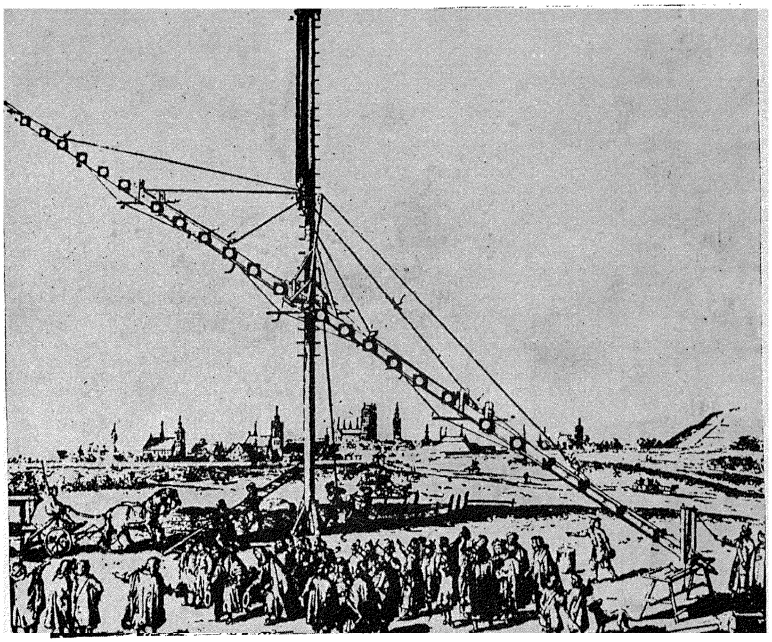


Fig. 143.—A seventeenth century telescope.

lens and finally again to mirror. This is not an accident. Each time the pendulum has swung, we have marked new progress along particular technical lines. Each time the telescope increased in size or efficiency, there was placed a new challenge before the technician and the engineer. And in every instance the observer was found capable of extracting the very last ounce of usefulness from his instrument.

Even though the Galilean telescope was but a toy (Figure 142), it became in the hands of its builder and skilled observer a powerful tool, and gave an impetus for the better understanding of the structure of the solar system. For it was Galileo's little telescope that revealed the phases of Venus, the satellites of Jupiter, and the thousands of faint stars that could not be seen with the naked eye. If a telescope only an inch in diameter

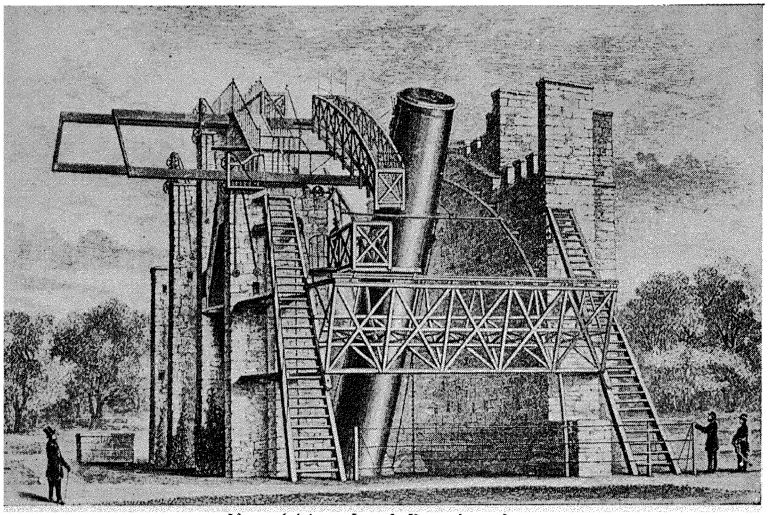


Fig. 144.—Lord Rosse's telescope.

could reveal such remarkable phenomena, what could be revealed with a more powerful instrument? This question was the impetus that sent out the call for larger and larger telescopes. But with increased size the shortcomings of the optical parts became more pronounced, especially color and spherical aberration. In order to minimize these the length of the tube was increased until we find in the latter part of the seventeenth century telescopes of 50 and 100-foot focal-length (Figure 143). Even with such unwieldy instruments the observers continued to add to our knowledge of celestial objects, and established the telescope as a tool of research. In the meantime the pendulum had already begun to swing toward the mirror telescope. The development of speculum metal made it possible to figure mirrors* of large aperture (Figure 144) on a surface that was fairly easy to polish and that remained relatively bright for a

*John Hadley in 1722 not only presented the Royal Society a six-inch parabolic mirror, but disclosed the method used by him in the polishing, parabolizing, and testing for true figure.

considerable time. Such mirrors had the further advantage that they were free from color and spherical aberration.

After that there followed the development of new techniques in the manufacture of glass that yielded large discs* of optical glass, both of crown and flint, that permitted the making of large color-corrected objectives. For a while it seemed as if this development gave lenses preference over mirrors. However with the development of chemical deposition of silver on glass,† which meant that the reflecting surface could be renewed without the necessity of refiguring, the ever growing demand for larger telescopes for the second time caused the pendulum to swing toward the mirror telescope.

In the meantime the technique of optical glass manufacture had been much improved and the world witnessed in the completion of the Lick 36-inch and the Yerkes 40-inch refractors the ultimate in lens size, at least as far as rigidity of glass was concerned. The mirror on the other hand offered further possibilities. It could readily be supported from the back so that the size of the telescope once more depended only upon the diameter of glass disc that could be properly annealed. When the manufacture of glass in the United States reached a high degree of development, the electrical annealing oven made it possible to cast the largest disc, the 200-inch for the Palomar Observatory.

It is perhaps not too bold to ask at this point: What does the future hold? Surely one cannot foretell the coming scientific or industrial developments, but we can point to the new trends in optical design, in photographic plate sensitivity and the like. Perhaps the most significant of recent developments is the Schmidt type lens-mirror combination (Chapter 4) which has the advantages of both the mirror and the lens, while it eliminates some of the disadvantages of both. As we have already seen, the correcting plate can be made of thin material because its change

* The Swiss artisan Pierre Louis Guinand had by 1799 produced "flawless discs of flint as much as 6 inches in diameter."

† Dr. Karl August Steinheil 1856, and Jean Bernard Léon Foucault 1857.

in figure due to sagging is a second order effect. This thinness eliminates the undesirable absorption by the relatively thick lens of the refractor, and presents no manufacturing obstacle, so far as size is concerned, since the lens problem now reduces to casting a large size plate glass. On the other hand we already

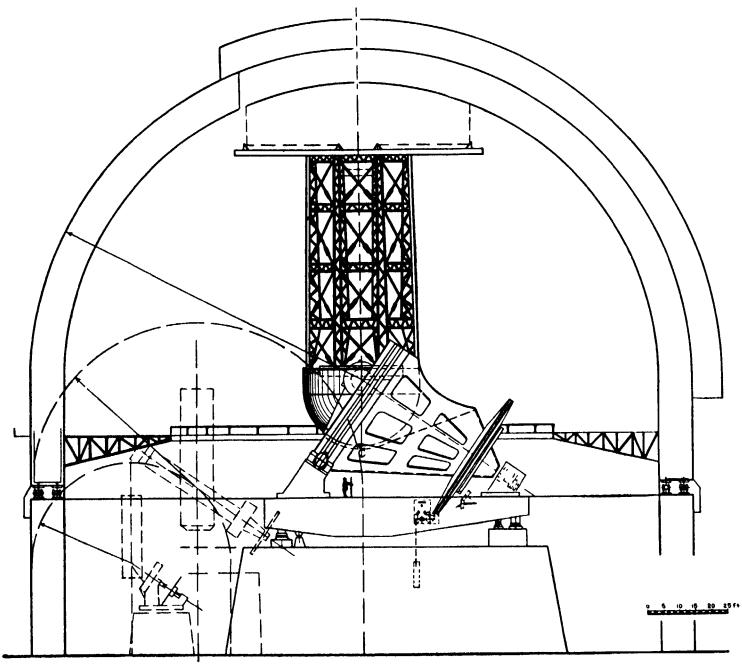


Fig. 145a.—Sketch of a twenty-five foot reflecting telescope, side elevation.
(F. G. Pease, Mount Wilson Observatory.)

have the 200-inch mirror disc. Is it possible that the year 2000 will see a 200-inch Schmidt? Or are we going to build still larger reflectors with mirrors of 400, 800, or 1000-inches diameter?

We should not forget the possibility of an electron telescope. One way of constructing such an instrument has already been suggested, but we cannot now foresee what possibilities may exist for the future when we consider how recent is the development

of photoelectric and fluorescent surfaces, the discovery of the electron multiplier and vacuum tube amplifiers. The suggestions are well beyond the dream stage, and even if they were not, one should not be afraid to dream. Back in 1921 F. G. Pease thought of a 300-inch telescope; he even designed one. Today's 200-inch

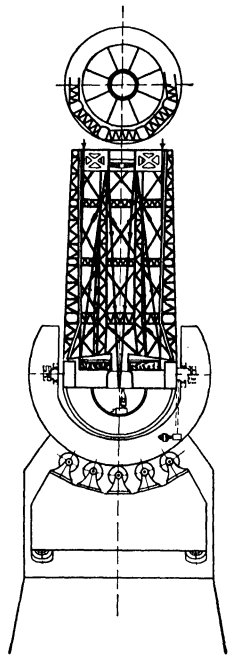


Fig. 145b.—View looking down the Polar Axis of the twenty-five foot reflecting telescope.

incorporates many features of the dream of twenty years ago. Compare Figures 145 and 115, 116 et al.

We must remember too that an increase in the efficiency of the telescope does not necessarily imply an increase in size. With each doubling of size we increase fourfold the light gathering power, being able thus to photograph stars that are more than a magnitude fainter. Suppose we start from the other

end. Can we increase the efficiency of the photographic plate? In the past twenty-five years the increase in emulsion speed has been due mainly to improving the sensitivity of the emulsion to yellow and red light. Actually the increase in sensitivity of the emulsion to blue light has not changed in proportion. How far would the money and effort expended in the past twenty-five years in working for larger telescopes have gone toward the increase of telescopic power through an increase in the sensitivity of the photographic emulsion?

Have we explored sufficiently the possibilities of other methods for recording the amount of light which we receive at the focal plane of the telescope? We know that light changes the rate at which certain processes are going on, as in the case of the growth or decay of micro-organisms. Is it possible that astronomers will be growing cultures in their dark rooms and counting bacteria in order to obtain a better picture of the universe? Astronomy has borrowed from many other sciences in the past and is today ready to try out new developments. After all, the photographic process is but one means for determining the intensity of star light and the results will be just as interesting whether we count silver grains or micro-organisms, provided that we can count accurately enough.

APPENDIX

I. Invisible Glass.
II. Radial Velocities.
III. The Largest Reflectors (30-inch diameter and over).
IV. The Largest Refractors (15-inch diameter and over).
V. Schmidt Cameras (to January 1, 1941).
VI. Schwarzschild Cameras. Wright Cameras.
VII. Diffraction Images.

APPENDIX I

INVISIBLE GLASS

OF PARTICULAR IMPORTANCE TO FURTHER INCREASES IN instrumental efficiency are recent successes in removing reflection losses at glass-air surfaces. The story of "invisible glass," by no means complete even now, illustrates how scientists sometimes overlook rather obvious possibilities. Since Young's work about 1800, experiments on interference fringes produced by interferometers, bi-prisms, and small apertures have been commonplace. Everyone, however, seems to have overlooked the possibility of applying the results of these experiments towards overcoming the rather serious reflection losses at glass-air surfaces.

Since the first use of glass, it has been noted that a beam of light incident on a polished glass-air surface divides into a refracted and a reflected ray. At an ordinary glass-air or air-glass surface about 4% is reflected and about 96% continues on its way. (See Chapter 1.) If an optical system has ten glass-air surfaces, half crown and half flint, only about 50% of the incident light is transmitted usefully. Soiled surfaces and imperfect polish add to the light loss by reflections. Light losses plus flare spots and ghost images have in the past been considered serious enough to call for not more than ten glass-air surfaces in cameras and other systems.

In 1892 Dennis Taylor discovered that a tarnished telescope lens transmits noticeably more light than a new lens of equal

aperture. During the First World War Kollmorgen tried to tarnish surfaces artificially in order to reduce reflection losses.

In 1934 a new technique of applying such films was employed by Strong, and further improved in 1938 by Cartwright and Turner at the Massachusetts Institute of Technology, and at about the same time, but in a different way, by Katherine Blodgett of the General Electric Laboratories.

The general procedure consists of putting a thin interference film on the glass surface by one of several methods. If the relation $n^2_{\text{film}} = n_{\text{glass}}$ is satisfied, and if the film thickness is optically ¼ wave-length, total destructive interference takes place in the reflected beam. The 4% or 5% of energy thus destroyed in the reflected beam must be added to the transmitted beam by constructive interference. Thus, all incident light is refracted. At each glass-air surface, whether front or back, the same interference process takes place. As a result, apart from absorption losses, the optical system regains its complete efficiency.

Cartwright has found that films of magnesium chloride or magnesium fluoride are very durable, but that films of lithium or calcium fluoride are more efficient. By proper deposition, complete efficiency can be achieved at a particular wave-length; however, at no wave-length does the intensity of the reflected wave exceed the amount reflected from the untreated glass, as long as only the first order of interference is involved. Such films are optically ¼ wave-length thick; in sodium light they are therefore about 0.000003 inches thick. Thicker films introduce higher orders of interference, and indeed, by using thicker films one can actually increase the intensity of the reflected ray until the glass looks like a good mirror in some given color. The efficiency of a lithium fluoride film over the entire visible wave-length region reduces reflection from its original value of perhaps 5% to as low as 0.1%. The residual reflection is very weak and in white light has a purplish hue, if completely removed in the yellow. Lithium fluoride is unfortunately fragile and applicable only to well-protected surfaces. It is also water-

soluble enough to require protection from dewing. Calcium fluoride is superior in this respect. Problems of fragility of the films have been solved in several ways for military purposes. Astronomers will benefit from these methods after the war.

From the rule $n^2_{\text{film}} = n_g$, it follows that the index of refraction of the film must be about 1.23 for crown glass. Unfortunately, no solids have such low indices of refraction. Lithium fluoride, one of the lowest, has an index of 1.39. The difficulty of obtaining such low indices probably delayed the useful application of the invisible-glass theory.

By evaporating a film in a vacuum of certain optimum pressure, one can obtain a film of structure resembling Swiss cheese. Tiny holes are interspaced throughout the film. The average index of the medium is thereby lowered and can actually be made 1.23. By Huygens' principle the sub-microscopic holes merely behave as sources of secondary wavelets, and consequently do not scatter light. Indeed, the film is so thin that optical performance of even astronomical telescopes is unaffected. After the proper degree of vacuum has been obtained, it is necessary during deposition only to watch the reflected image of a white light from the glass surface. When the reflection becomes weak and turns to a purplish tinge, the coating is as nearly perfect as need be for yellow light.

Miss Blodgett has made interference films by the deposition of mono-molecular layers of fatty acids, like cadmium arachidate solution. About 22 dippings or 44 mono-molecular layers produce the proper optical thickness of one quarter-wave of light. In order to reduce the index to 1.23 the worker places the surfaces after coating in a bath of alcohol or acetone that dissolves the stearic acid component in the film, and leaves a skeleton structure whose average index is 1.23. The holes are molecular in size and presumably are vacua. Such soap-like films are very fragile and are suitable only on sealed surfaces.

Glass surfaces can be tarnished by appropriate chemicals. Nitric acid, for example, will tarnish certain types of glass,

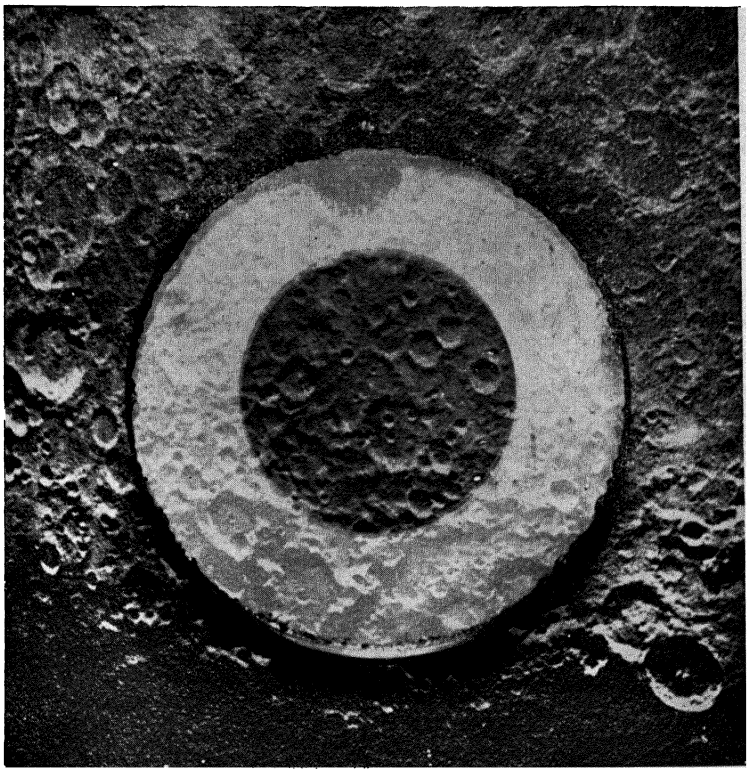


Fig. 146.—On the above picture of a portion of the moon's surface there has been placed a glass disc, the center of which has been coated on either side for non-reflection.

It is evident that in the glare of strong illumination the lunar craters show as well through the treated central portion of the glass disc as do the lunar craters outside the disc altogether. The craters are barely visible through the untreated ring.

including barium crown and lead glass. A tarnished surface may be more rugged than the evaporated film, but on the whole is less efficient.

Recent work employs fumes from hydrofluoric acid, which reduce the surface of the glass to a thin layer of nearly pure

quartz. Such films are quite durable. The present lack of control over the method will prevent scientists from risking valuable optical parts to fumes that can reduce precision surfaces to frosty layers. Other methods still better and more practical are in war use daily, but it is not permitted to discuss the more advanced techniques at this time.

Wherever glass-air surfaces are needed in astronomy or astrophysics, the new treatment will prove effective. The photograph in Figure 146 reproduces a striking contact print made through a series of four glass-air surfaces treated and untreated. By transmission the untreated ring appears dark, and the treated circle invisible except for dust and a purplish reflection. Astronomical spectrographs will benefit greatly from such gains in efficiency.

APPENDIX II

RADIAL VELOCITIES

THE DETERMINATION OF THE WAVE-LENGTHS OF STELLAR lines serves not only to identify the chemical element responsible for the production of a given line in the stellar atmosphere, but also serves to provide information on the motion of the star through space. When a source of light is in motion relative to the observer along the line of sight, the wave-lengths of the various spectral lines are shifted by that motion. This phenomenon is called the *Doppler effect.* If a source has a velocity v in the line of sight (called the *radial velocity* when reduced to the sun), then the spectral shift $d\lambda$ of any given absorption or emission line of wave-length λ is given by

$$d\lambda = \left(\frac{v}{c}\right)\lambda,$$

where c = 186,000 miles/second, the velocity of light in vacuo. The shift in a spectral line along the spectrum is proportional to the wave-length of the line. Therefore, absorption lines in the red are shifted more in wave-length than lines in the blue. The shifts are always exceedingly small, except in the spectra of galaxies at great distances. A velocity smaller than that of a cannon shell is scarcely perceptible, even with the most precise kind of spectrographic aid. The quantity $d\lambda$ can be measured from spectrograms taken with slit instruments. The important quantity v can then be determined from the above formula. The higher the dispersion and resolution of the spectrum, the more accurately the radial velocities can be measured. The motion of a star must be computed by comparison of the observed stellar wave-lengths with laboratory wave-lengths of the same

line or lines. Because of the motion of the earth around the sun and the rotation of the earth, the observed velocities must be corrected to the sun as a standard of reference.

Objective Prism Radial Velocities

From the time of the earliest use of the objective prism astronomers have endeavored to find a method of obtaining radial velocities on objective prism plates. The whole problem is one of obtaining suitable standard wave-lengths impressed beside or on each stellar spectrum.

Figure 59 illustrates the large number of stellar spectra available on a single objective prism plate. The most successful method to date in obtaining radial velocities from these spectra has been to impress on the spectrum of each star some standard absorption line of known wave-length, by means of a filter over the photographic plate. The only suitable filter known is a solution of neodymium chloride. Part of the neodymium absorption spectrum lies in the yellow and red, and consists of broad bands of uncertain wave-length. In the blue there is a single quite sharp band suitable for a reference wave-length. This neodymium band is nearly as sharp as the stellar lines to be measured. It would be desirable to have at least two standard wave-lengths, however, for the sake of increased measuring accuracy and for reduction of radial velocities of cooler stars whose absorption lines blend with the single neodymium line and prevent measurement. The use of neodymium chloride as a practical standard has been perfected at Harvard by Bok and McCuskey, who have obtained the velocities of several hundreds of stars.

E. C. Pickering attempted to obtain radial velocities from objective prism plates in the following manner. A first exposure of a star field was made in the normal way. Then the prism was rotated about the optical axis through 180°, and the telescope reset for the same star field. The final plate contained two spectra for each star, side by side, but running in opposite

directions. Thus, the blue of each spectrum could be made to coincide. The shifts in the absorption lines caused by the Doppler effect are in opposite directions. This method proved unsuccessful, since it demands impossible rigidity of a large telescope tube. This fact is easy to understand when we recall that one micron on the plate may equal 10 kms/sec. Radial velocities in error as much as this are near the limit of utility.

Beyond doubt the twin spectra method can be successful *only* if the spectra are simultaneously exposed. R. W. Wood has proposed what is called the bi-prism-grating method. He covers the aperture of the camera with two prisms with parallel bases of approximately the same prism angle but opposite orientation. Each prism covers half the aperture. Transmission gratings on each prism provide most of the dispersion. The gratings alone provide first order spectra that, except for the presence of the prisms, would be far apart on the plate. The deviation of the prism is employed to bring the two spectra side by side. The dispersion of the prisms adds slightly to the grating dispersion but the amount is small relative to the linear dispersion yielded by the gratings. At the moment efforts are being made to construct such bi-prism-gratings of sufficient size to photograph stellar spectra not already within reach of slit spectrographs.

The same method can be employed with equal effectiveness by the use of prisms alone. Two zero-deviation prisms are employed, one for each half of the aperture. The dispersions are oriented 180 degrees apart. The zero-deviation ensures that the resultant spectra will lie side by side. Spectra so obtained ought to provide radial velocities nearly as accurate as *slit* velocities of the same dispersion.

A similar arrangement involving two zero-deviation prisms of opposite dispersion can be employed in a slitless spectrograph. An ideal radial velocity spectrograph for faint objects might be built by combining a McCarthy-type slitless spectrograph with split prism and masks in the focal plane to eliminate undesirable sky fog.

APPENDIX III

THE LARGEST REFLECTORS

(30-INCH DIAMETER AND OVER)

Observatory	*f/*	*Diam. inches*	*Focal-length inches*	*Date*	*Maker*	
					Mirror	*Mounting*
Palomar, Mt. Palomar, Calif.	3.3	200*	660	Unfin.	Brown	Westinghouse
Mt. Wilson, Pasadena, Calif.	5.1	100	508	1917	Ritchey	Ritchey
Michigan, Ann Arbor	...	96†				
McDonald, Mt. Locke, Texas	4.0	82	324	1939	Lundin	Warner & Swasey
Radcliffe, Pretoria, South Africa	...	76*	...	Unfin.	Grubb-Parsons, both.	
Dunlap, Richmond Hill, Ontario	4.9	74	358	1933	Grubb-Parsons, both.	
Lord Rosse, Parsonstown, Ireland	8.7	72	624	1845	Now unmounted, museum display	
Dominion Astrophysical, Victoria, B. C.	5.0	72	358	1919	Brashear	Warner & Swasey
Perkins, Delaware, Ohio	4.3	69	300	1932	Fecker	Warner & Swasey
Harvard, Oak Ridge, Mass.	5.1	61	310	1937	Fecker	Fecker
Harvard, Oak Ridge, Mass.	5.2	61	320	1900	Common mirror now unmounted	
Bloemfontein, South Africa	5.1	60	315	1933	Common-Fecker (refigured)	
Mt. Wilson, Pasadena, Calif.	5.0	60	300	1908	Ritchey	Ritchey
Cordoba, Bosque Alegre, Argentina	5.0	60	300	1940	Fecker	Warner & Swasey
Berlin-Babelsberg, Germany	6.7	49	330	1926	Zeiss	

Melbourne, Australia	7.6	48	365	1870	Grubb	Grubb
Herschel, Slough, England	8.2	48	394	1789	Herschel	Herschel
Lassell, Malta	...	47	...	1860	Lassell, destroyed	No longer exists
Paris Obs., Paris, France; remounted at Saint Michel, Haute-Provence 1942	6.5	47	...	1875 1932	Martin Couder (refigured)	
Flagstaff, Arizona	5.0	44	221	....	Clark	
Merate, Italy	5.0	40	201	1926	Zeiss	Zeiss
Crimea, Simeis (Poulkovo)	5.0	40	201	1928	Grubb-Parsons	Grubb-Parsons
Stockholm, Saltsjöbaden	5.0	40	201	1931	Grubb-Parsons	Grubb-Parsons
Bergedorf, Hamburg, Germany	3.0	39	118	1913	Zeiss	Zeiss
Geneva, Switzerland	3.0	39	118	1922	Schaer	
Meudon, France	3.0	39	118	....	Gauthier	
Royal Obs., Uccle, Belgium	3.0	39	118	....	Zeiss, both.	
Michigan, Ann Arbor	6.1	37	228	1911	Brashear	
Cath. Obs. Santiago, Chile	5.7	37	208	1904	Brashear	
Goethe Link, Indiana	5.0	36	180	1939	Indianapolis A.T.M.	
Cambridge, Solar Physics, England	4.2	36	150	....	Common	
Cambridge, England	3.7	36	133	1890	Calver	
Edinburgh, Scotland	5.0	36	181	1929		
Greenwich, England	5.0	36	181	1929		
Lick, Mt. Hamilton, Calif.	5.8	36	209	1879	Common, Grubb-Parsons	
Steward Obs., Tucson, Arizona	5.0	36	181	....	Brashear	Warner & Swasey
Lord Rosse, Parsonstown, Ireland	...	36			Rosse, now unmounted	
Toulouse, France	6.0	33	197	1887	Gauthier	
Forcalquier, France	6.0	32	228	1932	Couder	
La Plata, Argentina	6.3	32	197	....	Gauthier	Zeiss
Marseille, France	5.6	32	180	1873	Foucault	
Jenkintown	4.0	32	...	1930	Fecker	
Cordoba, Argentina	...	30				
Greenwich, England	4.6	30	138	1897	Grubb-Parsons	
Helwan, Egypt	4.6	30	138	....	Reynolds	
Allegheny, Pittsburgh, Pa	5.0	30	150	1906	Brashear	
Norman Lockyer, Sidmouth, England	...	30				
University of Illinois	2.5	30	75	....	Brashear	

* *Mirror ready for parabolizing. Mounting essentially complete.*
† *Blank only.*

APPENDIX IV

THE LARGEST REFRACTORS

(15-INCH DIAMETER AND OVER)

Thanks are due to Dr. Roy K. Marshall for nearly all of the following informative tabulation

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
40.0 in.	63.5 ft.	1897	Alvan Clark, Warner & Swasey	Yerkes Observatory, Williams Bay, Wisconsin. The discs were originally imported for a telescope for the University of Southern California, to be set up on Mount Wilson. The objective was figured by the elder Lundin, and younger Clark.
36.0	57.8	1888	Alvan Clark, Warner & Swasey	Lick Observatory, Mount Hamilton, California. There is a 33-inch photographic corrector.
32.7	53.0	1889	Henry Brothers, Gauthier	Astrophysical Section, Observatory of Paris, Meudon. There is a 24.4-inch refractor on the same mounting.
31.5	39.4	1899 1916	Steinheil Steinheil, refigured Repsold	Astrophysical Observatory, Potsdam. This is a photographic lens; there is a 19.7-inch visual on the same mounting.
30.0	46.3	1914	Brashear, Warner & Swasey	Allegheny Observatory, Pittsburgh, gift of Wm. Thaw and Wm. Thaw, Jr. This is a photographic lens; there is a 12-inch visual corrector to insert at about the middle of the tube.
30.0	52.6	1886	Henry Brothers Gauthier	Bischoffsheim Observatory of the University of Paris, at Nice. It was built for R. Bischoffsheim, a Paris banker, and by him given to the University in 1899.

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
30.0 in.	46.3 ft.	1885	Alvan Clark Repsold	Central Astronomical Observatory, of the Academy of Science, Poulkova
28.0	27.9	1893	Grubb, Ransome & Simms	Royal Observatory, Greenwich. This visual objective can be made photographic by reversing the crown component and altering the separation.
27.0	....	1927	McDowell, Local shops	Lamont-Hussey Observatory of the University of Michigan, Bloemfontein, O.F.S., South Africa
26.8	68.9		Steinheil	Treptow Observatory, Berlin. This telescope is used for the public only.
26.8	34.4	1880	Howard Grubb	University Observatory, Vienna.
26.5	35.1	....	Howard Grubb	University Observatory, Johannesburg, Transvaal.
26.0	32 5	1873 1893	Alvan Clark Warner & Swasey remounted	United States Naval Observatory, Washington, D. C.
26.0	32.8	1883	Alvan Clark	Leander McCormick Observatory, University of Virginia, Charlottesville, Virginia
26.0	22.4	1897	Howard Grubb	Royal Observatory, Greenwich. This is the gift of the surgeon, Sir Henry Thompson, hence known as the "Thompson Equatorial." The objective is photographic. The mounting carries a 30-inch reflector as counterbalance.
26.0	36.1	....	McDowell Local shops	Southern Station of the Yale Observatory, Johannesburg, Transvaal. This is a photographic objective.
25.6	34.1	....	Zeiss	Berlin-Babelsberg University Observatory, Neubabelsberg (Berlin)

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
25.6 in.	.... ft.	....	Zeiss	Imperial University Observatory, Mitaka (Tokio). There is a 13.8-inch photographic on the same mount.
25.6	34.1	....	Zeiss	Astronomical Observatory of the University of Belgrade, Jugoslavia.
25.6	....	....	Zeiss	Projected (1939) for an observatory on Mount Albano, Roma.
25.0	29.9	1869	T. Cooke & Sons	Solar Physics Observatory, Cambridge University, Cambridge, England. This instrument was built for R. S. Newall at Gateshead and by him given to the University in 1889. The "Newall Telescope."
24.4	52.2	1891	Henry Brothers Gauthier	Astrophysical Section, Observatory of Paris, Meudon. This lens is photographic, on the same mounting as the 32.7-inch visual.
24.1	32.2	1896	Alvan Clark	Lowell Observatory, Flagstaff, Arizona. First mounted near Mexico, D. F.
24.0	22.5	1902	Grubb	Radcliffe Observatory, Oxford, England. This is photographic; there is an 18.0-inch on the same mounting. Transferred to University of London.
24.0	35.0	....	Grubb	National Astronomical Observatory, Santiago, Chile.
24.0	24.5	1901	Grubb	Royal Observatory, Cape of Good Hope. This photographic lens, an 18.0-inch visual, and an 8-inch visual, all of the same focal-length, form the "Victoria Telescope," the gift of McClean.
24.0	26.7	1931	Grubb-Parsons	Stockholm Observatory, Saltsjöbaden. This is photographic; there is a 19.7-inch visual on the same mounting.

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
24.0 in.	36.0 ft.	1911	Brashear Warner & Swasey	Sproul Observatory, Swarthmore College, Swarthmore, Pennsylvania.
24.0	11.3	1893	Alvan Clark Fecker, remounted	Southern Station of the Harvard College Observatory, Bloemfontein Orange Free State. This is the "Bruce" photographic doublet, first used at the Boyden Station in Arequipa, Peru, 1896, moved to Africa in 1927.
23.6	29.5	1916	Steinheil Repsold	Hamburg Observatory, Bergedorf. This is visual; there is an equal photographic lens on the same mounting.
23.6	29.5	1916	Steinheil Repsold	The photographic lens in the mounting mentioned above.
23.6	59.0	1890	Henry Brothers Gauthier	National Observatory, Paris. This is the great equatorial coudé; this is visual, but there is a photographic lens for the mounting, of the same dimensions.
23.6	35.4	....	Zeiss	Bosscha Observatory, Lembang, Java; the Astronomical Society of the Netherlands East Indies. This is a visual lens; there is a photographic of 23.6 inches aperture on the same mounting.
23.6	35.2	....	Zeiss	Bosscha Observatory, Lembang, Java. This is the photographic lens on the mounting mentioned above.
23.0	28.9	1882 1932	Alvan Clark Fecker, remounted	Princeton University Observatory, Princeton, New Jersey. Originally it was the Halsted Observatory.
20.0	27.9	....	Clark Warner & Swasey	Van Vleck Observatory, Wesleyen University, Middletown, Conn.
20.0	28.0	1894	Alvan Clark Saegmuller	Chamberlin Observatory, University of Denver, Colorado. This is visual, but can be converted to photographic by reversing the crown component.

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
20.0 in.	28.0 ft.	....	Brashear Warner & Swasey	Chabot Observatory, Oakland Public Schools, Oakland, Cal.
20.0	11.7	....	Fecker Warner & Swasey	Lick Observatory, Mount Hamilton, California. This is photographic, and in operation; a 10-inch visual is on the same mounting, together later on with a 20-inch photovisual not yet built.
20.0	11.7	....	Fecker Warner & Swasey	Lick Observatory. This is the photovisual of the mounting mentioned above. Not yet started.
19.7	41.0	1899 1916	Steinheil Repsold Schmidt, refigured	Astrophysical Observatory, Potsdam. This is the visual objective on the mounting with the 31.5 photographic.
19.7	26.7	1931	Grubb-Parsons	Stockholm Observatory, Saltsjöbaden. This is the visual lens on the same mounting with the 24.0-inch photographic.
19.7	....	....	Schaer	Private Observatory of G. Fournier, Chelles (Paris) France.
19.2	22.7	....	Merz Repsold	National Observatory, attached to the University of Strasbourg, France.
19.1	....	1892	Merz Saegmuller	Manila Observatory (Jesuit), Philippine Islands; telescope can be used both photographically and visually.
18.5	27.0	1862 1864	Clark Clark remounted	Dearborn Observatory, Northwestern University, Evanston, Ill. Ordered originally for the University of Mississippi, purchased by Chicago Astronomical Society, put into keeping of old Chicago University, which burned. Transferred to Northwestern, 1889, deeded to Northwestern in 1929.
18.1	....	....	Cooke	National Observatory, Rio de Janeiro, Brazil. There is a 12.6-inch on the same mounting.

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
18.0 in.	25.3 ft.	1896	Brashear Warner & Swasey	Flower Observatory, University of Pennsylvania, Upper Darby, (Philadelphia) Pennsylvania. This was first used by Lowell.
18.0	23.5	1901	Grubb	Royal Observatory, Cape of Good Hope. This is the visual lens on the same mounting as the 24.0-inch, and forms a part of the "Victoria" telescope.
18.0	22.5	1902	Grubb	Radcliffe Observatory, Oxford; this is a visual lens on the same mounting as the 24.0-inch photographic. Transferred to University of London.
18.0	....	1903	Clark	Amherst College Observatory, Amherst, Massachusetts
17.7	22.8	?1934	Cooke Zeiss	Royal Observatory of Belgium, (Uccle)
17.0	31.5	....	Henry Brothers Gauthier	Observatory of the National University, La Plata, Argentina
16.1	....	1900	Brashear Grubb	University Observatory, Heidelberg, Germany. This is the "Bruce," a photographic doublet; there is another of the same size on the same mounting, in addition to a 9.8-inch visual by Pauly.
16.1	....	1900	Brashear Grubb	University Observatory, Heidelberg. This is the other photographic lens on the "Bruce" telescope mentioned above.
16.1	....	1891	Brashear Warner & Swasey	Goodsell Observatory, Carleton College, Northfield, Minnesota.
16.0	....	....	Clark	Cincinnati Observatory, University of Cincinnati, Ohio
16.0	7.0	1910	Metcalf	Oak Ridge Station of the Harvard College Observatory; a photographic doublet.
16.0	22.0	1883	Clark Warner & Swasey	Mt. Lowe Observatory, California. This was originally in H. H. Warner's Observatory in Rochester N. Y., then was taken by Lewis Swift to California. (1893).

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
15.7 in.	6.6 ft.	1934	Zeiss	Royal Observatory of Belgium, Uccle. This is photographic; there is an equal photographic on the same mounting, as well as a 9.8-inch visual.
15.7	6.6	1934	Zeiss	Royal Observatory of Belgium, Uccle. This is the other photographic on the mounting mentioned above.
15.7	16.4	....	Gauthier	National Observatory, Athens, Greece
15.7	19.7	1934	Zeiss	Castel Gandolfo Observatory, Rome.
15.7	6.6	1934	Zeiss	Castel Gandolfo Observatory, Rome, with 23.6-inch reflector.
15.7	16.4	....	Grubb	Astronomical Observatory of Madrid, Spain.
15.7	18.0	....	Steinheil	Berlin-Babelsberg University Observatory, Neubabelsberg. This is photographic; there is an 11.8-inch visual guide.
15.7	....	....	Zeiss	Bischoffsheim Observatory, University of Paris, at Nice. This is photographic; there is another of same size on the same mounting.
15.7	....	....	Zeiss	Bischoffsheim Observatory, Nice. This is the other lens mentioned above.
15.7	....	....	.....	Bischoffsheim Observatory, Nice. This is an equatorial coudé.
15.7	22.5	1897	Henry Brothers Gauthier	Observatory of the Catholic Mission of Shanghai (Zo-Sé Obs.) at Zi-Ka-Wei, near Shanghai. This is visual, and there is an equal photographic on the same mounting.
15.7	22.5	1895	Henry Brothers Gauthier	Observatory of the Catholic Mission of Shanghai. This is the photographic lens on the mounting mentioned above.

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
15.7 in.	6.6 ft.	1931	Zeiss	Saltsjöbaden, Stockholm Observatory. This is photographic, used with objective prisms.
15.7	....	....	Zeiss	Projected (1939) for an observatory on Mount Albano, Rome. This is one of two photographic lenses on one mounting.
15.7	....	....	Zeiss	Projected (1939) for Mount Albano. This is the other photographic lens of the instrument mentioned above.
15.6	20.3	1879	Alvan Clark	Washburn Observatory, University of Wisconsin, Madison, Wisconsin.
15.5	19.4	1885	T. Cooke & Sons	Cerulli Royal Astr. Observatory, Collurania (Teramo) Italy. It was originally the property of a Mr. Wigglesworth but passed into the hands of Cerulli, who in 1917 gave it to the state.
15.4	17.3	....	Steinheil Cavignato	Royal Observatory of Rome, Italy.
15.4	19.7	....	.....	University Observatory, Toulouse, France.
15.4	13.5	....	Merz Schupmann	Private Observatory, P. Fauth, Grunwald (Munich), Germany. This telescope was mounted at Landstuhl, 1895–1930.
15.2	15.2	1878	Grubb	Royal Observatory of Scotland, Edinburgh. This is visual, with a Grubb 10-inch photographic, of 5.0 feet focal-length, mounted with it. This telescope was used by Copeland at Dun Echt, and was a gift to the government by Lord Crawford, who had it in his observatory.
15.0	22.5	1847	Merz Mahler	Harvard College Observatory, Cambridge, Massachusetts.

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
15.0 in.	21.8 ft.	....	Henry Brothers Repsold	Astronomical Observatory of the State University, Moscow, Russia. This is photographic; an equal visual is on the same mounting.
15.0	22.4	....	Henry Brothers Repsold	Astronomical Observatory of the State University, Moscow. This is the visual lens of the mounting mentioned above.
15.0	16.1	....	Grubb	Nizamiah Observatory, Hyderabad, (Deccan), India.
15.0	15.1	1893	Grubb	University of Mississippi Observatory, Oxford, Miss. This is visual, and there is a 9-inch photographic mounted with it.
15.0	15.0	1893	Grubb	Stonyhurst College Observatory, Stonyhurst (Blackburn) England.
15.0	15.0	1880	Grubb	National Astronomical Observatory, Tacubaya, Mexico.
15.0	13.1	?1905	Mailhat	Fabra Observatory of the Royal Academy of Sciences, Mount Tibidabo (Barcelona), Spain. This is photographic, with a visual of equal aperture on the same mounting.
15.0	19.7	?1905	Mailhat	Fabra Observatory. This is the visual lens mentioned above.
15.0	....	....	Brashear Warner & Swasey	Dominion Observatory, Ottawa, Canada
15.0	....	....	Brashear Fecker	Cook Observatory, University of Pennsylvania, Wynnewood, Pa. This lens was made to replace an equal lens destroyed in a fire in Central High School, Philadelphia. It is mounted horizontal, with a Foucault-type siderostat.
15.0	22.4	....	Merz Repsold	Astronomical Observatory of Lisbon, Portugal.

THE LARGEST REFRACTORS.—(*Continued*)

Diam.	*Focal-length*	*Date*	*Makers*	*Location*
15.0 in.	22.4 ft.	1880	Merz Gauthier	Observatory of the University of Bordeaux, Floirac (Gironde), France.
15.0	15.0	1870	Grubb	Solar Physics Observatory, Cambridge University, Cambridge, England. This instrument, with an 18-inch Cassegrain reflector on a separate declination axis, was the property of the Royal Society lent to Wm. Huggins for his Tulse Hill Observatory; after his death given to Solar Physics Observatory.
15.0	....	....	Gauthier	Bischoffscheim Observatory of the University of Paris, Nice, France.
15.0	29.5	....	.....	National Observatory, Paris. This is the "East Equatorial."
15.0	19.7	....	Merz Prin	National Observatory, Bucharest, Romania. This is a photo-visual lens.
15.0	....	....	.....	University Observatory, Vienna. This is an equatorial coudé.
15.0	39.4	....	McDowell	Yale University Observatory, New Haven, Conn. This is photographic, mounted as a polar telescope, with an 8.9-inch visual lens.

APPENDIX V

SCHMIDT CAMERAS

(TO JANUARY 1, 1941)

Thanks are due to Professor Charles Smiley, Director of the Ladd Observatory, for providing the larger portion of the following list.

Observatory or individual	*f/*	*Diam. plate inches*	*Diam. mirror inches*	*Maker*	
				Optics	*Mounting*
Harvard	2.5	60 (unfin)	60	Fecker	Fecker
Palomar	2.5	48 (unfin)	72	Hendrix	
Tonanzintla	3.5	26	31	Perkin-Elmer	Harvard
Case School	3.5	24	36	Lundin (Warner & Swasey)	both.
Harvard	3.5	24	33	Perkin-Elmer	Harvard
Flagstaff	3.5	24 (blank)	31 (blank)	Perkin-Elmer	
Mellish, Escondido	2.25	20	20	Mellish	Mellish
Palomar	2.0	18	26	Hendrix	Cal. Tech.
M. R. Schottland	2.7	16	24.75	Fecker	Fecker
Bergedorf	1.74	14	17	Schmidt	
Hildom, Los Angeles	2.5	12	16	Hildom, A.	
Cook Observatory	2.5	10	15	Fecker	
Hume Cronyn Observatory, U. of Western Ontario	2.7	8	12	Perkin-Elmer	
Bartlett, San Francisco	2	8	12	Bartlett, K. R.	
Lowers, San Diego	1	8	12	C. A. & H. A. Lower	
	1.5	8			
Waitkus, Pittsburgh	1.0	8	12	N. Waitkus	

SCHMIDT CAMERAS.—(*Continued*)

Observatory or individual	*f/*	*Diam. plate inches*	*Diam. mirror inches*	*Maker*	
				Optics	*Mounting*
Pearl, Melrose, Mass.	1	8	12	H. F. Pearl	
M. R. Schottland	1.5	8	12.5	Fecker	Fecker
David Dunlap	....	.....	12	R. K. Young	
Herbig, Los Angeles	4	8	10	G. Herbig	
Ice, West Reading, Pa.	1	8	10	H. C. Ice	
Bailey, Riverside, Calif.	2.4	8	9	H. P. Bailey	Bailey
Brown, N. Y. C.	1.5	7	10	E. B. Brown	
Grinch, Passaic	1.5	7	10	J. L. Grinch	
Elmore, Dallas	1	7	10	C. H. Elmore	
DeVany, Davenport	0.85	6	8	A. DeVany	
Pearson, Chicago	8	6	8	F. E. Pearson	
Staffa, G. E.	3	6	6	G. Staffa	
Lucy, Jersey City	2 0	6	8	F. A. Lucy	
Seely, N. Y. C.	2	5	8	R. A. Seely	
Economou, Manchester	1	5	8	G. A. Economou	
Harvard	1	5	6	L. S. Barnes	
Brower, Plainfield	1.4	4.5	6	S. E. Brower	Brower
Cagnon, Williamsett, Mass.	1	4	6	R. C. Cagnon	
Ladd Observatory, Brown University	1	4	6	MacKnight-Reed	Hoflman
Schleter, Wilkinsburg, Pa.	1	4	6	G. H. Schleter	
Nicholson, Chicago	2	4	5	C. F. Nicholson	
Knowlton, N. Y. C.	1	4	4.5	Philip Knowlton	
	1.9	3	7.5		
D. O. Hendrix, Pasadena				Several cameras	
Vreeland, Grants Pass, Ore.	....	.....	12	F. K. Vreeland	
Kimmens, Jefferson, Mass.	1.5	.....	6	A. P. Kimmens	
Abastumani, Georgia, USSR	1.75	16?	16?	Zeiss	
Dunlap	1?	.....	.....	Young	
U. of Western Ontario	1	8	12	Perkin-Elmer	
And others, mostly in Europe.					

APPENDIX VI

SCHWARZSCHILD CAMERAS

Cogshall, Univ. of Indiana, 24-inch aperture, 80-inch focal-length.

Smiley et. al., Brown University, 12-inch aperture, 36-inch focal-length.

WRIGHT CAMERAS

R. T. Smith, Lick Obs. $f/4$, 8-inch plate, 10-inch mirror.

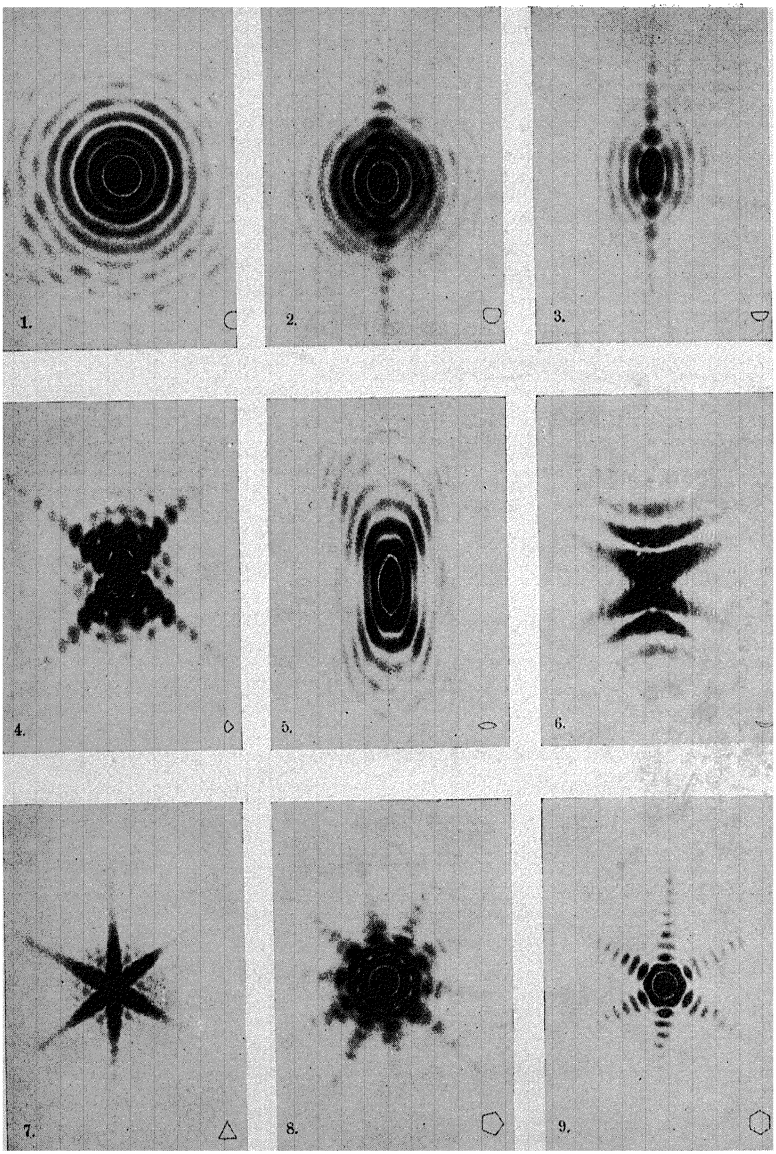
Harvard (Barnes) $f/4$, 5-inch plate, 8-inch mirror (for flat-field spectroscopy).

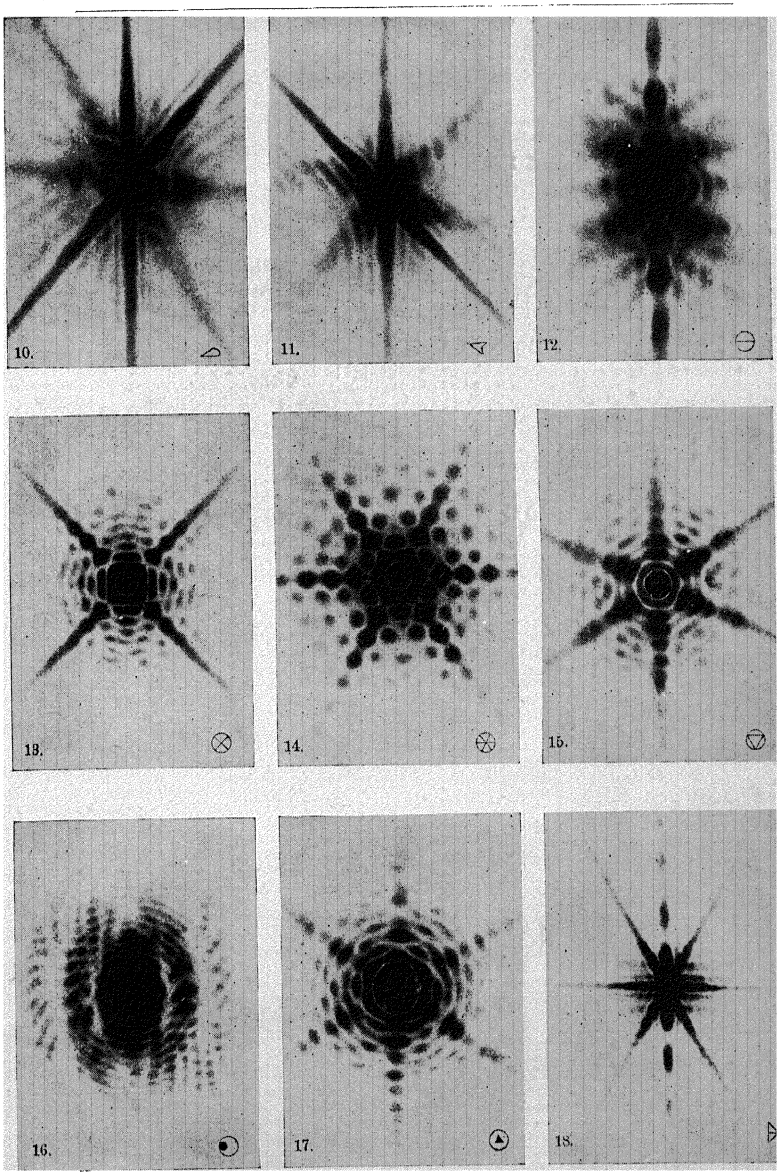
C. E. Wells, Roseville, Calif. $f/4$, 8-inch plate, 10-inch mirror.

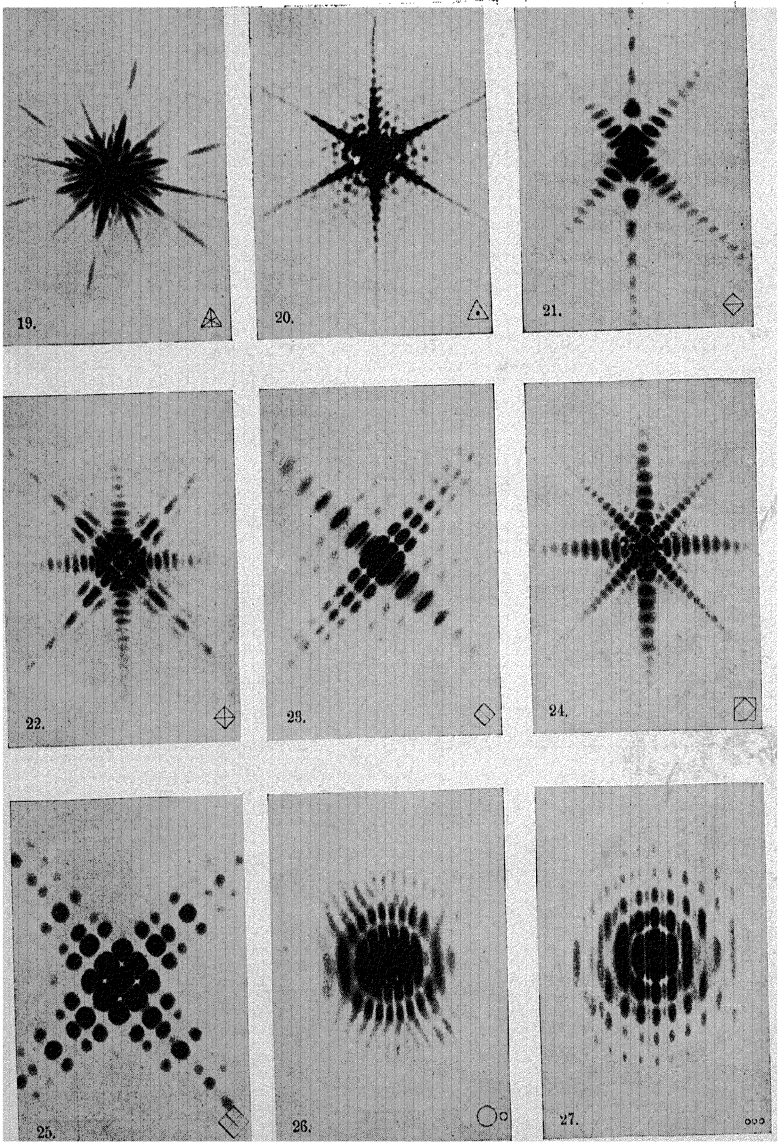
APPENDIX VII
DIFFRACTION IMAGES

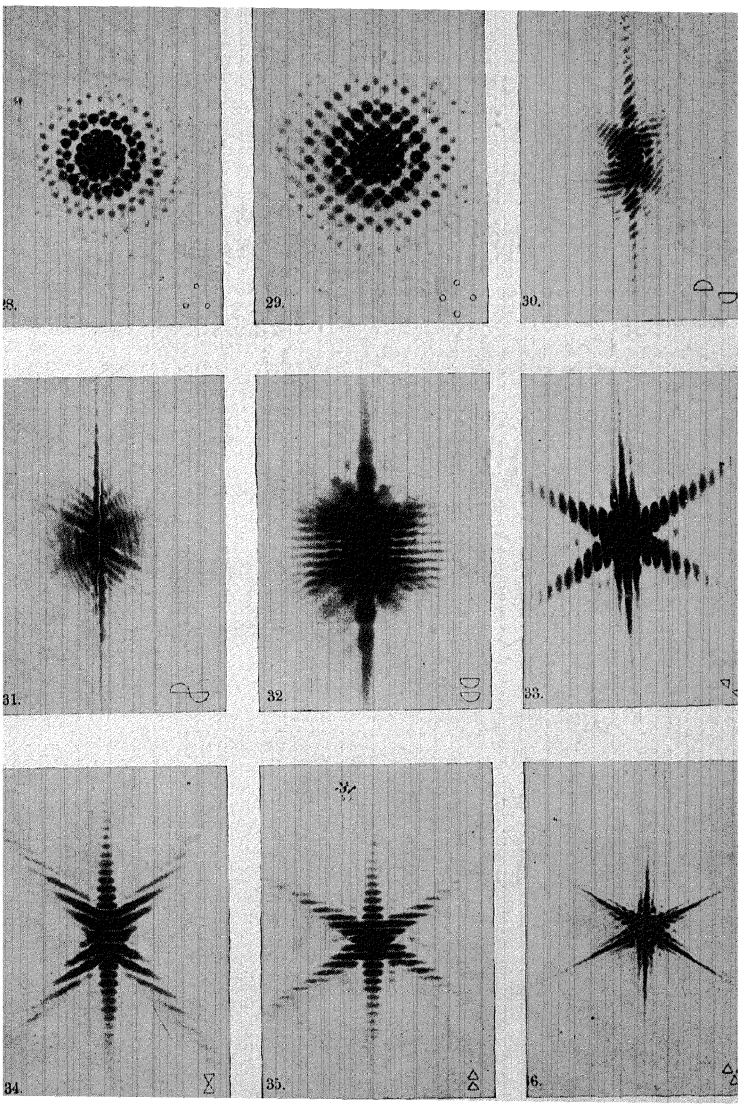
The following photographs are reproduced from a valuable old publication by Scheiner and Hirayama. In each small numbered picture is the general appearance of the diffraction image of a star viewed through a telescope covered with an aperture of the shape indicated in the small outline in the lower right-hand corner. For example, the image in 1. is that given by a circular aperture; in 7 by an equilateral triangular aperture; etc. The pattern in 13. will be familiar to the amateur as resulting from a support system for a secondary of the kind indicated.

Even a brief study of the pictures should convince the reader of the wave nature of light, which in turn causes diffraction. The reader who is fortunate enough to possess a telescope can readily verify the photographs by placing the specified shapes or occulting patterns over the objective. The reader might also study the appearance of the image of a bright star in his telescope when a screen wire is covering the objective.


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