## CHAPTER II

# Telescopes in Particular

Both the variety of telescopes and the wide divergence in their prices can be confusing to the prospective buyer. A 6-inch Newtonian reflector costs about $300; a Cassegrainian of the same size, $600; a Maksutov, $1,800; and a refractor, as much as $5,000. Furthermore, the prices of different-sized models of the same type vary widely. The 12-inch Newtonian, instead of costing twice as much as its 6-inch counterpart, is usually at least six times as expensive.

Why should there be this great variation in cost? Let's look at the Newtonian again, considering only basic requirements and forgoing fancy fittings. Doubling the diameter of a mirror increases its area only four times, but it increases the difficulty of producing the same smooth curve by a factor of 16. In addition, the tube must be longer (if we want the same f-ratio) as well as wider, the mounting must be heavier and more solid, the drive system more rugged, and everything else disproportionately larger, and therefore more costly.

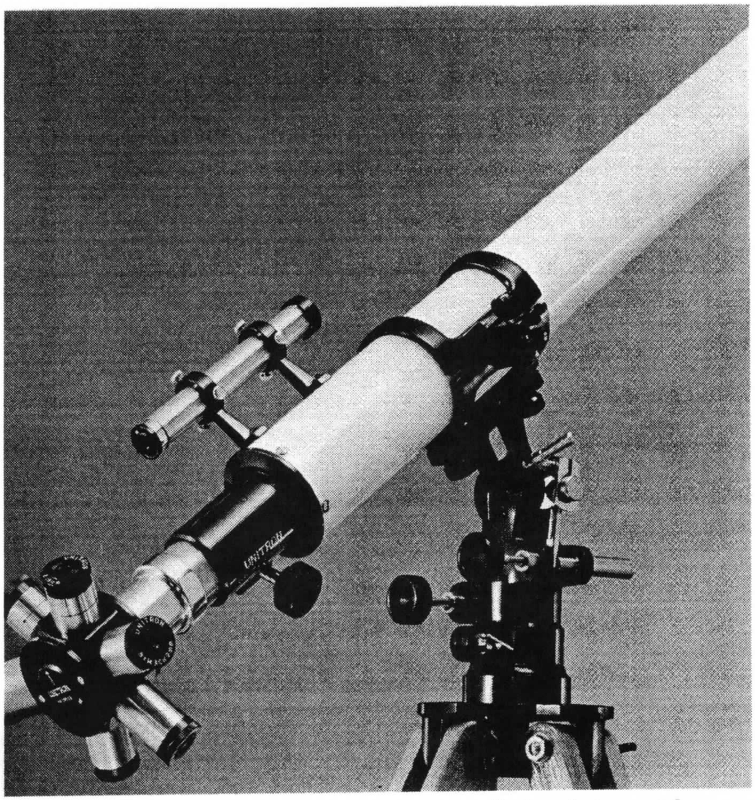
The cause of the great disparity in price between one type of telescope and another lies in their optical systems. The Newtonian requires a precise curve over only one surface of glass, the Cassegrainian over two, the Maksutov over three, and the refractor must have four delicately curved and polished surfaces. Moreover, when more than one curve is required in an optical system, each must match the others with the same precision possessed by each individual curve. To complicate the problem even further, instruments that refract light must have glass of infinitely higher quality than those that only reflect it. No wonder a good refractor costs so much more than a reflector of corresponding size and quality!

Now the question arises whether one type of telescope possesses enough better qualities than another to justify a large price difference. We have pointed out some of the variations in telescopic performance, but to answer the question fully, we will here consider the advantages and drawbacks of each of the main types of telescope.

### The Refractor

The most appealing attribute of the refractor is its permanence. Once the optical system is aligned, it need never again be adjusted in normal use. Of course no telescope can stand rough handling, but a well-made refractor is more resistant to misuse than any other type of telescope. Properly cared for, it lasts practically forever. The inside glass surfaces are sealed from the atmosphere and rarely need cleaning. In the unlikely event that some interior housekeeping is required—probably as the result of allowing the eyepiece end of the tube to remain open—it is easy to remove the cell that holds the objective. In almost all refractor objectives, the crown glass element is on the outside. Because it is harder and tougher than flint glass it can be cleaned many times without deterioration, provided only that reasonable care is exercised in the cleaning process.

There are two main types of refractors: the Gali-



*Unitron Instrument Company*

A refracting telescope on an altazimuth mounting. Note that six different eyepieces with varying degrees of magnification can be turned into place with a minimum of fuss.

lean and the astronomical. The Galilean—the "spyglass" type of refractor—gives an erect image, seldom has a magnifying power greater than 5 and usually has an aperture of less than 2 inches. Its great deficiencies as an astronomical instrument are its low resolving power, its small field, and its lack of image brightness.

The astronomical refractor gives an inverted image and requires an erecting eyepiece or prism system if you wish to use it for looking around the countryside. It may have one of several types of objective lens. For small apertures—up to 2 inches —the objective is a cemented doublet, used because of its efficient light transmission and good contrast. These advantages are paid for, however, by coma and astigmatism, which limit the usable field. Larger refractors have objectives of either the Fraunhofer or air-spaced type. The Fraunhofer is a contact doublet: the two lenses touch each other but are not cemented together. It is free from coma and has a wide field of excellent definition with very little astigmatism. The lenses of the air-spaced objective are usually separated by a distance equal to about 1.5 percent of the focal length. This distance is very important because it influences the color correction, and should never be disturbed once it has been set by the manufacturer. The air-spaced doublet is well corrected for color, has only a moderate amount of coma—it is midway between the cemented objective and the Fraunhofer type in this respect—and yields a flat, well-defined image. There is a very small difference in chromatic magnification, but the discrepancy in the size of the images formed at the red and violet foci is only about .2 percent.

Another advantage of the refractor is its portability. In sizes up to 4 or 5 inches it is easy to carry around and set up for use. This is an important feature—not only for the city dweller who must observe away from home, but also for the man who can stargaze in his back yard. And, besides being portable, the refractor is easy to use: the eyepiece is conveniently located for viewing heavenly objects with altitudes of less than 45°, and a star diagonal can quickly be attached for viewing objects with altitudes of more than 45°. Most observers like the convenience of merely sighting along the tube to find the approximate location of a planet or star and then moving their eye just an inch or so to the eyepiece.

But the refractor's greatest appeal lies in its optical qualities. It is little affected by changing temperatures; the closed tube eliminates the bothersome air currents that are the bane of many reflectors, especially those constructed by amateurs. It is an "all-weather" instrument. Under bad seeing conditions its images are steadier than a reflector's and it will stand higher magnification with less loss of definition, especially at the edge of the field. It is also free from diffraction patterns, since there is no secondary mirror or prism to set up interference effects. Star images are sharp, double stars are well resolved, and extended images show good contrast since almost no extraneous light can reach the eyepiece.

The large focal ratio of the refractor gives it several advantages over shorter-focus, reflecting instruments of the same size:

1. The refractor produces a higher magnification with the same eyepiece: *Example:* A 1-inch eyepiece used with a 6-inch f/8 reflector magnifies 48 times. The same eyepiece used with a 6-inch f/15 refractor magnifies 90 times. Conversely, the refractor can produce the *same* magnification as a reflector with an eyepiece of longer focal length, a characteristic that is a boon to the average observer, since long-focus eyepieces are easy to use.
2. The refractor does not require expensive, highly corrected eyepieces.
3. The "average" refractor is likely to perform better than the "average" reflector because the longer the focal length of a telescope, the less apparent its optical defects.

The many advantages of the refractor are quite impressive. Yet there are observers who feel that the one disadvantage of secondary spectrum outweighs all of them. It is true that in larger refractors secondary spectrum can be obtrusive and at times very annoying. But in smaller instruments, of 2- to 6-inch range, it is hardly noticeable. Certainly for those who want only to get acquainted with the heavens and for those who need a small, portable, rugged telescope, the refractor cannot be surpassed. In any size its merits outweigh its deficiencies by a wide margin.

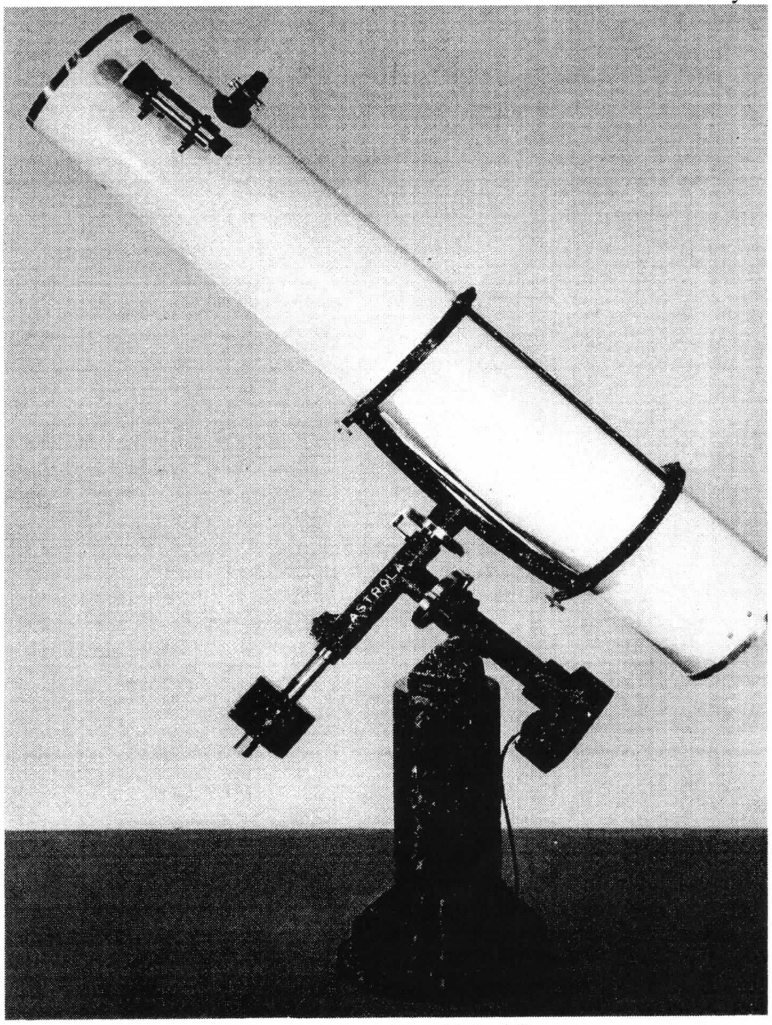
## Simple Reflectors

The simplest type of reflector is the Newtonian. In the 6- and 8-inch sizes, it has been constructed by thousands of amateurs, and is the choice of the great observatories of the world. It can be constructed in almost endless variations, from the short-focus telescopes designed for wide-field observing, to the long-focus giants used in studying remote galaxies. If any one telescope can be designated as a universal instrument, the Newtonian must be the choice.

The most appealing aspect of the Newtonian to the majority of amateurs is its relative inexpensiveness. A 12½-inch model costs about as much as a 4-inch refractor, and a 6-inch can be built at home for as little as $50. Inch for inch of aperture, it is the cheapest telescope one can buy.

But it has many other advantages as well. In the first place, the Newtonian, regardless of its aperture, is the perfect achromatic telescope. Whether its images are viewed directly through an eyepiece or are recorded on film, they are flat and color free. In apertures of over 7 inches, reflectors are superior in light-gathering power to refractors of equal size. With good seeing conditions, the reflector equals and often surpasses the refractor for observations of nebulae, the planets, and the moon. In some respects, it is easier to use than a refractor. Its short focal length permits a more compact instrument that is simple to mount and often more stable than the equivalent-sized refractor with its longer tube. But when it is mounted equatorially, the Newtonian can be a very awkward instrument indeed, for the eyepiece sometimes presents itself at difficult angles. Many an amateur has ended an evening's observing with a stiff neck and aching muscles. Fortunately, this is now almost a condition of the past, for the manufacturers of today's Newtonians provide for rotation of either the tube or the eyepiece so the latter can be turned to a comfortable position for observing.

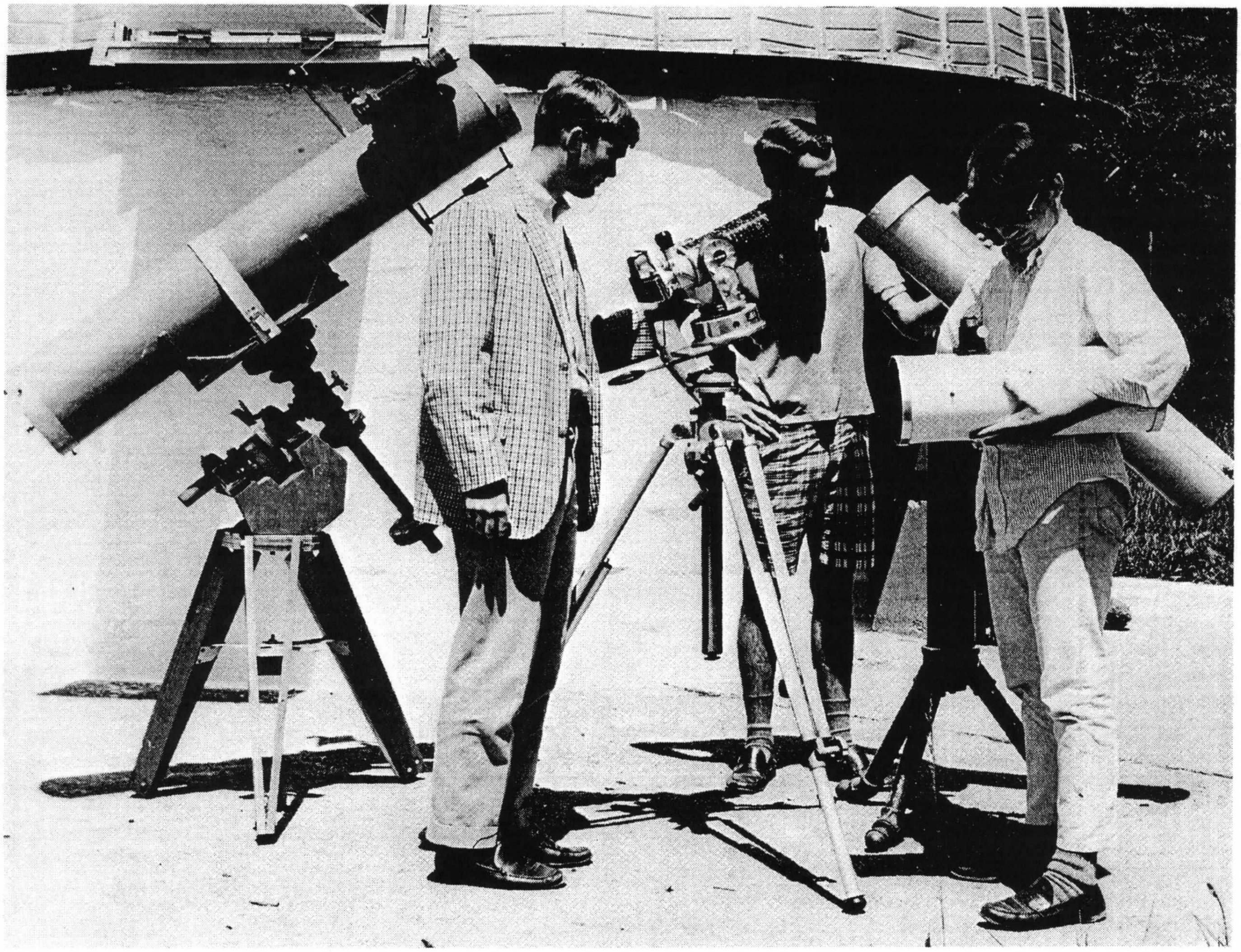
Perhaps the most serious limitation of the Newtonian, especially a portable instrument, is its tendency to get out of alignment. The optical train involves a right angle at the diagonal, and a very small shift in the position of either the primary mirror or the diagonal has drastic effects on the image. Then, too, the diagonal causes diffraction effects because it must be mounted in the path of incoming light. The final objection to this reflector is that its short focal length emphasizes any imperfections in the optical elements. A poor-quality Newtonian, therefore, is almost useless for serious observing.



*Cave Optical Company*

A 10-inch Newtonian reflector. The rugged construction of the equatorial mounting reduces vibration to a minimum.

It is difficult to make rigorous comparisons between refractors and reflectors. Both are, in a sense, special-purpose instruments. The small refractor is probably to be preferred to the small reflector, especially when portability is required. But there is one notable exception to this general statement. If you are looking for expanded views of the heavens—the open star clusters, the gaseous and galactic nebulae, the star clouds of the Milky Way—there is no finer instrument than a short-focus Newtonian. These are called RFT's (richest-field telescopes), and they are so compact they can be carried under the arm. Although they can be made in any size,



*Millbrook School Observatory*

From left to right: an 8-inch reflector, a commercial Maksutov-type with camera, a 6-inch reflector, and a 6-inch RFT.

the two most widely used models are the 4-inch f/5 and the 6-inch f/4. The 6-inch size gives a magnification of about 20 and has a tube a little over 2 feet long. The field is nearly 2½°—about five full moons—enough to take in most of the big objects of the sky, such as the Andromeda Galaxy (dimensions: 160′ × 40′). Like all short-focus instruments, the RFT produces poor images at the edge of its field, but this distortion is a minor inconvenience when you consider the beautiful views that such a wide and brilliant field affords.

Permanently mounted, the large reflector of 12 inches or more is superior to the refractor of equal size in nearly every respect. Indeed, the long-focus reflector in the f/10 to f/15 range is probably the best instrument available for viewing the moon and planets.

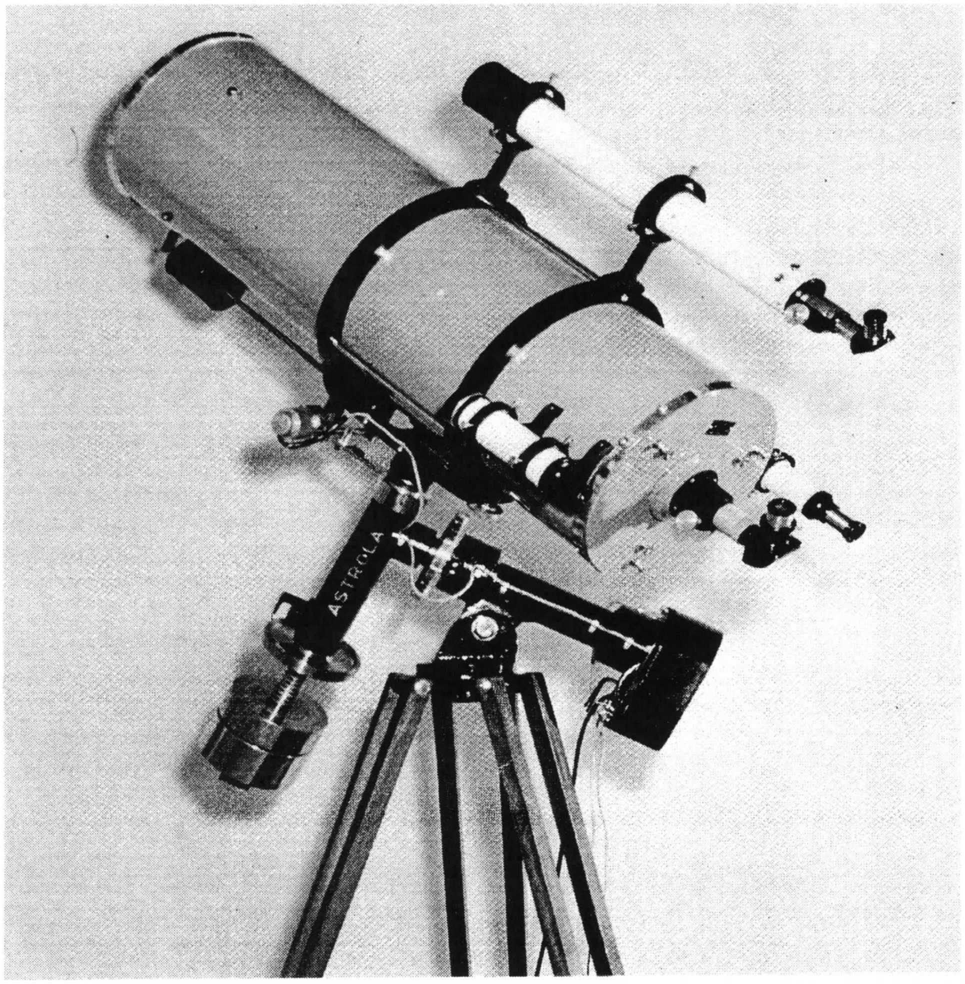
## Compound Telescopes

Although the term *compound* may be applied to any telescope with more than one reflecting surface, we shall apply it only to instruments with more than one curved optical element, excluding eyepieces.

Compound telescopes can be subdivided into two main groups: Cassegrainian and catadioptric. The essential difference between the two is in their method of correcting for aberrations. The catadioptrics use large lenses, or plates; the Cassegrainians, special curves in the primary and secondary mirrors.

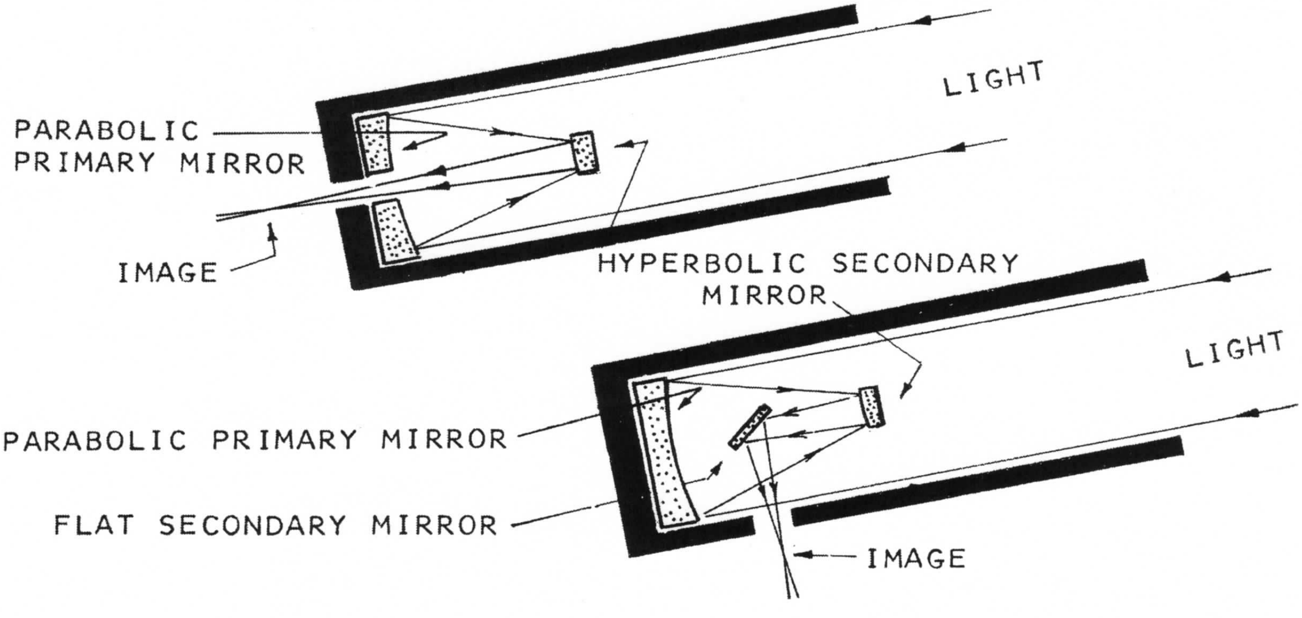
### CASSEGRAIN TELESCOPES

There are many variations of the Cassegrainian, all characterized by short tubes but long equivalent



*Cave Optical Company*

Above: A 10-inch Cassegrainian telescope. Below: Two possibilities in the Cassegrainian design for telescopes.



focal lengths, which allow high magnifications with greatly reduced coma (as compared to short-focus Newtonians) and almost no spherical or chromatic aberration. This combination would seem to produce the "perfect" telescope. The fact is, however, that although the Cassegrainians are excellent telescopes they have a few shortcomings, such as astigmatism, field curvature, a limited field of view, and reduced contrast. Manufacturers of Cassegrainians compensate for this latter defect either by placing field stops near the Ramsden disk or by placing one baffle tube at the exit hole in the primary mirror and another behind the secondary mirror.

How can the Cassegrainian simultaneously have a short tube and a long focal length? The secondary mirror, acting as a sort of amplifier, narrows the angle of the cone of light produced by the primary until the equivalent focal length becomes very long. The amplification factor is the distance of the secondary mirror from the final focal plane ($P_1$) divided by the distance of the secondary inside the focus of the primary ($P_2$). This result multiplied by the focal length of the primary mirror gives the equivalent focal length. Let's suppose we have a 6-inch Cassegrainian in which $P_1 = 21$ inches, $P_2 = 3.5$ inches, and the focal length of the primary is 15 inches. Then,

$$\text{equivalent focal length} = \frac{P_1}{P_2} F = \frac{21}{3.5} \times 15 = 90 \text{ inches}$$

and the telescope is therefore a 6-inch f/15 Cassegrainian.

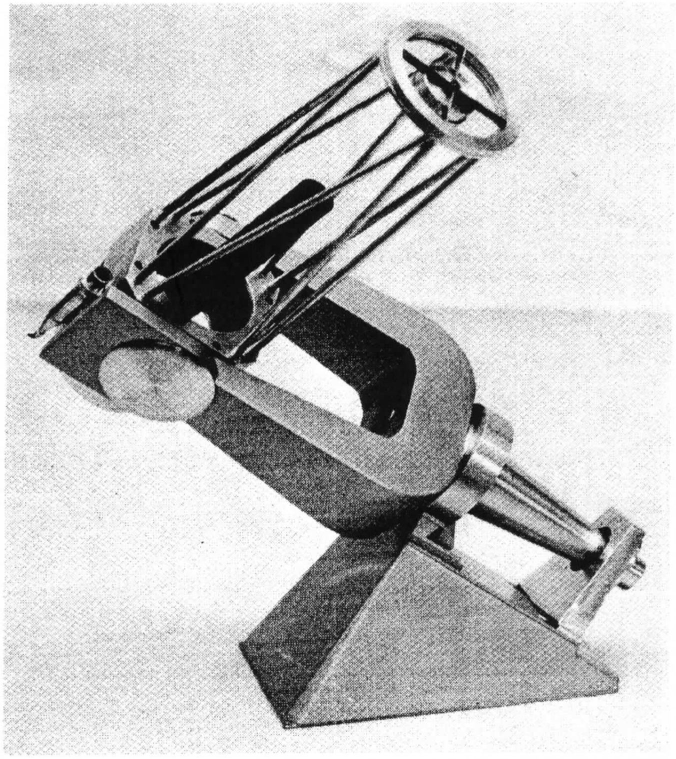
The short tubes, long focal lengths, and large focal ratios (a 10-inch is usually f/16, for example) give Cassegrainians most of the advantages of both reflectors and refractors, plus the added convenience of simplicity in mounting, excellent portability, and steady performance, since the shortness of the tube almost eliminates the air currents that plague the Newtonian.

Three variations of the Cassegrainian are in wide use.

The true Cassegrainian exemplifies most of the characteristics noted above. It is free from spherical aberration and has only about the same coma as an ordinary reflector of equal focal length—which is not much. The primary mirror is a paraboloid,* the secondary a convex hyperboloid. The primary (paraboloidal) mirror brings parallel rays to a perfect focus, but they are intercepted before they reach this focus by the secondary (hyperboloidal) mirror, which reflects them to another focus, usually through a hole in the primary mirror. Some forms have a nonperforated primary and the rays are reflected to the side of the tube by a diagonal. This form has some advantage over the ordinary Cassegrainian, for it does not allow extraneous light to fog the image and it has a more conveniently placed eyepiece. But it also produces a reversed image—bothersome to lunar and planetary observers—and it has a smaller field of full illumination.

Since the curves of the true Cassegrainian are difficult to produce and test, this type is relatively expensive. Another type of Cassegrainian, the Dall-Kirkham, employs simpler curves, an ellipsoid primary mirror, and a spherical secondary. In performance this telescope parallels the true Cassegrainian except for increased coma and a consequent narrowing of the usable field. But Dall-Kirkhams are simpler to make than true Cassegrainians and so are more favored by amateur telescope-makers. More important to the observer who buys a telescope, professionally made Dall-Kirkhams are less expensive than their more complex cousins. In common with all Cassegrainians, they are excellent instruments.

A third Cassegrainian type, the Ritchey-Chretien, has more complex curves than either of its companion instruments and hence is much more difficult to make. The curves employed, hyperboloidal sur-



*U.S. Navy Photograph*

A model of the 60-inch telescope at the U.S. Naval Observatory, Flagstaff, Arizona. This exemplifies beauty as well as rugged design in a telescope.

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* The terms paraboloid, hyperboloid, etc., represent 3-dimensional curves derived from their 2-dimensional counterparts in plane geometry. The sphere is a curve of uniform radius of curvature, the paraboloid is deeper in the center than at the edges, the hyperboloid is still deeper than the paraboloid and flattens more at the edges, and the ellipsoid is the curve generated by rotating an ellipse around its long axis.

faces on both primary and secondary mirrors, yield a completely coma-free image, and the only remaining defects are astigmatism and curvature of field. Because it is difficult to manufacture, it is usually made only in large apertures for observatory use. An example of this type is the beautiful 40-inch telescope at the Naval Observatory at Flagstaff, Arizona. Many experts regard the Ritchey-Chretien as the Cassegrainian telescope at its best.

### CATADIOPTRIC TELESCOPES

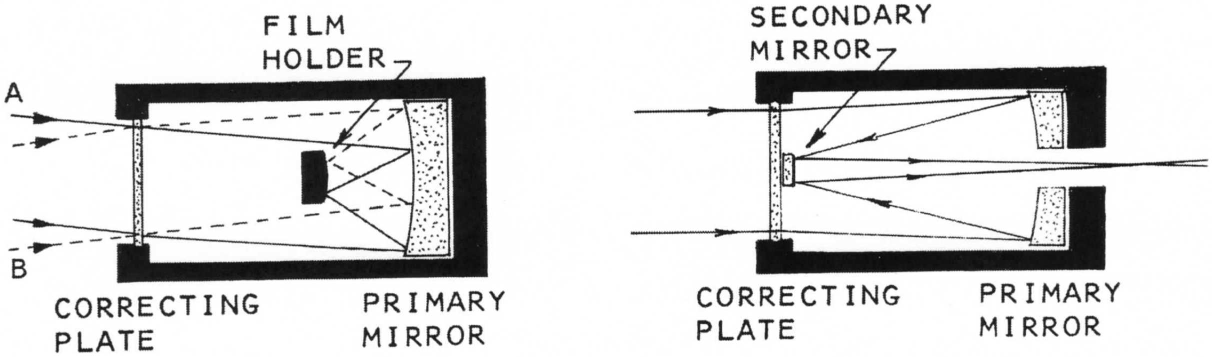
The mouth-filling adjective catadioptric refers to a pair of optical elements that oppose one another. One element is a lens that causes negative spherical aberration; the other is a mirror that causes positive spherical aberration. The result is cancellation, and a system that has no spherical aberration at all. As we shall see, the catadioptrics have many other merits.

Like their close cousins, the Cassegrainians, the catadioptrics come in several variations. They range from telescopes designed for photography only—the Schmidts—to the photovisual instruments called Maksutovs. Unlike the Cassegrainians, these telescopes represent brand-new ideas in optics, relatively speaking. Bernard Schmidt developed his telescopic camera in 1930; A. Bouwers patented his idea for a photovisual catadioptric telescope in February of 1941, and eight months later D. Maksutov was granted a patent on exactly the same principle. Bouwers worked in Amsterdam, Maksutov in Moscow. Neither, apparently, knew what the other was doing, yet each came up with an idea that was to change the whole concept of small telescope design. In contrast to these recent designs, the principle of the Cassegrain has been well known since the seventeenth century.

The claims made for catadioptric telescopes are perhaps somewhat exaggerated, yet it is true that these instruments are nearly aberration-free: Spherical aberration is eliminated, as noted earlier; coma, chromatic aberrations, astigmatism, and curvature of field are reduced to negligible proportions.

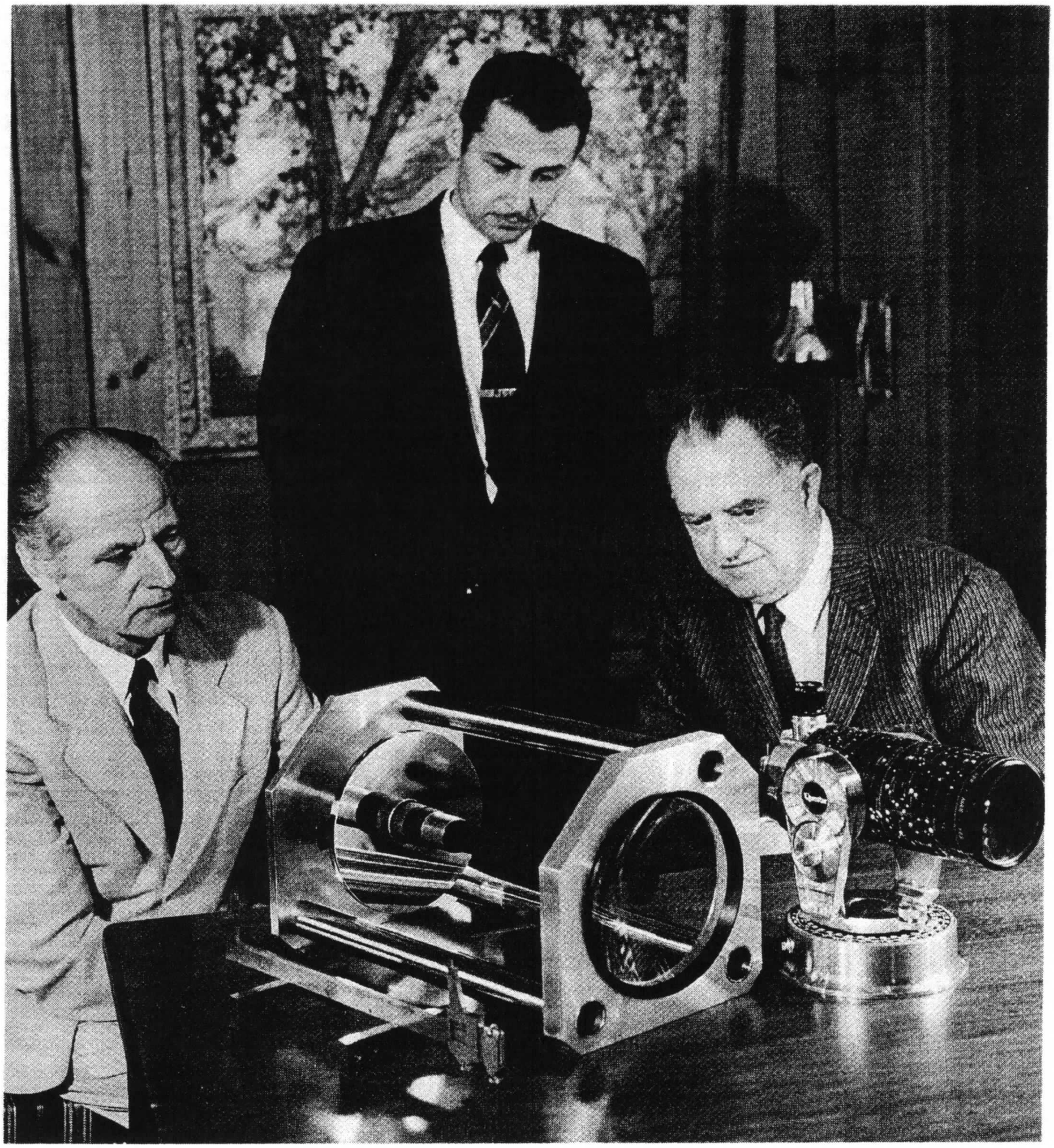
We shall not be much concerned with the Schmidt telescope itself, since it is primarily a photographic instrument. But it is interesting as a prototype—the first telescope to use a correcting plate or lens in front of the center of curvature of the primary mirror. As Schmidt used it, the correcting plate was a thin, almost flat piece of glass, plane on the outside but curved on the inside facing the mirror. This curve is convex at its center and is surrounded by a concave ring that extends to the edge of the plate. The primary mirror is spherical, focusing at a curved focal plane that acts as the plate-holder. The combination produces a very fast telescopic camera, free from coma, astigmatism, distortion, and chromatic aberration. Its most remarkable feature (as if those already mentioned are not unusual enough in themselves) is its tremendous field of excellent definition. An f/1 Schmidt yields beautifully sharp images over a 20° field; the field of good definition of other telescopes is measured in *minutes* of arc rather than in degrees.

There are several visual adaptations of the Schmidt principle, but these have been superseded in large part by the Maksutov-type telescopes. A notable exception is the Schmidt-Cassegrain, which has all the Maksutov characteristics as well as a larger clear aperture than a comparable Maksutov. The optics are complex: a Schmidt-type correcting plate, a spherical primary mirror, and an elliptical secondary. Hence it is difficult to construct and expensive to buy. But it is a particularly fine instrument, providing well-defined images whose quality is limited only by small diffraction effects from the secondary.



Left; Schmidt camera; right, Schmidt-Cassegrainian adaptation for visual work.

The outstanding feature of the Maksutov is a meniscus lens—a lens that looks very much like a large, deep watch crystal—placed inside the radius of curvature of the primary mirror. In the original design, a secondary mirror, located immediately behind the correcting lens, reflected rays back



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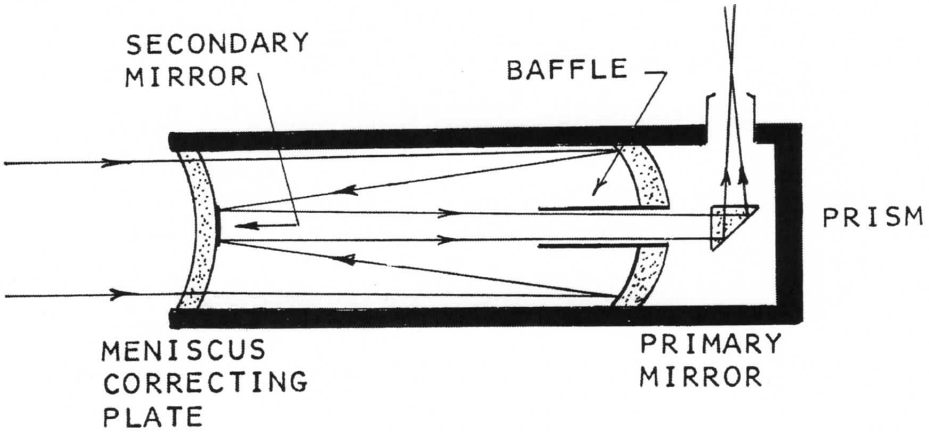
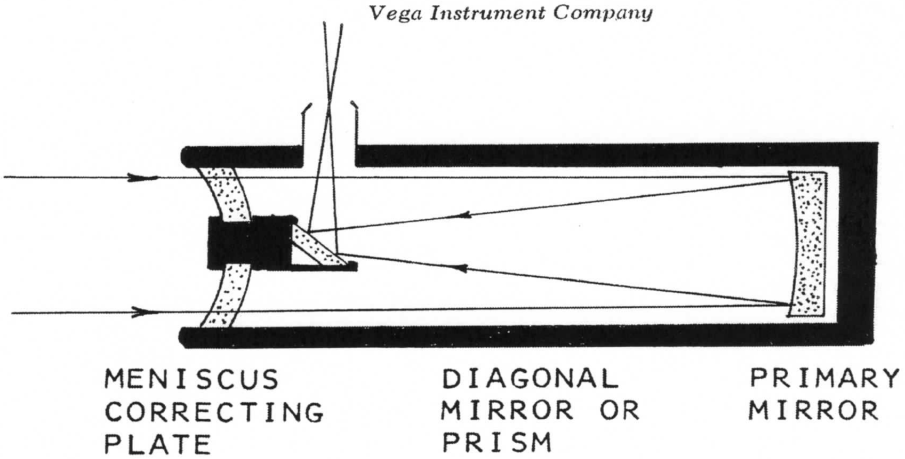


Left: one arrangement for the elements of the **Maksutov** design. Here the primary is perforated, and the secondary is an aluminized spot on the curved back surface of the meniscus-shaped correcting plate. Above: The larger telescope, left, shows the elements arranged as in the diagram above. The smaller telescope, right, shows the normal eyepiece position for these instruments. The light train is bent by a totally reflecting prism to to reach the eyepiece.

*Vega Instrument Company*

Above: an exceptionally fine and sturdy design in a Maksutov telescope. The optical system for this telescope is shown at right.



through a hole in the primary to the eyepiece. With the formation of the now-famous Maksutov Club (founded by Allan Mackintosh in Glen Cove, Long Island), the Maksutov telescope caught on like wildfire with amateur telescope-makers. As could be expected, there are several variations in design and construction. The most widely used was designed by John Gregory; it employs spherical surfaces for both the correcting plate and the primary mirror. The secondary has been eliminated and replaced by an aluminized spot on the back of the corrector. The Gregory-Maksutov, as it is now known, is designed in two focal ratios, an f/15 and an f/23. The f/15 is intended as an all-round instrument with a wide field at low powers and excellent definition at high powers. The f/23 is primarily a planet-observing instrument, but it too is amazingly versatile. Another variation, the Newtonian-Maksutov, replaces the Cassegrain-type secondary with a Newtonian diagonal. This arrangement turns the Maksutov into a low-focal-ratio (f/4) RFT, but with none of the coma of the short-focus Newtonian. The addition of a Barlow lens increases the focal ratio to f/12, making possible high powers with good definition.

The Maksutovs are extremely sensitive to any maladjustment of the optical train, but once the optical elements are fixed in position they are practically immovable. The tube is short; as a result, it can be ruggedly constructed without becoming too heavy. For the observer's comfort, a diagonal is usually added behind the secondary mirror so that the eyepiece can be placed at right angles to the tube. Like the refractor, the Maksutov is a sealed instrument. Hence, the tube is free from air currents that might distort the image, and the optical surfaces are protected. The correcting lens is usually a tough borosilicate glass, which, properly cared for, will last almost forever. They are light, portable, easy to set up and use.

The Maksutov, again like the refractor, is limited in size of aperture because of the difficulty of producing optically clear glass in large diameters. Since light passes *through* it, the correcting plate obviously must be flawless. Maksutovs are thus pretty much restricted to amateur use, where great light-gathering power is not required, and for amateurs they are ideal. Consider the qualities of a commercial model, similar to the Gregory-Maksutov, which the author has used for six years for teaching purposes. It has been handled by hundreds of teen-age boys, and consequently has had some very rough usage, but it still performs as well as when it was first unpacked from its shipping case. Its aperture is 3.5 inches, focal length 44.5 inches, f/14.4. It has no observable spherical aberration, coma, astigmatism, or chromatic aberration. Resolving power exceeds Dawes' limit and definition is excellent over the entire field.

The Maksutov, aperture for aperture, is superior to any other telescope, provided its optics are of high quality. Tolerances are very small; slight imperfections in the mirrors or lens or in the optical alignment become glaring defects. Workmanship must be painstaking, tedious, and near-perfect. Consequently, the Maksutov is an expensive instrument, but in the long run well worth its price.

Many observers start with a small telescope, then graduate to ever larger ones as they find their pursuit of the multitudinous heavenly objects ever more fascinating. A good telescope is a lifetime investment; starting with the best is the most sensible approach. But not everyone is fortunate enough to be able to do this, and even a poor telescope is better than none. After all, the great astronomical discoveries were made with "poor" telescopes. Galileo would have been delighted to have the telescope now gathering dust in your attic because you think you have exhausted its possibilities.

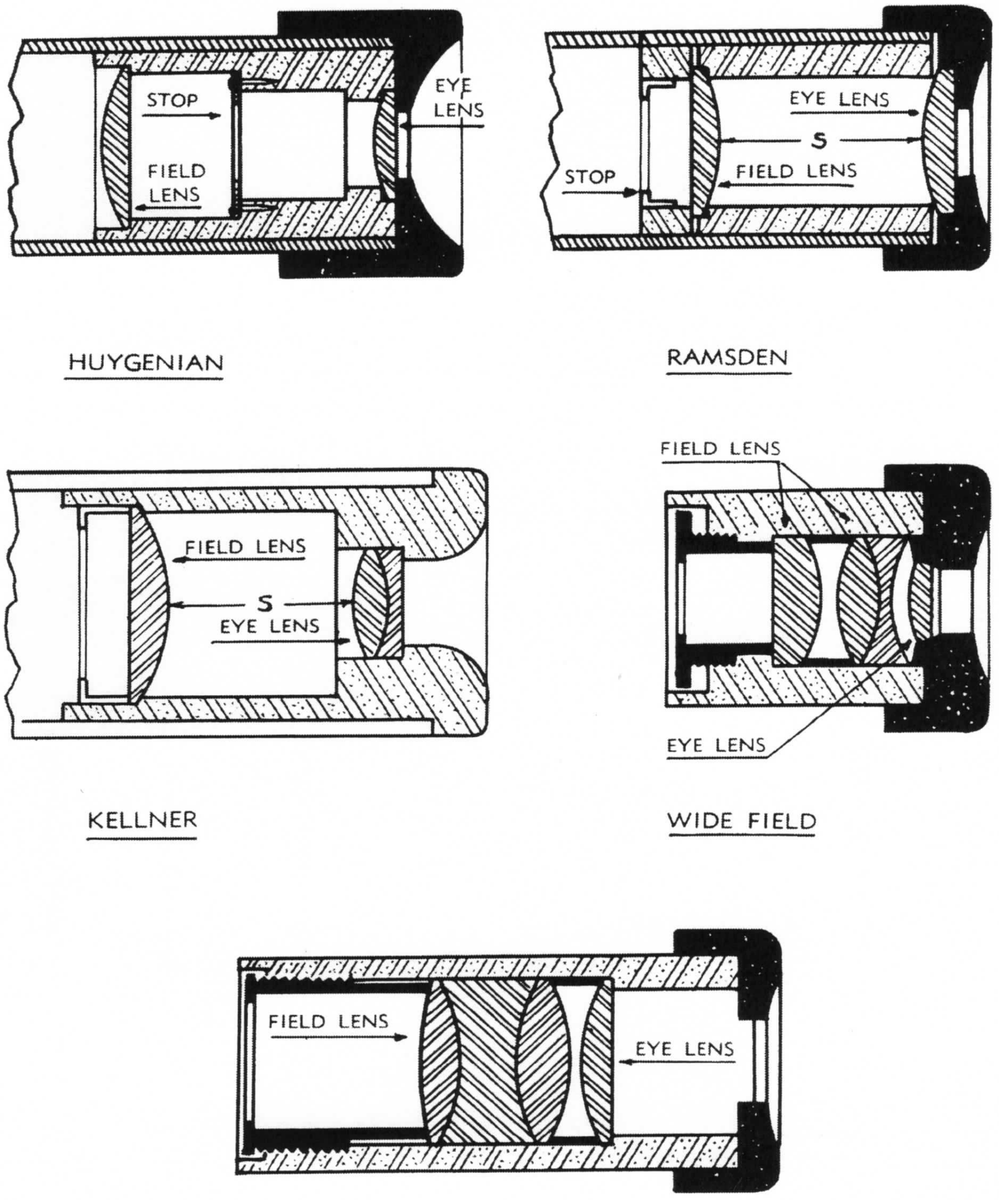
Thus far we have discussed only the main telescope types and have ignored many others. The Gregorian reflector, the off-axis telescopes (Herschelian, neobrachytes, and many others), the Schwartzchild, the Couder reflector, the Sampson telescope—all these have been omitted, not because they are unimportant, but chiefly because they are variations of the main types of telescopes. Before we proceed to our primary objective—a discussion of how to use telescopes—we have one other important topic to consider: eyepieces.

## Eyepieces

Much of the blame for the inferior performance of a telescope should be put squarely where it belongs: on the eyepiece. The eyepiece itself may not actually be inferior, but perhaps a poor choice. Few people realize that eyepieces should match the optics with which they are used. You can demonstrate this for yourself by trying an eyepiece that works perfectly well with a refractor in an f/5 Newtonian, or by trying a Ramsden eyepiece (designed for short-focus Newtonians) in a refractor. The result is likely to be unsatisfactory in both cases. And for this reason many of the war-surplus eyepiece "bargains" are not bargains at all; usually they are designed for instruments with entirely different characteristics than those of astronomical telescopes.

What are the characteristics of a good eyepiece? Here are a few of the most obvious:

**1.** Since eyepieces exhibit the same aberrations as objectives, ideal performance would be characterized by freedom from spherical aberration, astigmatism, coma, curvature of field, distortion, and chromatic aberration. Curiously enough, an eyepiece which has one or more of these aberrations may



HUYGENIAN

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Types of eyepieces.

still be useful, provided the objective with which it is used exhibits a defect that is identical but opposite in degree. In such cases, the aberration is canceled to a large extent. For example, if the residual spherical aberration of an eyepiece is positive (undercorrected), it will work very well with an overcorrected objective.

In general, eyepiece aberrations become more noticeable as relative apertures increase; short-focal-length telescopes demand a greater degree of perfection than those of long focal length. This also applies to the eyepiece itself; deficiencies appear more pronounced with an increase in eyepiece focal length. Since longer focal length decreases magnification, it follows that defects in a low-power eyepiece are more noticeable than the same defects in one of high power.

**2.** The field of an eyepiece should be dark, flat, and wide. Dark fields help increase contrast; a flat field brings more parts of the image into focus at one time. And of course the wider the field, the better, provided definition is good over all of it.

**3.** Images must be bright, with no annoying "ghosts" from internal reflections.

**4.** Eye-relief should be as large as possible. A large-eye-relief eyepiece is not only a boon to the wearer of glasses, but also a great help to the beginning observer. Many people looking through a telescope for the first time can see no image at all simply because they find it difficult to get close enough to short-eye-relief eyepieces.

**5.** Finally, eyepieces used with relatively large aperture objectives should be achromatic, because chromatic aberration becomes more objectionable as apertures increase. This applies to reflectors as well as refractors. When you see color in a Newtonian image, blame the eyepiece rather than the mirror.

As a general rule, long-focus telescopes do not require exceptionally high-quality eyepieces unless they are used at low magnifications. Nevertheless, *all* telescopes deserve the best eyepieces obtainable, no matter what magnification is used. A cheap eyepiece may perform reasonably well at high powers, but getting full potentialities out of an excellent objective demands equal excellence in the remainder of the telescope optics.

There are literally hundreds of different kinds of eyepieces, ranging from simple single-element units to those employing half a dozen elements or more. Fortunately, they can all be divided into three broad groups, each including wide variations in performance and quality. The first group includes eyepieces consisting of only one lens; the second, eyepieces consisting of two lenses separated from each other; the third, eyepieces consisting of more than two separated lenses. This is an arbitrary grouping, for some of the single-lens eyepieces are actually made up of several pieces of glass cemented together. But because they act as a unit, we consider them single lenses.

### SINGLE-ELEMENT EYEPIECES

This group includes three types of eyepieces: the thin-lens, the thick-lens (made from a single piece of glass), and the thick-lens cemented.

Thin-lens eyepieces, the simplest type, are chiefly of historical interest, although some cheap telescopes still employ them. The Kepler, a plano-convex lens, is used with the plane side toward the eye. Even though it produces bright images and has good eye-relief, it is practically useless because of its chromatic aberration, small field, and distortion. The Galilean is a double-concave lens; its greatest advantage is an erect image, good for terrestrial use but of doubtful value in astronomy.

Solid, or thick-lens, eyepieces are cut from crown glass rods and are usually ground spherical at each end. One form, the Tolles, has a groove cut around it two thirds of its length from the eye. When blackened, the groove acts as a lens stop. Eyepieces of this type suffer from chromatism and poor eye-relief, but they have wide, dark fields without internal reflections (ghost images) and produce bright images.

Cemented eyepieces represent an attempt—usually successful—to combine the virtues of the single lens with those of the two-element eyepiece. The cemented doublets (Steinheil, Hastings, Chevalier), give good eye-relief and produce bright images without ghosts and flat fields of good definition. They suffer from slight distortion, but not enough to impair their usefulness.

Cemented triplets, such as the monocentric Steinheil and Zeiss eyepieces (so called because the curves in the three elements are sections of concentric spheres, or very close to it), are excellent in all respects. Some observers, indeed, think these are the best eyepieces now available, chiefly because they work well in any telescope no matter what the focal length of the primary. They have wide fields of good definition; excellent light transmission that produces a bright image; no ghost images or scattered light, so that the bright image is seen against a dark field; almost perfect achromatism; and good eye-relief.

### TWO-LENS EYEPIECES

The *Huygenian* eyepiece is made up of two Kepler lenses of different curvature, both of which have their plane surfaces facing the eye. It is called a "negative" eyepiece because the image is formed between the two lenses; for this reason it cannot be used as a magnifying glass.

The Huygenian is a standard eyepiece for the refractor and it works very well with objectives of long focal ratios—f/15 and over—especially at low and medium powers. When it is used with short-focus Newtonians, however, strong color appears, accompanied by spherical aberration and distortion at the field edges. But properly employed, it produces a field of good definition and illumination and it has less obvious ghost images than any other two-lens eyepiece. One of its deficiencies is poor eye-relief; also, because the image is formed between the lenses, it is difficult to use a reticle successfully.

In the Ramsden the lenses are turned so that their convex surfaces face one another. In all two-lens eyepieces, the lens nearest the objective is called the *field lens;* the one nearest the eye, the *eye lens.* The function of the eye lens is to magnify the image formed by the field lens, which acts more as a light collector than as a magnifier. The two lenses are placed just far enough from one another so that the image is formed on the eye-side of the eye lens. One difficulty with this arrangement is that if the image plane is far enough from the lens to allow comfortable eye-relief, serious color is introduced. Consequently most Ramsdens are somewhat hard to use. Nevertheless, they have enough advantages—wide field, less spherical aberration and less field curvature than the Huygenian, low cost—to be very widely used, especially with short-focus reflecting systems.

The chromatic aberration of the Ramsden can be greatly reduced by adding another element to the eye lens, making it a cemented doublet. In this form the eyepiece is called an achromatic Ramsden, or Kellner. Some observers refer to this combination as a "haunted ocular," since it is more subject to ghost images than any other type. Because it has wide (up to 45°), flat fields of excellent definition and almost no chromatism, it is very useful in short-focus telescopes.

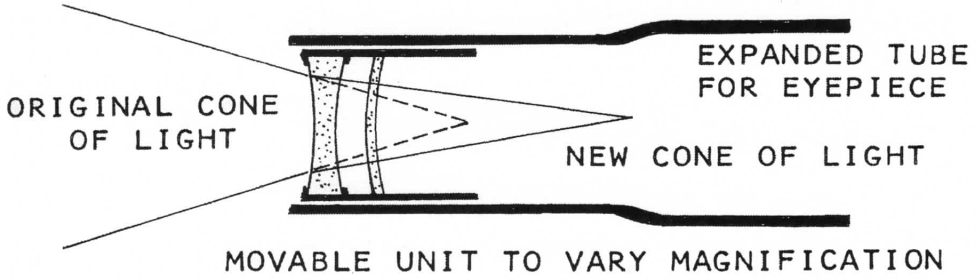
There are many other variations of two-lens systems—too many, indeed, to include here. But there are at least three which must be mentioned: the Euryscopic, the Ploessel, and the orthoscopic. The Euryscopic is similar to the Kellner, but its field lens is double-convex; as an even further departure, the Ploessel's field lens is a cemented doublet exactly like the eye lens except reversed in direction. Because of this similarity of eye and field lenses, the Ploessel is called a *symmetrical* eyepiece. Both the Euryscopic and the Ploessel give excellent definition over a wide, flat field and are particularly adapted to short-focus systems. In the *orthoscopic* eyepiece the field lens becomes a cemented triplet while the eye lens reverts to a single, plano-convex piece of glass. The principle operating here is simple: The field lens produces color aberrations exactly opposite to those of the eye lens; color neutralization is the outcome. In addition, the usual eyepiece aberrations, especially spherical aberration and distortion, are reduced almost to the point of disappearance. The field is wide and flat, ghost images are negligible, scattered light is practically eliminated, and the result is an excellently defined image against a dark background. Add good eye-relief and the end product is a very fine eyepiece that can be used in telescopes of almost any focal ratio.

### COMPOUND EYEPIECES

The addition of a third element between eye and field lenses transforms the two-lens eyepiece into a compound eyepiece. The extra element may be a simple lens or a cemented combination. It further reduces residual aberrations, but at the cost of a slight loss of light. Its advantages make up for this loss, however. A compound lens is completely achromatic and has only traces of distortion, coma, astigmatism, field curvature, and spherical aberration. Definition is exceptional over most of its tremendous dark field—up to 80° in some lenses. Examples are the Erfle, the fine component of so many Moonwatch telescopes; the Koenig, supplied as standard equipment on at least one fine commercially made instrument; and the Bertele and Goerz, used on many military instruments.

An important adjunct to many eyepieces, especially those with short eye-relief, is the Barlow lens. This is an additional lens, mounted in its own bushing, which is slipped into the eyepiece tube in front of the eyepiece itself. It is usually either a single negative lens, or an achromatic, cemented negative doublet. Its function is to act as a magnifier by lengthening the cone of light which enters the field lens of the eyepiece. The simple Barlow is usually made to magnify from 1½ × to 2 ×, the achromatic up to 4 ×. These figures are multipliers. If an eyepiece yields a total telescope magnification of 100 ×, the addition of a 3 × Barlow lens increases the total magnification to 300 × and at the same time increases the eye-relief to a comfortable margin.

The recently developed "zoom" eyepiece is a combination of lenses with one movable component. By simply twisting a knurled ring on the barrel, the observer may vary the effective focal length. The zoom eyepiece retains the excellent characteristics of the orthoscopic lens throughout its range of magnification and is a boon to the observer who doesn't like switching oculars. When he is using a zoom eyepiece with an f/8 Newtonian, for example, the observer may shift from a magnification of 55 × to 250 ×, or to any magnification between, in a



The Barlow lens.

matter of seconds. Zoom eyepieces are, of course, more expensive than most of the highly corrected oculars, but since they encompass the range of several individual units they are well worth the extra cost.

### USING EYEPIECES

It is a great temptation to blame inferior telescope performance on the eyepiece; sometimes, but rarely, this is justified. If you possess a high-quality, commercially made telescope, the manufacturer has carefully matched the eyepieces he supplies with the characteristics of his particular telescope. On the other hand, if your telescope is homemade, you must make your own eyepiece selection. A cardinal rule is that large-aperture telescopes demand good-quality eyepieces; a corollary is that long-focal-length eyepieces should be coupled with good quality. The characteristics we have listed for eyepiece types speak pretty much for themselves; beyond this only a few generalizations need be made. Huygenians, Kellners, and symmetrical eyepieces work well with refractors; Ramsdens and monocentrics with reflectors. Orthoscopics and compound eyepieces can be used with any telescope.

If you plan to buy a new eyepiece for your telescope, try it out first, if possible. Check all parts of the field by looking at as many different objects as you can under a variety of seeing conditions. Remember that almost any eyepiece will give good images at the center of the field; you are looking for "fringe" benefits. Finally, there is no substitute for quality; in eyepieces, as in anything else, you get what you pay for. Fine telescope objectives must be matched by fine eyepieces if their full capabilities are to be realized.

Eyepieces are supplied in focal lengths from 4 mm (.16 inch) to 102 mm (4 inches). The outside diameter of the bushings is usually 1¼ inches, a standard width for the adapter tubes of focusing mounts. The simpler eyepieces (Ramsdens, Kellners, Ploessels, Huygenians) cost from $3 to $8, depending on their source. The more highly corrected types (orthoscopics, triplets, compound eyepieces) cost from $10 to $20. Add a dollar or two if the lenses are coated.* They should be carefully chosen to give the correct range of magnification for your telescope: 3 diameters per inch of aperture for lower limits, 60 per inch for upper limits. Thus, if you own a 6-inch f/8 Newtonian, a full range of eyepieces might run from 6-mm (¼-inch) to 75-mm (3-inch) focal length. You will probably find that the intermediate focal lengths will get the most use.

## Telescope Accessories

What extra equipment do you need for your telescope? The answer to this depends on the answer to another question: What is the principal use to which you are going to put the instrument? If you are interested in solar observation, you will need high-density filters, a Herschel wedge, or some other device to cut down on light and heat. If you are primarily interested in planetary or lunar work you will want an array of filters to bring out contrast. If you wish to hunt for Messier† objects or faint nebulae, you will find that a good finder telescope is a great help. For pinpointing objects beyond the reach of a finder, setting circles become a necessity. If you are interested in photography, your telescope must be fitted with a drive and slow-motion devices, both of which require an equatorial mounting. If you own a refractor, you must have a star diagonal for your eyepieces in order to view objects near the zenith. Any accessory that increases your comfort is usually worth what you spend for it.

We shall talk about the various types of telescope mountings, drives, and setting circles in the next chapter. For the moment, let's confine our attention to some of the other accessories.

### FINDER TELESCOPES

A finder is a wide-field, low-power telescope with an optical axis parallel to that of the main telescope. Although not needed on RFT telescopes—where the field of the telescope is so wide that objects can be easily located—a good finder is an essential addition to all others, even if setting circles are also provided. There are few requirements for finders, but those that apply are important:

**1.** The field must be oriented in the same direction as that of the main telescope. Many amateur telescope-makers use elbow telescopes for finders because of the convenient position of their eyepieces. An elbow telescope, however, is little better than no finder at all because the fields of finder and telescope are exactly reversed—a star appearing to the right in one will be on the left in the other, and the observer must constantly make allowance for the difference. For the same reason, when a star diagonal is used with the main eyepiece a diagonal should also be added to the finder eyepiece.

**2.** The finder must be located near the eyepiece of the main telescope and must be mounted high enough that the tube of the main telescope does not interfere with viewing. If the telescope is a Newto-

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* Coated lenses have a thin application of magnesium fluoride, which reduces reflections and therefore increases light transmission.

† The list of 103 star clusters and nebulae compiled in 1781 by Charles Messier, the great comet hunter.

nian, there should be *two* finders. When a telescope is mounted equatorially the finder may sometimes be in an awkward position. The observer may find himself crouching under the telescope, twisting his neck in a tiring attempt to bring his "seeing" eye to the eyepiece—most of us are left- or right-eyed, just as we are left- or right-handed. The addition of a second finder obviates this difficulty, since one will always be in a convenient position.

3. A reticle or cross hairs should be placed on the field lens of the eyepiece. The wide field (3° to 6°) makes centering an object difficult unless there are some guide lines to help. Triple cross hairs that form a small triangle at the center of the field or a glass reticle with a small circle in its center are particularly helpful. The supports of the finder must be strong, and the adjusting screws must be kept tight. A finder that gets out of adjustment is more of a nuisance than a help.

Ordinarily, a finder has a much shorter focal length and a wider field than its companion telescope. But if the finder is to be used as a guide telescope for photography, its focal length must approach that of the main instrument. If there is a great disparity in the two focal lengths, a change in position of the telescope may produce only a small shift in the finder, and at the same time move an object out of the field of the telescope eyepiece or the photographic plate.

### FILTERS

Filters have two main purposes: to reduce the glare of bright objects at low power—e.g., the moon, Venus, Jupiter—and to improve definition by providing more contrast in extended images.

Neutral density filters are used to reduce glare. These filters have no color and are usually made of partially silvered glass or of colloidal carbon deposited on a glass surface. You can make your own by exposing black-and-white photographic film for different periods of time and then developing it to maximum density.

The density of a filter can be determined by this formula:

$$D = \log \frac{\text{incident light}}{\text{transmitted light}}$$

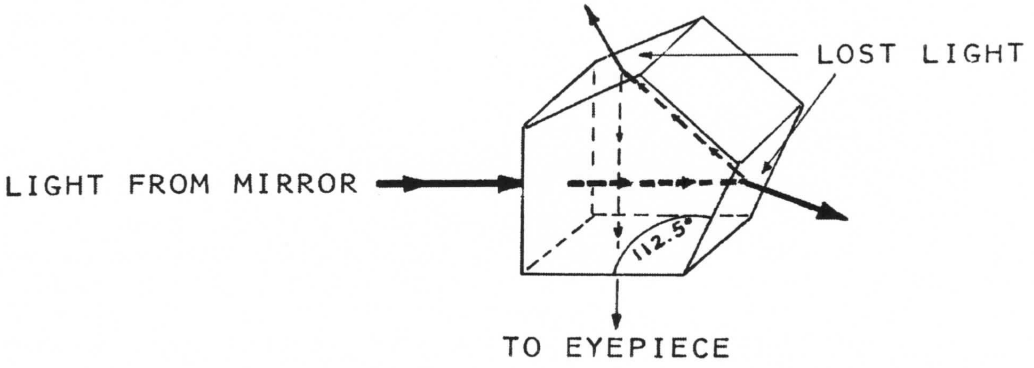
The range in density is from 0 to 5, the former transmitting 100 percent of the light that strikes it and the latter, none. Some typical values follow:

| *Density* | *Percentage of transmitted light* |
|---|---|
| 0 | 100 |
| .3 | 50 |
| .5 | 32 |
| .8 | 16 |
| 1 | 10 |
| 1.3 | 5 |
| 1.6 | 2.5 |
| 2 | 1 |
| 4 | 0.1 |

Neutral density filters are useful in bringing out details often obscured by the brightness of the object being viewed: irregularities on the terminator of Venus, double stars (when one is much brighter than the other, as in the case of Pollux and its companion), details on maria of the moon, and so forth.

There are a great many colored filters to choose from. The Wratten series (Eastman Kodak), for example, offers more than one hundred. Filters are invaluable in bringing out lunar and planetary detail. Amber, yellow, or orange are excellent for improving the contrast of Martian details. Jupiter's belts show up well with green filters, and the white markings on the belts are enhanced by blue filters. Green, blue, and yellow filters used when viewing the moon may change your ideas about some of the lunar configurations, especially the inside areas of the wide craters, such as Plato.

Never use a filter at the eyepiece to view the sun unless the light and heat in the optical train are



Some of the light that enters the unsilvered pentaprism is reflected internally and eventually reaches the eyepiece, but most of it escapes and is lost.

being reduced by some other means as well. The danger involved is equivalent to placing your eye at the focus of a burning glass. The heat at the focus of a telescope objective is intense enough to crack glass filters and allow the full power of the sun to strike the observer's unprotected eye. But this light can be cut down by a Herschel wedge or an unsilvered penta-prism, for when light strikes an unsilvered glass surface at any angle other than the critical angle (where it is completely reflected), some of it is reflected and some transmitted through the glass. The transmitted light is again only partially reflected by the inner surfaces of a prism, some of it passing through. In the Herschel wedge, only a small percentage of the original light and heat is reflected to the eyepiece; the remainder is safely reflected or transmitted in other directions. The penta-prism acts in the same way. Each of these devices is placed in the train of light in front of the eyepiece, and each should be supplemented by a medium neutral density filter. With these prisms, the telescope may now be used safely for direct solar viewing. In the absence of such safety devices, you can view the sun by projecting its image onto a piece of white cardboard or screen. Don't use cemented eyepieces for this purpose, however, because the heat may melt the Canada balsam that holds the lens elements together. A Herschelian or Ramsden eyepiece is best for projection purposes.

Some telescope manufacturers avoid the use of Herschel wedges or other devices by filtering light *before* it enters the telescope. This is done in two steps: First, the aperture of the telescope is reduced by placing a mask with a small hole cut in it over the front of the telescope. The amount of light entering the telescope is thus diminished by a factor proportional to the squares of the diameters of hole and mirror. Then this hole is covered by heavily silvered, optically flat (to 1/10 wavelength of light) glass. The result is to cut down light transmission to about one part in 50,000, or by 99.998 percent! The eyepiece needs no further protection and filters are not necessary with this arrangement.

### STAR DIAGONALS

Unless you lie flat on your back, it is almost impossible to use a plain refractor to observe heavenly objects at the zenith. The addition of a right-angle prism or mirror diagonal to the adapter tube in front of the eyepiece makes it possible to observe zenith objects in comfort. You cannot use just *any* prism or *any* diagonal, however, for their optical qualities must be in keeping with other telescope elements, or flat to within 1/4 wavelength of light. And remember that a diagonal will change the orientation of the field under observation in one plane (right and left, or up and down, depending on the way the diagonal is turned with respect to the rest of the telescope).