CHAPTER I

# Telescopes in General

What can you expect from a telescope—not *your* instrument in particular but *any* telescope? What part does telescope diameter play in what you can see? How important is focal length? What effect does the optical system have upon telescope performance? What role does light itself have? How important are the deficiencies or qualities of the human eye? The answers to these and many other questions will help you predict the ultimate performance of any instrument you may now own or wish to acquire. Before we can talk about any particular type of telescope, we must discuss telescopes in general.

## The Principle of the Telescope

Every telescope, whether it be a homemade instrument or one of the giants of the western observatories, operates in essentially the same manner. It gathers a part of the light produced by, or reflected from, an object or objects, concentrates this light in a single area—the focal plane—and then, by means of an eyepiece, magnifies the image formed there. That part of the telescope which gathers the light is called the objective. In the reflecting telescope, the objective is a curved, aluminized mirror of some sort. The rays of light from the object to be viewed are reflected from the mirror surface directly to the eyepiece (as in the off-axis reflector), or are picked up by the eyepiece after being reflected from a flat secondary mirror (as in the Newtonian reflector). In the simple refracting telescope, or refractor, the light rays are bent toward the focal plane as they pass through a curved lens. This lens serves the same purpose as the mirror of the reflector, although it is usually referred to as an object glass instead of an objective. The compound telescope is a combination of lenses and mirrors; each plays a part in bending the train of light toward the focal plane. No matter what the type of telescope, the basic principle is always the same. The cone of light from an object is reduced in diameter and is concentrated at the focal plane, where it can be examined by means of either a photographic plate or an eyepiece. The result is always a magnified image of the original object.

## What Is a Good Telescope?

A good telescope must perform five main functions:

**1.** It must gather sufficient light from an object to produce a brightly illuminated image. The amount of illumination depends on the diameter of the mirror or the aperture of the object glass.

**2.** It must have sufficient resolving power to separate close-together objects that appear as one to the naked eye. This ability to reproduce detailed images of good resolution depends on the aperture.

**3.** It must be able to produce images with good definition; that is, sharp images of uniformly excellent quality. Here the quality of the optical elements is all-important.

4. It must magnify the image. Both the objective and the eyepiece take part in this function, and the magnification produced depends on their focal lengths.
5. It must have a range, or field of view, wide enough for a number of objects to be seen in relation to each other. Here again focal length is the main factor.

## Some Telescope Terminology

It will be worth our while to go into these aspects of the telescope's function a little more deeply, but it will first be necessary to define a few of the terms used in describing telescopes.

The useful diameter of the objective, $D$, or aperture, is the diameter of that portion which transmits light to the eyepiece. It may be varied, as in a camera, by using a diaphragm to cover part of the surface. Don't judge the aperture of your telescope by the size of the tube (as many people do.) The term refers to the *effective* diameter of the mirror or object glass.

The *focal length, F,* is the distance from the objective to the focal plane (the area where the rays of light cross each other to produce an image).

The focal ratio (usually called the f-number) is the focal length divided by the aperture, or $F/D$. This often misunderstood term applies only to the objective, never to a combination of focal lengths of objective and eyepiece. The focal ratio is ordinarily indicated by a single number. For example, a refractor of 60-inch focal length and 4-inch aperture is referred to as an f/15 refractor. But if a circular stop is applied to the lens so that the diameter is cut in half, the instrument becomes an f/30 refractor.

The exit pupil consists of the light which emerges from the eyepiece. A cross section of this light at its narrowest point is known as the Ramsden disk.

Magnification is the increase of the apparent size of the image, as compared with the apparent size of the object. It is measured in terms of the relative diameter, never in terms of the area.

These are only a few of the fundamental terms we must know and understand to talk about the telescope. We will introduce and define others as the occasion demands.

## Image Brightness

Why is it that in the late afternoon, stars which are invisible to the naked eye can readily be seen through a telescope? Part of the answer to the question is that the light from the sky causes the pupil of the eye to contract and thus reduces its ability to register faint objects. The telescope, however, is not trained on the full sky, only a very small part of it. Thus, the total light is reduced, the contrast between starlight and sky light is increased, and the star becomes visible. But the important factor is the light-gathering power of the telescope compared with that of the eye alone. The telescope amplifies the light of both star and sky and the brighter object becomes still brighter by contrast.

The theoretical ability of your telescope to gather light depends primarily on its aperture and, to a lesser degree, upon the magnification used. This theoretical value can be found from the formula

$$\text{light-grasp} = \text{transmission factor} \times \frac{D^2}{d_e^2 \times M^2}$$

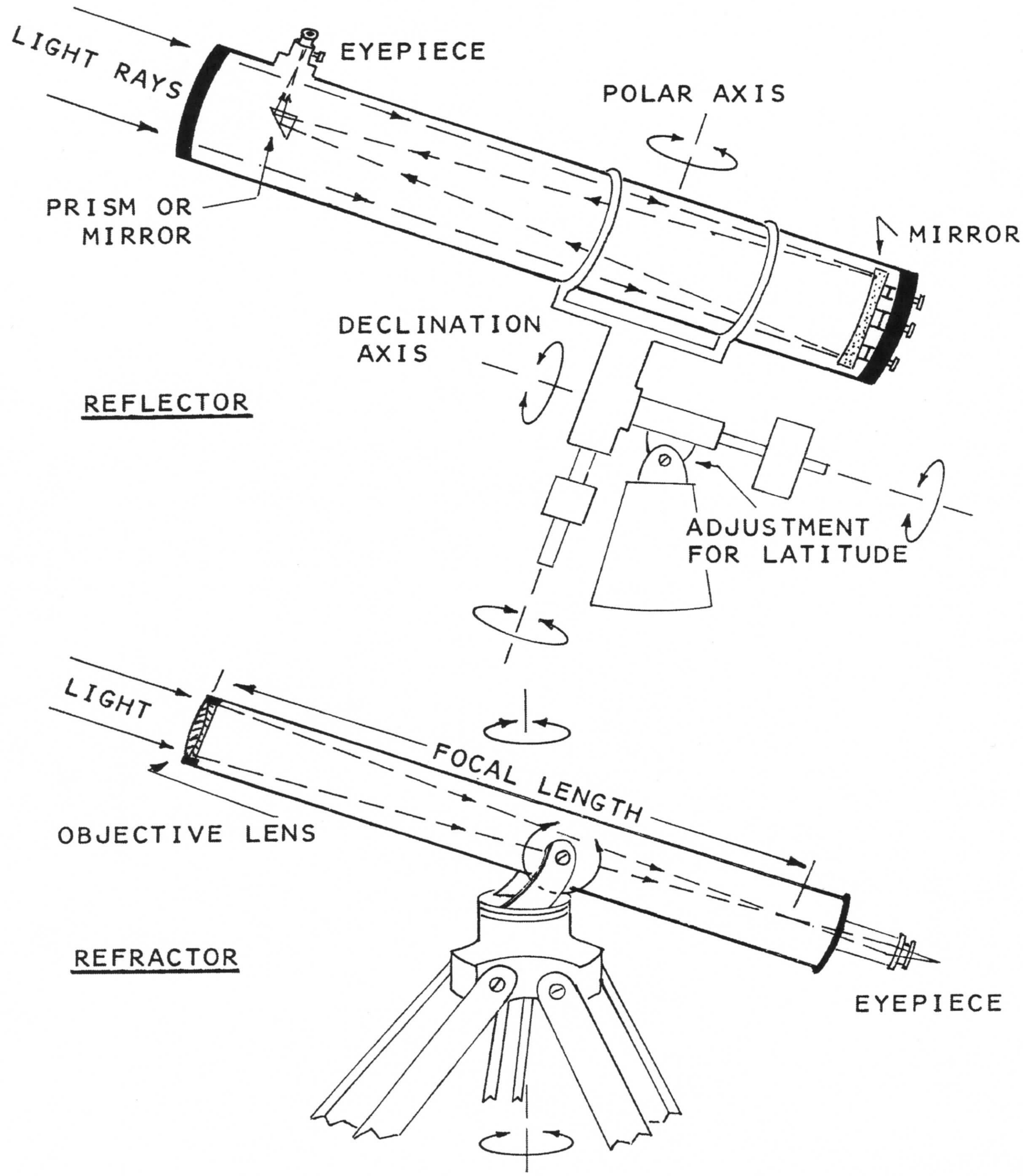
where $D$ is the aperture of the objective, $M$ is the magnification, and $d_e$ is the diameter of the pupil of the eye. The pupil when fully open for nighttime vision is about three tenths of an inch in diameter. (The size of the pupil varies, of course, from one individual to another, but three tenths of an inch is a good average.)

Telescopes waste some of the light they take in. Much of it is lost by partial reflection and absorption at the objective lens (or by poor reflectivity of the primary and secondary mirrors in reflectors) and by absorption in the eyepiece. In reflectors the loss is about 38 percent; in refractors it is slightly less—about 36 percent. If we take 37 percent as an average value for any instrument, only 63 percent of the light gets through the telescope. This percentage loss appears as the transmission factor (t.f.) in the formula above. This formula is for use with telescopes up to 7 inches in diameter. Above this size, because of the increasing thickness of the objective lens of the refractor, the reflector becomes superior in light-grasp.

In spite of the fact that telescopes actually waste light, they are still infinitely superior to the human eye as light-gathering instruments. We can see that this is true by applying the formula given above, ignoring magnification for the moment:

$$\text{light-grasp} = .63 \times \frac{D^2}{.3^2} = 7D^2$$

As a rule of thumb, then, for telescopes up to 7 inches of aperture used at the same magnification, the light-grasp equals the square of the aperture multiplied by 7. As an example, let us take two telescopes of 3-inch and 6-inch aperture, respectively. The light-grasp of the 3-inch is 63 times as great as that of the human eye and the light-grasp of the 6-inch is 252 times as great! The point of this discussion is that if you are interested in the very faint objects of the heavens, the aperture of your telescope is very important. Stars and other objects




The mirror in the reflecting telescope serves the same function as the objective lens in the refractor: Both bring light rays to a focus, where the image they produce can be examined by an eyepiece. Two types of mounting are shown—The reflector is mounted with one axis parallel to the axis of the earth, while the refractor's main axis is parallel to the plane of the observer. However, either type of telescope may have either type of mount.

that cannot even be seen with small telescopes immediately become visible with large ones.

### STELLAR MAGNITUDES

How do we measure the brightness of a star? Apparent star brightness, or *apparent magnitude,* is based on a system in which a first magnitude star is 100 times as bright as its sixth magnitude cousin. The limit of human vision, on this scale, is about magnitude 6.5,* and that of telescopic vision is mag-

* A commonly accepted value although, like all values based upon human attributes, it is only an average. Many people have difficulty seeing stars of sixth magnitude, but there are some who can see stars below seventh magnitude on clear, dark nights. A chosen few can, on occasion, pick up stars as dim as magnitude 8.5.

nitude 23 (the 200-inch giant at Mount Palomar in California). As the magnitude decreases in numerical value each star is 2.512 times as bright as those in the preceding group. This relationship gives us a way of comparing brightness. For example, how much brighter than a star of fifth magnitude is one of the second? The difference is three magnitudes, each representing a 2.512 increase in brightness. Then $2.512^3 = 15.85$, or the second magnitude star is approximately sixteen times brighter.

But there are stars brighter than first magnitude. What numbers are assigned to these? The scale is continued into negative numbers, so that magnitude 0 is 2.512 times brighter than magnitude 1, magnitude $-1$ is 2.512 times brighter than magnitude 0, and so on. On this scale Venus at her brightest shines with magnitude $-4.4$, the full moon is about $-12$, and the sun is represented by the figure $-27$.

Actually, there is no star which is *exactly* first magnitude, even though there are about twenty-one which come close. These stars range from 1.48 for Adara to $-1.42$ for the glittering Sirius.

### TELESCOPES AND STAR MAGNITUDES

Now let's apply these facts to your own telescope. What are the faintest stars you can expect to see with it? A rule of thumb is that a 1-inch objective will reveal stars of the ninth magnitude, and the rest can be scaled accordingly. More exact, and much more applicable to our problem, is the formula

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

where $m$ is the magnitude and $D$ the aperture of your telescope in inches. Using this formula and a table of logarithms, we can make a table for various apertures.

**Limiting Magnitudes**

| *D* (*inches*) | *Limiting magnitude* | *D* (*inches*) | *Limiting magnitude* |
|---|---|---|---|
| 1 | 8.8 | 9 | 13.6 |
| 2 | 10.3 | 10 | 13.8 |
| 3 | 11.2 | 12 | 14.2 |
| 4 | 11.8 | 13 | 14.4 |
| 5 | 12.3 | 16 | 14.8 |
| 6 | 12.7 | 18 | 15.1 |
| 7 | 13.0 | 20 | 15.3 |
| 8 | 13.3 | 200 | 23.0 (*approx.*) |

The magnitudes in this table can be converted to relative brightness as they appear to the human eye. Earlier it was pointed out that a 6-inch telescope can pick up stars 252 times fainter than those visible to the unaided human eye. What magnitude would such a star have? By trial and error, or by using some simple algebra,* we find that 252 is the sixth power of 2.512. Therefore the star is six magnitudes dimmer than those seen with the naked eye. But we started with magnitude 6.5, the usual limit of the human eye, and six magnitudes less than this gives a value of 12.5, which compares roughly with the 12.7 listed in the table. This table is only an approximation—it shows the theoretical limits of magnitude for a telescope of given aperture. When seeing conditions are excellent, you may be able to find stars one and a half magnitudes dimmer than those listed. When conditions are poor, you may fail to see stars that are several magnitudes brighter. There are a number of reasons for this variation:

**1. Your own vision.** How good are your eyes and how well do you employ them? When you are looking for faint objects it is best to use averted vision; that is, look out of the corner of your eye. Test the truth of this by looking at some point in the heavens where there is a reasonable concentration of stars—the Little Dipper, for example. You will be able to see some very faint stars at either side of the point on which your eyes are focused. But if you shift your gaze directly toward these stars they will disappear, only to reappear as soon as you look slightly away from them. This happens because your most acute vision is at a point off to one side of the center of the retina.

The quality of your eyesight is, of course, very important in the performance of your telescope. The telescope can do its part within the limit of its capabilities, but no two pairs of human eyes interpret what the telescope presents to them in quite the same way. Perhaps you would like to test your eyes against a time-honored standard. If you can see all the stars in the Little Dipper, you need not worry about oculists. The Pleiades (Seven Sisters) also provides a good trial ground. Five of them seen in bright moonlight is a good score; on a dark night, six is normal, ten is very good, thirteen is exceptional.

**2. The telescope itself.** Defects in objective and eyepiece, dirt on the optical surfaces, a poor reflective coating on the mirror, improper adjustment (collimation) of the optical elements—all are factors that reduce the efficiency of the instrument. You can precisely check your telescope's performance by checking it against the stars of the North Polar sequence. This list of ninety-six stars located near the polar region provides tests for magnitudes between the fourth and the twenty-first.† The excellent charts issued by the American Association

*
$$2.512^x = 252$$
$$x \log 2.512 = \log 252$$
$$x = 6$$

† E. C. Pickering, *Adopted Photographic Magnitudes of 96 Polar Stars*, Harvard Circ. 170.

of Variable Star Observers (AAVSO) list star magnitudes down to the fifteenth.

**3. Poor seeing conditions.** There are many causes of poor seeing conditions, the chief of which is turbulence of the atmosphere. Turbulence may occur at any level from the ground up and, curiously enough, may at times be completely unsuspected as a source of poor telescope performance. Lens-shaped masses of air high in the atmosphere are usually invisible until their rapid passage distorts the image of a star. At ground level, the atmosphere may appear to be completely calm and transparent.

A rapidly falling or rising temperature during the observing period will create changes in the "figure" on your mirror or object glass. The only remedy for the resulting distortion is to wait for the mirror temperature to reach the same level as that of the surrounding air. If your telescope is portable, don't attempt to use it immediately after taking it from a warm house to the cold outdoors. Wait at least half an hour for it to cool off. Air currents within the tube of the telescope—these are caused by differences in temperature inside and outside the tube—also have disastrous effects upon good seeing; again, the only recourse is to wait for the temperature to level. You can recognize temperature effects easily because the stars appear to jump and twinkle.

**4. Background light.** The lights of a nearby town, the presence of the moon, and even the light from a bright star in the field can cut visibility by an amazing amount—sometimes by as much as 50 percent.

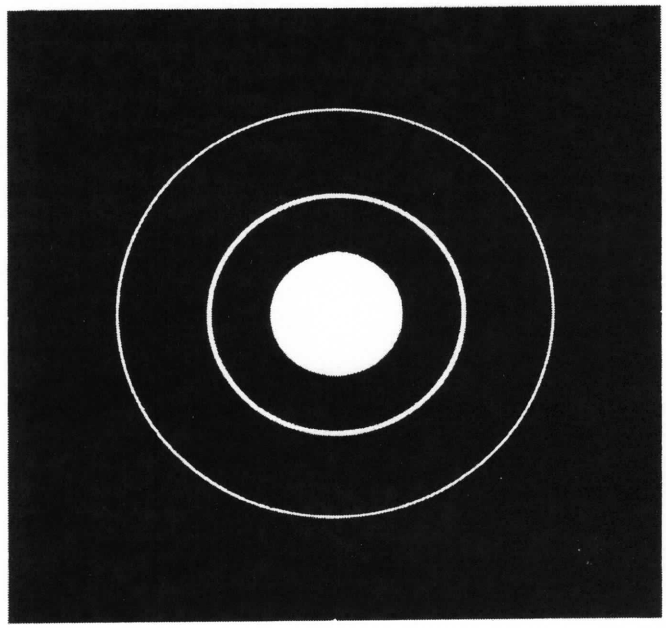
**5. Excessive magnification.** Ordinary magnification has little or no effect on the visibility of point sources such as the stars. When the optics of the telescope are pushed to their magnifying limit, however, the attenuation of light from dim objects such as nebulae, faint clusters, and distant galaxies may become so great as to make them invisible to the viewer.

### SOME CONCLUSIONS

The light-gathering power of your telescope is one of its most important qualities. It is the factor that determines the visibility of objects far up in the scale of magnitude—the dim comparison stars used in variable star work, faint nebulae, the distant planets, and the feeble light of many galaxies. Some authorities think that a 6-inch reflector or a 4-inch refractor is the smallest useful telescope for planetary work, and they recommend larger instruments. Yet even if your telescope is small there are many objects you can find and observe with it. Even a 2-inch refractor will pick up objects as faint as the tenth or eleventh magnitude under good seeing conditions!

## Resolution

Because light travels in waves rather than in a straight, undeviating line, the light produced by a star can never be focused to a sharp point. These light waves, wiggling up, down, sideways, and at all possible angles to their line of travel, produce in a telescope a bright blob called a *spurious disk* or, in honor of its discoverer, *Airy disk.** At definite



Diffraction pattern: An out-of-focus star image has interference rings where light is diffracted.

distances from this disk the light waves interfere with each other and cancel each other out. At such distances a dark ring is formed around the spurious disk. At other points, however, the waves reinforce each other and produce bright rings. The resulting image, a bright central disk surrounded by alternating bright and dark rings, is known as a diffraction pattern. About 86 percent of the light from the star is concentrated in the central disk; the remainder is distributed through the illuminated rings. Because of this concentration, the rings of many stars, especially the fainter ones, may not be apparent.

The fact that stars observed through a telescope do not register as points of light, but as disks, is very important, for the size and distribution of these disks determine how much detail will be evident. For example, if two stars are so close together that their disks overlap, they will appear as one. So, to determine what double stars you can expect to separate you must know something about the rela-

* Named for Sir George Airy, Astronomer Royal at the Greenwich Observatory from 1835 to 1892.

tionship between the size of spurious disks and the aperture of the telescope.

There are two formulas that can be used to measure spurious disks; one gives the disk's *linear* size, the other its *angular* size:

$$\text{1. linear radius of disk} = \frac{1.22\,\lambda\,F}{D}$$

where $\lambda$ = the wavelength of green-yellow light, .000022 inch
$F$ = the focal length of the telescope in inches
$D$ = the aperture of the telescope in inches

This first formula shows that the linear size of the disk is very small indeed. As an example, the typical instrument built by many amateurs (56-inch focal length, 8-inch diameter) produces a disk only two ten-thousandths of an inch in radius.

$$\text{2. angular radius of disk} = \frac{1.22\,\lambda}{D} \times 206{,}265$$

For our purposes, this second formula is the more important of the two, because it is the *angle* between two objects that determines whether or not we can distinguish one from the other. But each formula shows that the radius of the disk is inversely proportional to the diameter of the objective producing it. In other words, a larger aperture produces a smaller disk. Why is this important? Well, as we learned earlier, if the disks of two stars overlap, the two stars appear as one.

### DAWES' LIMIT

If the spurious disks of two stars overlap only enough so that the center of one lies in the first dark ring of the other, each can be seen. The distance between them must be equal to the radius of one of the disks. You can find the resolving, or separating, power of your telescope from the above formula.

$$R = \frac{1.22\,\lambda}{D} \times 206{,}265^{*} = \frac{5.45 \text{ seconds of arc}}{D}$$

In practice, however, this limit is even lower. As the result of a series of tests made with various apertures, the great English astronomer W. R. Dawes established a practical value of

$$R = \frac{4.56 \text{ seconds of arc}}{D}$$

which is still used as a standard for testing the resolving power of telescopes. Suppose, for example, that you have a 3-inch refractor. Its resolving power, using Dawes' criterion, should be 1.52 seconds of arc and your telescope should show clear separation between two equally bright stars separated only by this amount in the heavens. A list of double stars is given in the star atlas. Try your telescope out on pairs above and below this theoretical value, but remember that in such a test there are several additional factors you must take into consideration:

**1.** As in tests for light-gathering power, the test for resolution is very much influenced by the sharpness of your own vision. How does the resolution of unaided vision compare with that of a telescope? Experiments have shown that the smallest separation of stars that can be observed with the naked eye is in the vicinity of 2 *minutes* of arc, while in a 3-inch telescope the smallest separation is about 2 *seconds* of arc. In other words, the resolving power of a telescope of this size is about sixty times that of the eye alone. You can test your eyes for this kind of vision on a few familiar objects, if you wish. Alcor, the companion of Mizar (which lies at the crook of the handle of the Big Dipper—map 4), is separated from its bright neighbor by about 12 minutes of arc. Good eyes can "split" these two easily on a dark night. Much more difficult is the separation of the two stars that make Epsilon Lyrae (map 5). They lie only 3.5 minutes of arc from one another.

**2.** If the test stars are too bright, or of unequal brightness, the eye becomes dazzled and the lower limit of vision increases. Mizar, for instance, has a tendency to "flood out" its dimmer companion. In fact, if the two components of a double star differ by more than three magnitudes, Dawes' limit must be quadrupled, and if the difference is six magnitudes Dawes' limit increases over seven times. Curiously enough, stars that are of equal brightness but that are dim—say, of the eighth or ninth magnitude—also increase the Dawes criterion. To be safe, find a pair in which each star is around the sixth magnitude.

**3.** As in testing for light-grasp, watch out for atmospheric turbulence, because seeing conditions must be excellent when testing for double-star separation. If the light from the stars varies or if the stars jump around in the field of view, wait for another night. The best time to test for resolution is when stars seem to glow rather than twinkle.

**4.** Finally, refractors are slightly inferior to reflectors in resolving power, assuming the quality of the optical system to be the same. Even though this difference is small—only about 5 percent—it must be taken into consideration.

Now let's sum up. The resolving power of your telescope is its ability to present detail, and this depends chiefly upon its aperture. Obviously, then, a big telescope is superior to a smaller one in this respect. But before you rush out to exchange your

* In this expression $\lambda$ is expressed in radians. (1 radian = 57.3°.) Since there are 206,265 seconds of arc in a radian, the final result is given in seconds of arc.

3-inch for a bigger model, remember that an increase in aperture also increases the effect of atmospheric disturbances, and that you can take advantage of your new telescope's greater resolving power only when the seeing conditions are good. So if you live in a locality where the skies are troubled —a big city or an industrial area—you may actually be happier with your smaller telescope.

## Definition

Definition is a term applied to the extended image of an object, such as the moon or a planet. It refers mainly to the fidelity of the reproduction of the object in all parts of the image, and this, of course, includes sharpness of the image and the amount of detail in it. Although definition depends to some extent on the resolving power of the telescope, and therefore is also a function of the aperture, it depends chiefly on the quality of the optical system.

The image of any extended surface, such as the moon, is composed of diffraction patterns formed by light coming from a multitude of tiny areas. If these light patterns were of equal value, they would form an overlapping pattern to the extent that *no* resolution would be possible and therefore no detail could be seen. Fortunately, different light values produce spurious disks of varying intensity, and this is what creates the image. Each part of the surface of the objective is instrumental in building up the final image, so absolute uniformity in the delicate curvature of the optical surfaces is of paramount importance. This is why definition depends to such a large extent upon the quality of the optical system.

Dawes' limit, which is so important in the separation of double stars, does not apply to extended images. You can distinguish objects much closer together than the Dawes criterion calls for, sometimes separated by as little as one fifteenth of the amount theoretically possible. As an illustration, the Cassini Division (the fine dark line between two of the rings of the planet Saturn) is only .5 second of arc in width. But it was discovered with a 2½-inch telescope!* Applying Dawes' formula, such a telescope should have been capable of separating objects no more than 1.8 seconds of arc apart. Thus the instrument was performing three and one half times better than Dawes' limit predicts.

We shall in many instances refer to telescopes in terms of definition. No matter what other qualities your telescope may have, its ability to produce sharply defined images is the final measure of its performance.

## Magnification

Magnification is what is usually referred to as a telescope's "power." It is, of course, only one of the "powers" which the telescope possesses, for the final image depends on the capability of the telescope to collect light (light-grasp), to produce detail (resolving power), to present a clear image (defining power), as well as to enlarge the image. But it is clearly one of the most important functions of the telescope, without which most of the other "powers" would be meaningless. The total magnification of a telescope depends on objective and eyepiece acting in unison; each plays a part in the process.

### MAGNIFICATION BY THE OBJECTIVE

The size of the image produced by the objective at its focus (called the *prime focus* of the telescope) depends only on focal length. This is given by the formula

$$\text{image size (inches)} = \frac{\theta F}{57.3}$$

where $\theta$ is the angular diameter of the object as seen from the center of the objective, $F$ is the focal length of the telescope in inches, and 57.3 is the number of degrees in a radian.

Let's suppose you have a telescope of focal length 48 inches, and want to make a practical application of this formula. Train the telescope on a 1-foot rule placed 100 feet away, remove the eyepiece, and bring a piece of ground glass (semitransparent paper will do) up to the focal plane. When the image of the rule is in sharpest focus, measure it with a pair of dividers. You will find it to be about ½ inch long.

The angular height of a 1-foot rule at a distance of 100 feet is 36 minutes of arc. Substituting into the equation, we get

$$\text{image size (inches)} = \frac{36 \times 48}{57.3 \times 60} \text{ or .51 inch}$$

Having verified our formula by experiment, we can use it to find the size of the image formed at the focal plane if we know the angular size of the object at which we are looking. This is very important in astronomical photography, where we wish to know the actual dimensions of the image as it is formed on the photographic plate. Take, for example, the moon, whose angular diameter is 31 minutes of arc. If we plan to take its picture at the prime focus of a telescope whose focal length is

* Cassini's discovery is all the more remarkable because his telescope was over twenty feet long, and its mounting was none too secure. Guiding this elongated pencil of a telescope must have been a task in itself, to say nothing of seeing anything with it.

forty-eight inches, we should expect to get an image size of six tenths of an inch.

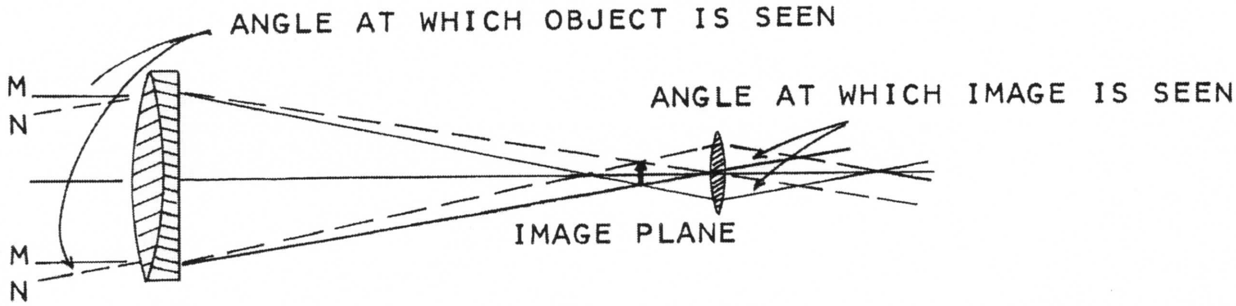
### THE NATURE OF MAGNIFICATION

How can we consider the result of the experiment with the foot rule as magnification? All we seem to have done is to reduce an object twelve inches long to an image that is only one half inch in length. The key to the riddle is the distance of the *eye* from what is seen. After all, the rule was one hundred feet away from the eye and its twelve inches of length seems much shorter than the half-inch image which is close to the eye.

dary magnification is large and the magnification of the telescope is also large. The total magnification is in inverse proportion to the focal length of the eyepiece. But there is a limit to the minimum focal length of an eyepiece, as we shall see later on, so the focal length of the objective is of prime importance in magnification.

To sum up, we may say that magnification in a telescope is in inverse proportion to the focal length of the eyepiece and in direct proportion to that of the objective. We can write this relationship as

$$M = \frac{F_o}{F_e}$$




The nature of magnification: An object appears to be larger when seen through a telescope because the viewing angle is larger.

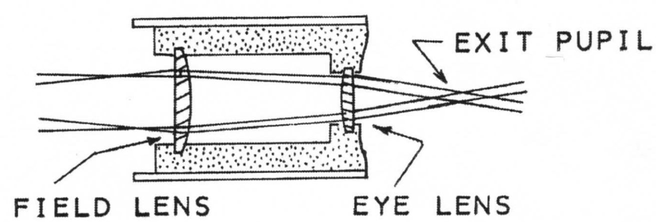
To make this point more real, try this practical demonstration. Support a fifty-cent piece in an upright position on a shelf about three feet away. Now hold a dime between the fingers and bring it slowly toward the eye, looking at both coins simultaneously. The coin closer to the eye appears larger than the other, and as it approaches the eye, the difference between the two becomes increasingly great. This illusion is caused by the difference in the angular diameter of the coins. Because the fifty-cent piece is seen at a greater distance, the angle it makes with the eye is smaller, and it therefore appears smaller than the dime.

### THE FUNCTION OF THE EYEPIECE

In the coin demonstration, the one closer to the eye is blurred and out of focus. But if you hold a magnifying glass between your eye and the closer coin, you can see both coins simultaneously in sharp focus. The shorter the focal length of the magnifying glass, the closer the coin can be held to the eye, and the greater the apparent difference in size between the two.

A telescope operates under the same principle, except that the image is magnified both by the objective and by the eyepiece. In other words, the objective produces a magnified image of the object; then the eyepiece magnifies this image still more. If the focal length of the eyepiece is short, the secon-

This simple formula is very important because it gives us an easy way to find magnification: Divide the focal length of the objective by the focal length of the eyepiece. Thus, if your telescope has a focal length of 50 inches, an eyepiece with a 1-inch focal length will give a total magnification of 50, while one of ¼-inch focal length produces a magnification




A typical eyepiece.

of 200. To yield a complete range of magnification, therefore, a telescope must have several eyepieces. An alternative is a single eyepiece of variable focal length, a development in telescopes that has grown out of the "zoom" lenses in cameras.

## Limits of Magnification

You probably know that there is an upper limit to magnification—too much magnification destroys the original clarity of the image just as blowing up a photographic print reduces its sharpness. But you may not know that there is a lower limit of magnification as well. In order to discuss this we must bring in exit pupil size, which depends upon the magnification as well as the aperture of the objective. The three factors are related by the formula

$$d = \frac{D}{M}$$

where $d$ = exit pupil diameter
$D$ = aperture of the objective
$M$ = magnification

You can see that if the magnification is decreased, the diameter of the exit pupil must increase. If the exit pupil diameter becomes larger than the diameter of the pupil of the eye (about .3 inches for the night-adapted eye), much of the light will be wasted, for it will be blocked off by the iris. So it is important to use magnifications in which this limit is not exceeded, and the smallest that can be employed without wasting light is therefore

$$M = \frac{D}{.3}\text{, or about } 3D$$

Even this figure, three magnifications per inch of aperture, is high unless the pupil of the eye is opened to its fullest extent. Under bright sky conditions, in which the pupil diameter shrinks, the lower limit of magnification is increased even more. On a bright day, for instance, if you are using your telescope to look around the countryside, the lowest magnification you can use profitably is $8D$. If you have a 3-inch telescope you are probably wasting light if you use it at less than 24-power.

Theory and practice do not always agree about the limit of high magnification; theory sets a much lower limit than practice allows. The minimum diameter to which the pupil of the average person's eye can contract is about .025 inch. If we admit a light beam whose diameter is smaller than this we are wasting eye potential rather than light. Using the formula to find out what the limit might be, we have

$$M = \frac{D}{.025} = 40M$$

or 40 magnifications per inch of aperture. Yet many amateurs who own telescopes with well-figured mirrors or object glasses know that on a good night this limit can be pushed up to $60D$, or even higher. We often find it advantageous to crowd the limit in this way when we wish to separate close double stars. Usually, however, an extended image magnified beyond theoretical limits suffers a serious loss, or dilution, of detail. High magnification also tends to exaggerate atmospheric disturbances, decrease image brightness, and diminish the field of view. Loss of light is the most serious drawback to high magnification. The amount of light gathered by a telescope is inversely proportional to the *square* of the magnification. Thus, when you double the magnification of your telescope you reduce the illumination of any given area of an expanded image to one quarter of its original value. To a lesser degree, this is also true of stars. You can actually magnify the image of a faint star into invisibility!

Yet, within the limits mentioned above, high magnification is something greatly to be desired. On a clear night, look at Mars under low power. Then increase the magnification by using eyepieces of shorter and shorter focal length until you pass the limit of useful magnification. (You can raise this limit a little by using an amber filter to improve contrast.) You will find an optimum value somewhere along the line—one that probably exceeds the theoretical one.

There are many tables that show upper and lower limits of magnification. Most of them are based on theoretical values. The one given below is intended for the average observer using an average telescope under good seeing conditions. It will be useful to you only insofar as the performance of your own telescope approaches that of such an average instrument.

**Magnification Limits**

| *Aperture (inches)* | *Highest* | | | *Lowest* |
|---|---|---|---|---|
| | *Based on theory* | *Based on 60M per inch* | *For average telescope* | |
| 2 | 60 | 120 | 130 | 6 |
| 3 | 90 | 180 | 170 | 9 |
| 4 | 120 | 240 | 210 | 12 |
| 5 | 150 | 300 | 250 | 15 |
| 6 | 180 | 360 | 290 | 18 |
| 7 | 210 | 420 | 330 | 21 |
| 8 | 240 | 480 | 370 | 24 |
| 9 | 270 | 540 | 410 | 27 |
| 10 | 300 | 600 | 450 | 30 |
| 12 | 360 | 720 | 530 | 36 |
| 16 | 480 | 960 | 690 | 48 |
| 20 | 600 | 1200 | 850 | 60 |

## Telescope Field

Telescope eyepieces are designed to cover an area of the focal plane called the apparent field. The angular diameter of this area is usually limited to about 40° by a circular fixed diaphragm, called a stop, placed in the eyepiece itself. The apparent field is limited in this way because the eye itself can take in only about 45° without moving, and because images usually deteriorate in quality as they near the edge of the field.

The true field of the telescope is the angular diameter of the sky whose image is included in the apparent field of the eyepiece or, put more simply, it is the area of the sky you can see through your telescope with any given eyepiece.

You have probably noticed that when you increase the magnification of your telescope the true field becomes smaller and dimmer. The relationship between true field size and magnification can be expressed by the formula

$$\text{true field} = \frac{\text{apparent field}}{\text{magnification}}$$

Suppose you have an eyepiece whose apparent field is 40° and whose focal length is one inch. If your telescope objective has a focal length of, say, fifty inches, this eyepiece gives a magnification of 50. How much of the sky does this combination cover? We can easily find out:

$$\text{true field} = \frac{40}{50} = .8°$$

But if the eyepiece has a focal length of one half inch, the magnification is now 100, and the diameter of the true field shrinks to .4°.

Although eyepieces usually have an apparent field of about 40°, special wide-angle eyepieces may spread as much as 90°. If we use one of these, again assuming a focal length of one inch, then

$$\text{true field} = \frac{90}{50} = 1.8°$$

### FINDING APPARENT FIELD

But suppose you know neither the apparent field of an eyepiece nor the true field of the telescope when you use it. You can then let your telescope find the true field for you by rearranging the formula:

$$\text{apparent field} = \text{true field} \times \text{magnification}$$

From this you can compute the apparent field. The process is a little complicated, but here is how it's done:

Set the telescope on a star, let the star trail across a diameter of the field, and time its passage accurately. Now look up the declination of the star and the cosine of the declination in the star atlas. Then apply the formula

$$\text{true field} = 15 \times \text{time} \times \text{cosine of declination}^{*}$$

Here is an example: You observe the star Pollux (declination 31°59′) under a magnification of 50. You find that when the telescope is held motionless the star takes 4 minutes and 20 seconds to go across the field. Thus

$$\text{true field} = 15 \times 4 \text{ mins } 20 \text{ secs} \times .8479$$
$$\text{true field} = 55\tfrac{1}{4} \text{ mins of arc}$$

This is the true field—in this case less than one degree—and is what you really want to know when you use the eyepiece in your telescope. The apparent field of the eyepiece is

$$55\tfrac{1}{4} \times 50 = 2{,}763 \text{ mins} = 49°13'$$

But you need not use these formulas to find true field unless you have an eyepiece of odd apparent field size. The following table will help you estimate the true field size of almost any combination of apparent field and magnification:

**Table of True Field Sizes**

| | *If the apparent field diameter is* | | | | | |
|---|---|---|---|---|---|---|
| *Magnification* | 20° | 30° | 40° | 50° | 60° | 70° |
| | *the true field diameter will be* | | | | | |
| 50 | 24′ | 36′ | 48′ | 60′ | 1°12 | 1°24 |
| 100 | 12 | 18 | 24 | 30 | 36′ | 42′ |
| 150 | 8 | 12 | 16 | 20 | 24 | 28 |
| 200 | 6 | 9 | 12 | 15 | 18 | 21 |
| 300 | 4 | 6 | 8 | 10 | 12 | 14 |
| 400 | 3 | 4.5 | 6 | 7.5 | 9 | 10.5 |
| 500 | 2.4 | 3.6 | 4.8 | 6 | 7.2 | 8.4 |

### FIELD ILLUMINATION

There is little point in trying to use the complete field that can be taken in by the objective of the telescope. Light rays which come from an object far from the optical axis (the straight line passing through eyepiece, objective, and out into the sky) are bent to such an angle that some of them do not fall into the area of the focal plane taken in by the eyepiece. Such an object will not appear as bright (or as fully illuminated) as those nearer the axis. This is another reason for limiting the apparent field of the eyepiece, and in practice the eyepiece stop is of a size and position to provide equal brightness over all parts of the true field.

### IMPORTANCE OF FIELD SIZE

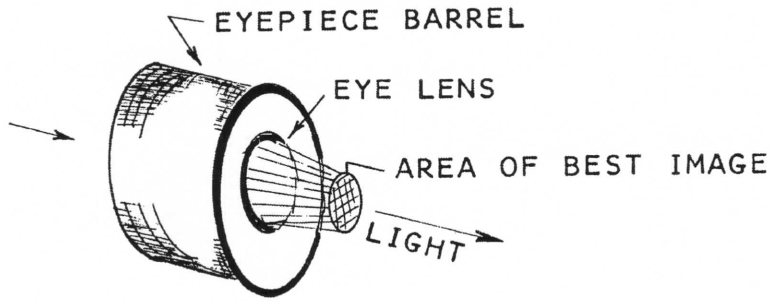
There are many occasions when a wide field can increase your observing enjoyment. Open star clusters or the bright diffuse nebulae observed under high power and narrow fields are often disappointing, for only sections of these beautiful objects are visible. But under low power and in wide fields, these objects can be seen in their entirety and be

* This formula will transform minutes and seconds of *time* into minutes and seconds of *arc*.

really appreciated. Wait for the crisp nights when the sky is transparent,* then train your telescope on the great star clouds in Sagittarius, the brilliant Cygnus area, or the glittering stars of the Perseus double cluster. Views of these objects, as well as of the moon in eclipse, the rare thrill of seeing a comet, and the awe-inspiring spectacle of the Andromeda galaxy, call for low power and a wide field. But on nights of good seeing, when the planets "hang" and the close double stars separate themselves, shift to high power and look for detail.

THE EXIT PUPIL AND FIELD SIZE

The exit pupil is also a very important factor in utilizing full field size. Unless the pupil of the eye and the exit pupil coincide both horizontally and longitudinally, loss in field size results. Field illumination is also greatest at this point. We speak of longitudinal displacement of the eye because there is only one area of the exit pupil, a cross section called the *Ramsden disk,*† where the rays cross




The Ramsden disk: The cross-hatched area is actually an image of the objective of the telescope.

each other. This point is where the eye must be placed. Many eyepieces have a cap back of the lens so that the eye can easily be placed at the point of fullest illumination and widest field. Test the importance of locating your eye at precisely the proper place by moving your head away from the lens. Notice how the width of field narrows. There is a relationship between field size and three other factors: diameter of the eye pupil, diameter of the exit pupil, and distance of the eye from the Ramsden disk. If the difference between eye pupil and exit pupil is .01 inch and the eye is placed .01 inch back of the Ramsden disk, the diameter of the field will be about 52°. If the eye is moved only .01 inch farther back, the field shrinks to 28°!

It is astonishing how many observers sacrifice width of field by failing to "crowd" the eyepiece a little. Of course, the wearer of glasses faces a special problem with short-focal-length eyepieces because the lens keeps his eye away from the Ramsden disk. The only way to avoid this difficulty is to remove the glasses and refocus.

## Optical Deficiencies

The quality of the glass surfaces which produce the image is a very important telescope factor—the *sine qua non* of telescope performance. Your telescope is only as good as its glassware. There are, of course, many other important considerations—trim design, a solid mounting, moving parts that are vibrationless and that work easily in all temperatures, and accessories such as setting circles, slow-motion devices, finders, filters, and the like. But most of these features are added for your comfort or convenience and have little to do directly with how much and how well you can see with the instrument itself.

It is important to remember that when we speak of optical deficiencies we are not necessarily referring to sloppy workmanship or poor quality. The nature of light itself is such that certain image defects can be eliminated only at the expense of adding others; it is impossible to eliminate all of them simultaneously.

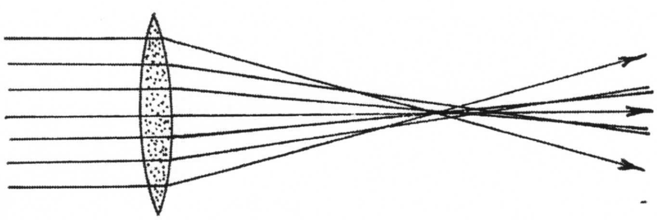
What telescope shortcomings can be attributed to the optical system and what specific aberrations cause them? Unfortunately, the list is rather long, consisting of defects which affect either the quality of the image, its position, or both. Among them are spherical aberration, coma, astigmatism and field curvature, distortion, and chromatic aberration. Space does not permit a full treatment of these defects, so we must be content to point out only the nature of each one, its source, and some ways to recognize it.

* The word *transparent* applies to the atmosphere when it is clear, rather than steady. At such times the stars glitter against the background in their brightest glory. But on nights when the stars *appear* clearest and brightest they are apt to jump around in the eyepiece because of turbulence.

† It is easy to find the exact location of the Ramsden disk for any eyepiece. Point the telescope at the sky in daylight and look at the eyepiece from a distance of a foot or so. The round spot of light which apparently floats in mid-air just outside the eye lens is the Ramsden disk. You can measure its diameter if you move a piece of ground glass toward the eyepiece until the circle of light is in sharpest focus. The distance of the glass from the eyepiece is where your eye should be when observing.

### SPHERICAL ABERRATION

The term spherical aberration refers to the fact that spherical reflecting surfaces do not bring rays from different parts of the mirror to a focus in the same focal plane. But the defect is not limited to mirrors; it is also a shortcoming of lenses. The effect of spherical aberration is a series of poorly defined images spaced along the axis of the objective (a line passing through its center and at right angles to its plane). The point at which the best image is obtained is called, appropriately enough, the *least circle of confusion.* To produce a sharp, well-defined image, a mirror must be curved in the shape of a paraboloid (the three-dimensional curve whose cross sections are all parabolas), and lenses must have a combination of curves for the same result.



Spherical aberration is a defect of both mirror and lenses. The focal plane is not sharp because the rays focus at different points.

If the rays from both the center and edges of the objective fall within an area of very small limiting size, the objective is said to be fully corrected. This area is cone-shaped, and is known as a caustic surface. The cross section of the caustic at its narrowest point is the least circle of confusion mentioned above. Its minimum size is determined by the Rayleigh limit (to be discussed in the next section). If rays from the periphery of the objective focus at a point closer to the objective than those from the central section, the curves are undercorrected. If the opposite is true, they are overcorrected.

A variant of spherical aberration (where the fault lies in the general curve of the surface) is termed zonal aberration. Here the objective has definite zones or areas, each of which has its own focal length. This is an intolerable defect in a professionally made telescope, as it indicates carelessness in workmanship and insufficient testing of the finished product. It is, needless to say, a characteristic of cheap, mass-produced instruments.

Unless of gross proportions, spherical aberration has little effect on resolving power; hence it does not greatly diminish the telescope's capacity for separating double stars. But it reduces contrast in such objects as the planets; thus an improperly corrected objective is a very serious defect.

### *The Rayleigh Limit*

When light is reflected from a mirror or passes through a lens it travels toward the focal plane in a spherical wave front, much as the upper surface of a soap bubble emerges from the bubble pipe. If the objective is perfect, all parts of the wave front are contained in the same spherical surface. If imperfect, the surface has "dents" or "bumps." If these defects are small enough to be contained between two concentric spheres whose distance apart is one quarter of the wavelength of yellow-green light (or the unbelievably tiny distance of 55 ten-millionths of an inch), the objective from which they come can be considered perfect for all practical purposes. This distance is called *Rayleigh's limit.*

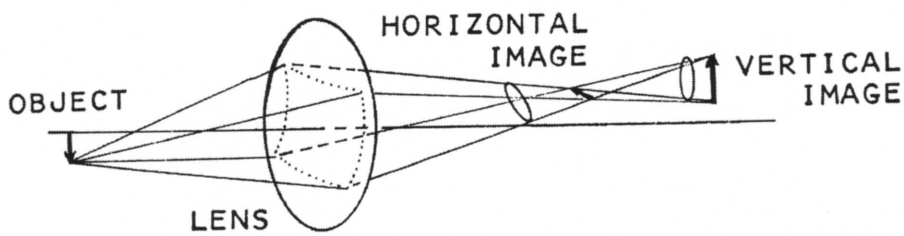
To produce a near-perfect wave front, a mirror can have no imperfection larger than ⅛ wave, or for a lens, ½ wave. This is why good telescopes cost so much. No machine can create curves within these tolerances, and the final work must be done by hand. The Hale telescope on Mount Palomar in California, for example, was polished to the point where no bump or dent larger than two millionths of an inch appears anywhere on the entire 31,400 square inches of its gleaming, curved surface. Even closer to perfection, the 60-inch astrometric (star-measuring) telescope at Flagstaff, Arizona, has no defect larger than 1/30 wave.

In lenses, the tolerances are less exacting because the light is refracted instead of reflected, and the effect of imperfections is less marked. To reduce spherical aberration, a lens can be ground so that the curvature of one convex surface is about six times that of the other. Since telescope object glasses are made up of two lenses, one converging (convex) and one diverging (concave), the four surfaces are ground to share the total refraction as equally as possible. The spherical undercorrection of one lens is thus compensated for by the undercorrection of the other. However lenses can never be completely corrected except for a single wavelength; the one chosen for visual work is the yellow-green part of white light, as we shall see later.

### *Testing for Spherical Aberration*

You can check your telescope for spherical aberration by watching the appearance of a star as you move the eyepiece inside and outside of its position of sharpest focus. Perform this test on a night of good seeing, and wait at least a half hour after you set up the telescope to be sure the optical parts have reached a constant temperature.

Choose a moderately bright star as near the zenith as possible. Focus the telescope; then move the eyepiece inside focus (toward the objective) until you can see diffraction rings around the star. Now move the eyepiece the same distance outside




Astigmatism: The image assumes different shapes and positions for different places on the optical axis.

focus. If the diffraction rings appear the same at both sides of focus, the telescope is well corrected. If your telescope is a refractor, you may be bothered by the appearance of color—a red fringe on the rings when inside focus that changes to green outside. But this phenomenon is normal and indicates no fault in the spherical correction of the objective.

If the objective is overcorrected, you will notice that the image inside of focus is almost the same as at focus; *i.e.*, the central disk remains about the same size and brightness. The only difference in the appearance of the rings is that they diminish markedly in brightness the farther they are from the central disk. The outside focus image has a weak central disk, and the outside rings are much brighter than those near the center. An undercorrected objective exactly reverses the above: The central disk is bright when outside focus and weak when inside. The appearance of the rings is also reversed.

Zonal aberrations in an objective show up in this test as a lack of uniformity in the brightness of the rings, most apparent inside focus in an undercorrected mirror and outside focus in an overcorrected mirror. A word of warning: Don't condemn your telescope for zonal errors on the basis of a single test. Nonuniform changes in the brightness of the rings are difficult to estimate at best, and the trouble may lie in seeing conditions or in the eye rather than the telescope—or even in your mood at the time of the test.

### ASTIGMATISM AND FIELD CURVATURE

Astigmatism and field curvature must be considered at the same time, since they arise from the same source. Astigmatism affects the images of points of light that are not on the axis of the lens; in other words, it affects images other than those in the center of the field. Field curvature is, as the name implies, a condition in which the image lies on a curved surface rather than on a plane.

Astigmatism results either when the incident light from a point source does not strike the objective perpendicular to the plane of the objective surface, or when the mirror or object glass is not uniform in its curvature for all diameters; *i.e.*, when the curve across one diameter differs from that across any other. The result of either condition is a series of images, none of which looks very much like the object it represents, strung along a line parallel to the optical axis. You can check your telescope for astigmatism by observing the same star both inside and outside of focus. Any change in shape of the stellar image as you change the focus is an indication of astigmatism, especially if the pattern rotates 90° on opposite sides of the focus.

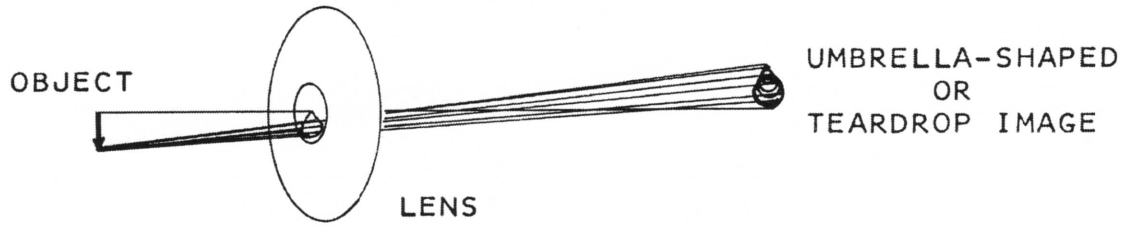
Textbooks on optics define the image seen inside focus as the *primary* image and the one outside focus as the *secondary* image. The best image lies in between, in the least circle of confusion. All three images are curved. Telescope makers can eliminate astigmatism by grinding the lens curves so that primary and secondary images coincide, but this adjustment increases the field curvature in the resulting surface of best focus. If, on the other hand, the primary and secondary images are given equal and opposite curvature, the result is a flat field, but astigmatism is back again! Field curvature being the lesser of the two evils, since it can be corrected to a great extent by the eyepiece, objective lenses are corrected for astigmatism.

An astigmatic objective is fatal to good definition; clear, well-defined images are an impossibility no matter how carefully the eyepiece is focused. Increased magnification does make the defect less noticeable. Furthermore, astigmatism is rarely so pronounced, except in very cheap instruments, that visual observation is ruined. But it is a very serious defect in photographic work, especially when wide fields are used. The photographic plate registers details invisible to the eye, and although the eye compensates to some extent for visual defects, the camera is less kind.

In testing for astigmatism be sure that the defect lies in the objective and not in the eyepiece. You can check the eyepiece by rotating it in its adapter tube. If the aberration rotates along with the eyepiece, try another. If you can spot the same defect with several eyepieces, the trouble must lie in the objective.

### COMA

Coma is an aberration that creates an umbrella-like (or pear-shaped) distortion of images away from the center of the field. Unlike astigmatism, the change in the image takes place in the focal plane, not on either side of it. But like it, the fault lies in images lying on either side of the optical axis



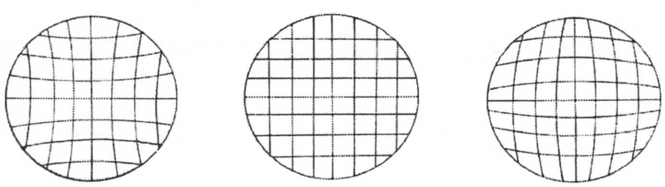

This schematic sketch represents the distortion of an object due to coma. It is characteristic of short-focus lenses and mirrors.

of the objective. As a matter of fact, it is sometimes difficult to distinguish between the two defects because they usually occur together.

Coma is a characteristic of telescopes with large apertures and short focal lengths; it is therefore more likely to occur in reflectors than in refractors. Often it is caused not by faults in the optical system itself, but by incorrect alignment or "squaring on" of the optical elements. If the coma is caused by too small a focal ratio, however, there is little that can be done except stopping down the aperture. While coma interferes with visual enjoyment of the heavens, it is not necessarily fatal to telescope performance.* It is disastrous only in photographic work, for the image is not only malformed but is actually shifted from its true position.

#### DISTORTION

Distortion is the condition by which a square object is transformed to a shape whose sides bulge outward. This is called negative (barrel) distortion; when the sides curve toward the center of the square, the defect is known as positive (pincushion) distortion. Each condition arises from unequal magnification for parts of the image lying at varying distances from the center of the field. An objective that permits equal magnification over all parts of the field is said to be *orthoscopic,* but this is a condition that is rarely fulfilled. Coma and distortion are interdependent; if the objective is completely corrected for coma, distortion is likely to be present.



Distortion: left, "pincushion" distortion; right, "barrel" distortion. The center lens shows no distortion—grid lines are straight and perpendicular to one another.

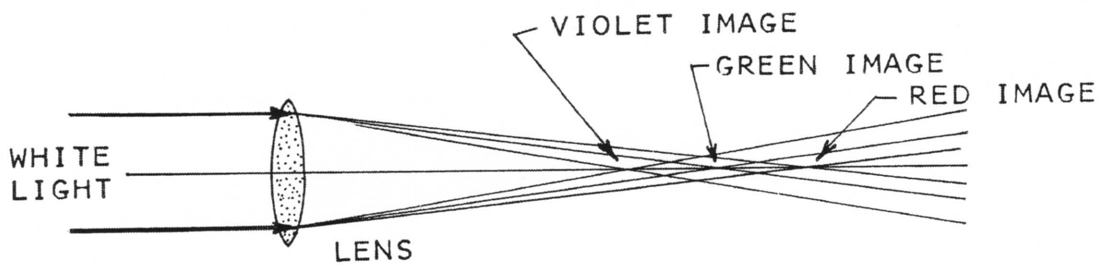
* One of the principal objections to the so-called "richest-field telescope" (RFT) is the presence of coma. But these telescopes are not intended for photographic work; they are designed primarily for panoramic visual enjoyment of the heavens and a certain lack of precision at the edge of the field is the price of their other qualities.

#### DIFFRACTION

Diffraction is a modification of light into patterns caused by the supporting elements of an optical system, not by the optical system itself. A common defect of reflectors, especially Newtonians, it occurs because an object placed in a train of light sets up interference patterns in the light waves. These patterns arise from the same causes and for the same reasons as the Airy disk, but their effect is different. A sharp-edged object placed in a beam of light causes alternate dark and bright lines to form on its shadow, with the brightest lines at the edge of the shadow itself. The "spider" support that holds the secondary mirror or prism in place in a Newtonian reflector is just such an obstacle, and its shadow falls on the primary mirror. But the mirror is also illuminated by light from other sources, so what is reflected to the image plane is not the shadow of the support but the intensification of light at the shadow edges. This light can be seen radiating from the edges of bright stars as tiny projections, or spikes, and it is what gives bright stars their "star-shaped" appearance in photographs.

#### CHROMATIC ABERRATION

The bane of refracting telescopes, chromatic aberration is inherent in lenses, never in mirrors. It occurs because so-called "white" light is actually a composite of all colors, from red to violet. When white light passes through a piece of glass at any angle other than the perpendicular, it is bent, or *refracted.* The smaller the angle at which the light meets the glass, the more it is bent; as a consequence, fat convex lenses have short focal lengths. Some of the colored rays are bent more than others and the light is spread out, or dispersed, into a band of colors, or spectrum. The amount of bending is inversely proportional to the wavelength of the color concerned. Thus violet light, with its short wavelength, is bent away from its path more than the




Chromatic aberration: Because the colored rays into which white light is separated by an uncorrected lens come to a focus at different points on the optical axis, an image formed at any point always has colored fringe areas.

longer wavelength red rays, and it comes to a focus closer to the lens than does red, with the other colors strung out in between. This displacement has two unhappy consequences: first, the images produced by each color do not coincide in a common focal plane; second, they are not equally magnified. The first is called *longitudinal chromatic aberration,* the second, *lateral chromatic aberration.* Their combination in a telescope with a single lens as an objective produces a fuzzy, colored image, much worse in short-focus lenses than in long ones. Because of this fact, the early astronomers made lenses of tremendous focal length. In the late seventeenth and early eighteenth centuries, few refracting telescopes had focal lengths of less than twenty feet and some were as long as two hundred feet.

The wavelengths of visible light range from about 4,000 to 7,000 angstrom units.* These wavelengths can be measured by a spectroscope, each color occupying a fixed position on the spread-out spectrum. In an absorption spectrum, numerous dark lines cross the colored bands, and the position of these lines has been very carefully measured. A line in the red regions at 6,563 Å is called a *C* line, one in the blue at 4,681 Å is the *F* line, and the *D* line appears at 5,890 Å in the yellow region. Color correction in lenses is usually referred to in terms of these lines; the typical correction is for the *C* (red) and *F* (blue) regions.

How is this correction accomplished? The lensmaker takes advantage of the fact that different types of glass may have similar refracting powers but wide differences in dispersion. Combinations of lenses made of different glasses will therefore bring two colors to the same focus. Such a combination occurs when crown glass and flint glass are used as the elements in a two-lens objective. The flint glass corrects the dispersion of the crown glass, although each refracts light by approximately the same amount. When a compound lens is made in this way, with a double-convex (biconvex) crown glass lens placed in front of a plano-concave flint glass lens, the result is an *achromatic doublet.* If the two lenses are separated, the combination is called an *air-spaced* doublet; if the two lenses are glued together with a transparent adhesive (usually Canada balsam) of the same refractive power, we have a *cemented* doublet. Unfortunately it is possible to correct only *two* colors this way. The remaining color is called *secondary spectrum* and it appears to a greater or lesser degree in all refractors. Usually the greater the aperture, the more noticeable the secondary spectrum.

The human eye is most sensitive to yellow-green light (wavelength about 5,500 Å). Since the *C* and *F* lines fall on either side of this wavelength, telescope makers choose glasses of dispersive powers such that the *C* and *F* lines are each shifted toward a common meeting ground, the *D* line.

What is the effect of chromatic aberration and why is it so objectionable? If you were to look through a telescope with an uncorrected objective, you might get the impression that you were looking at a poorly adjusted color television set in a fringe area. Images inside focus would have a red central area with blue fringes on the edges. At focus the colors would fade but the image would not be sharp; outside focus you would see an expanded image, blue on the inside, fringed with red. Even with a telescope corrected for color, the residual color is bothersome. Yet it is only about one twentieth as strong as that of the uncorrected lens.

Secondary spectrum has unfortunate side effects. One is a reduction in light grasp, not serious but still to be taken into account on the over-all performance of the telescope. The other is loss of contrast on extended images, such as the moon and planets. Delicate shadings are obscured or lost in the remaining blue and violet light, although this loss can be minimized by use of a red filter.

Secondary spectrum is not really objectionable, however, unless the aperture of the telescope is greater than 8 inches. But even in telescopes smaller than this, the focal length must increase with aperture. A useful formula for this relationship is that

* 1 angstrom unit (Å) = one hundred-millionth of a centimeter.

the focal length of any refractor must be at least three times the square of the aperture. For example, an aperture of 2 inches must have a focal length of at least 12 inches (f/6), one of 3 inches a focal length of at least 27 inches (f/9), and so on. Most small refractors go well beyond these limits, with f/15 almost standard.

Objectives corrected for color are subject to the other lens aberrations, chiefly coma and astigmatism. Each is present to a considerable degree in the various forms of cemented doublets, although much less so than in air-spaced objectives. The long focal lengths associated with refractors tend to minimize lens aberrations unless they are of gross proportions.

More serious, though, is the fact that the eye and the photographic plate do not react alike to color. The refractor used for photography must be corrected differently from one used for visual purposes only. In the visual telescope, the *C* and *F* lines are shifted to fall close to the *D* line, but for photographic purposes they are changed to fall on either side of the *D* line, with the *F* line in front. A visual refractor can be used photographically only if filters are used to blot up the unwanted colors.