CHAPTER TWO

The Classical Achromat

Achromatic refractors are everywhere. Advertisements for them pop up in shopping catalogs and newspaper supplements. They continue to adorn the windows of camera stores and toy stores. They flood the virtual warehouses of eBay, and even our youngest kids learn to recognize them from the many cartoons that feature them. They form the basis of our binoculars, monoculars, and opera glasses, and our rifle sights and finders for our big telescopes. That said, the vast majority of people are totally clueless about how they really work and how best to use them. A little knowledge can be a very powerful tool, though, and it may surprise you that with only a little bit of background information, you can more easily appreciate your telescope's strengths and weaknesses and how best to optimize its performance.

The year 1824 marks a very special year for the telescope. That was the year in which Joseph Fraunhofer created the first recognizably modern refractor, and chances are the one you own or have owned in the past is built on much the same blueprint. Most modern achromats use a roughly biconvex front element made from crown glass (BK7 most likely) and a near plano-concave flint element (F2 most likely). Both of these kinds of glass are very easy to produce and work with. As an added bonus, they are remarkably stable and weather resistant, so they should last several lifetimes if well cared for.

Later optical masters introduced slight modifications to the Fraunhofer prototype, most often to cut costs. As we saw in chapter "The Refracting Telescope: A Brief History", the Fraunhofer doublet consists of two lenses, an outer crown element and an inner flint element separated by a

small air gap. So there are four surfaces to shape. The outside surface of the crown lens (the surface exposed to the air) is usually denoted by R_1 and its inner surface by R_2. Similarly the outer surface of the flint glass is denoted by R_3 and the surface nearest the eyepiece (innermost) is R_4. Opticians define curvature as positive if it curves outward and negative if it curves inward. What's more, the amount of curving is denoted by a parameter known as the "radius of curvature." The greater the radius of curvature the more gently the lens curves. The signs are reversed for the back surface of the lens: if R_2 is positive the surface is concave, and if R_2 is negative the surface is convex. So, in an air-spaced achromatic doublet, just four radii of curvature need be specified in order to distinguish, say, a 'typical' Fraunhofer doublet from a Clark doublet. We can use these numbers to quantitatively illustrate the basic similarities and differences between the various objectives built by opticians over the centuries.

Suppose we wish to design a 4-in. F/15 Fraunhofer doublet. A typical prescription might be:

$R_1 = 912$ mm
$R_2 = -533$ mm
$R_3 = -539$ mm
$R_4 = -2,213$ mm

A 4-in. objective produced by Alvan Clark & Sons would have a simpler prescription:

$R_1 = 912$ mm $= -R_2$
$R_3 = -867$ mm
$R_4 = -2,213$ mm

Here's an even easier prescription for a 4 in. It's called the Littrow objective after the Austrian astronomer Joseph von Littrow (1781–1840), who first devised it.

$R_1 = 912$ mm $= -R_2 = R_3$
R_4 is flat

A typical Cooke achromatic doublet from the mid-nineteenth century would have a prescription like this:

$R_1 = 559$ mm
$R_2 = -839$ mm
$R_3 = -786$ mm
R_4 is flat

All of these classical achromatic objectives have air spaces between the crown and flint elements. Typically the separation is very small – about the same thickness as a postage stamp (between 0.02 and 0.05 mm). Although the original Fraunhofer doublet was designed with a narrow air gap, like the one illustrated above, other designs use a wide gap, or indeed others have a narrow gap with the edges of the lenses touching (called a contact doublet) or a bonded (cemented) assembly. The benefits of a bonded assembly are increased mechanical strength, durability, and overall transmission as a result of fewer reflections produced by external surfaces. Appendix 1 lists the types of objectives created by master opticians over the centuries.

Why the different original designs? Well, the Clark objective, for example, requires only three distinct surfaces to shape, as compared with four for the Fraunhofer design. What's more, the Clark lenses can be made thinner than in the Fraunhofer, which, taken together, means that a Clark objective can be produced more cheaply, easily, and quickly than its Fraunhofer counterpart. The optical properties of all of these achromatic doublets are very similar, differing only slightly in their ability to control the various optical aberrations. These early refractor builders, as we saw in chapter "The Refracting Telescope: A Brief History", were tightly constrained by the availability of high-quality glass blanks to grind their lenses. Thus, the basic designs used by the great refractors of yesteryear were driven, as they largely are today, more by economics than the attainment of absolute optical perfection.

That said, there are always mavericks in the field who tried entirely different ways of rendering a high-quality achromatic objective. For example, in the middle of the nineteenth century John Brashear in America and Carl August Von Steinheil in Germany often placed the flint element in front of the crown. The reasons for this are unclear (both designers believed it gave slightly better images than the Fraunhofer prescription), but it could be due to the fact that the grade of flint glass used at the time was slightly more weather resistant than the crown glasses employed at the time. Such 'flint first' objectives are rarely made today. The Steinheil, for example, requires stronger lens curvatures than the Fraunhofer doublet to function satisfactorily. Almost invariably, the Fraunhofer design is the one likely to be employed in the vast majority of high quality commercial achromats produced today and the kind we'll concentrate on.

Modern achromatic doublet objectives are designed to bring two precise wavelengths (colors) of light to a common focus – red (656 nm corresponding to the Fraunhofer C spectral line) and blue green (486 nm corresponding to the Fraunhofer F spectral line). That wasn't always the case, though. The great refractor builders of the nineteenth century chose to

achromatize the F with B line, which lies further into the deep red. This was done to best accommodate the simple eyepiece designs used at the time.

In a contemporary C-F corrected achromat, colors lying outside this range of wavelengths (called the C-F focus) remain unfocused. These include deep red at one end of the spectrum and violet at the other. But that's not a big problem. Fortunately, the human eye is not terribly sensitive to either of these radiations, and for the most part the position of C-F focus imparts a very natural color to the image. In an ideal objective, all wavelengths between the C (red) and F (blue-green) Fraunhofer lines ought to be brought to a single focus, but in practice there is some color spread in the final image. This is what opticians call secondary spectrum and is the origin of the false color (chromatic aberration) seen in almost all achromatic refractors.

The Truth about False Color

It's actually quite easy to see if your achromatic refractor is properly corrected for visual use. Although you can discern a lot in daytime tests, a nighttime star test will be more sensitive. We'll explore star testing in much more detail in chapter "Testing Your Refractor", but here's a brief overview. Take a nice, long-focus 3-in. F/15 instrument. Look at a bright star such as Vega or Sirius (if you live in the Southern Hemisphere) using a high magnification, say 30–50× per inch of aperture. First observe the star at sharp focus. At this focal ratio, our 3-in. refractor should display little or no false color when sharply focused. You'll probably see a faint violet halo around the brightest stars, but that's quite normal. Now rack the focuser outward until the image of the star takes on the form of a bright central spot surrounded by a series of diffraction rings. Look at the color of the rim of these rings. It should appear green or greenish yellow. Next rack the focuser inward, past the position of best focus, until you get a similarly sized diffraction pattern. The rim should now look purple-violet in color.

The amount of residual color observed in an achromat depends on only two parameters; the diameter of the object lens and the focal ratio of the telescope. The latter number is easily found by dividing the focal length of the objective lens by the diameter of the lens. For example, a 100 mm diameter achromat with a focal length of 1,000 mm is said to have a focal ratio of 1,000/100 or F/10.

One neat way of expressing the amount of false color to expect in an achromatic refractor is to divide the focal ratio of your scope by its diameter in inches. This called the Chromatic Aberration (CA) index. For example,

**Equivalent Chromatic Aberration
of Achromatic Refractors**

		F	O	C	A	L			R	A	T	I		O	
obj/mm	obj/in.	3	4	5	6	7	8	9	10	11	12	15	18	20
60mm	2.36	1.27	1.69	2.12	2.54	2.966	3.39	3.81	4.24	4.66	5.08	6.36	7.63	8.47
70mm	2.75	1.09	1.45	1.8	2.18	2.54	2.9	3.27	3.63	4	4.36	5.45	6.54	7.27
80mm	3.14	0.96	1.27	1.59	1.91	2.229	2.55	2.87	3.18	3.5	3.82	4.78	5.73	6.37
90mm	3.54	0.85	1.13	1.41	1.69	1.977	2.26	2.54	2.82	3.11	3.39	4.24	5.08	5.65
100mm	3.93	0.76	1.02	1.27	1.53	1.781	2.04	2.29	2.54	2.8	3.05	3.82	4.58	5.09
120mm	4.72	0.64	0.85	1.06	1.27	1.483	1.69	1.91	2.12	2.33	2.54	3.18	3.81	4.24
127mm	5	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	3	3.6	4
152mm	6	0.5	0.67	0.83	1	1.167	1.33	1.5	1.67	1.83	2	2.5	3	3.33

Conrady standard CA ratio>5
Sidgwick standard CA ratio>3
5" f/9 equivalent CA ratio>1.78
6"f/8 equivalent CA ratio>1.25

Visual levels of Chromatic Aberration
Minimal or no CA
Filterable levels of CA
Unacceptable levels of CA

f/ratio divided by objective diameter in inches=CA ratio

False color levels for different apertures and focal ratios (Image Credit: Chris Lord)

an 80 mm (3.14 in.) F/5 refractor has a CA index of 5/3.14 = 1.59. Most seasoned observers suggest that for false color to be reduced to an almost insignificant level, the F ratio needs to be greater than about three times the diameter in inches (or 0.12 times the diameter in millimeters). So, in order to be virtually color free, a 100 mm refractor needs to have a focal length of 1,200 mm – 20% longer than its actual focal length. That much is borne out in observations of bright stars made with this refractor. High magnification images of bright stars such as Vega reveal a tiny, sharp disc of light, technically known as the Airy disc, surrounded by a faint halo of unfocused violet light.

Many have come to accept the Sidgwick standard (CA index > 3) for an achromat to perform in such a way so as to ensure false color doesn't interfere with the view. Others are less forgiving, choosing instead to adopt the Conrady standard (CA index > 5) as the benchmark, a condition that requires the focal ratio to be five times the diameter of the aperture in inches. Which standard you adopt depends on your own experiences.

Chromatic aberration (false color) shoots up as the diameter of the lens increases and/or as the focal ratio falls. A 4-in. F/5 objective, for example, will display the proverbial 'gobs of color' around high contrast objects if used at moderate or high magnification. Indeed, while you can get clean images up to, and in excess of, 200× with a 4-in. F/10 achromat, you're limited to about 80× or so with the F/5 instrument.

Chromatic aberration does more than just make bright objects appear with purplish fringes; it actually robs the image of critical, high contrast

detail. That's so, whether you're observing by day or by night. During the day, high contrast details of objects such as green leaves set against a bright sky background are drowned out in a purplish haze. This is especially obvious when the magnification used is high. To see how it detracts from nighttime views, think back to the Airy disc one sees when a star is focused at high power. The greater the chromatic aberration, the smaller the fraction of starlight that ends up tightly focused inside the Airy disc. That corresponds to loss of information from the image. Even at lower powers – such as those employed to surf broad swathes of the summer Milky Way – excessive chromatic aberration can noticeably decrease the contrast between the star fields and the background sky.

That said, if you find chromatic aberration objectionable, there are steps you can take to reduce its effects. The easiest remedy is to stop down the aperture of the lens. For instance, stopping down the aperture from 4 to 2 in. results in an increase in focal ratio from F/5 to F/10. The resulting image will be considerably dimmer, but it will also be sharper and far less colorful. Another strategy is to simply filter out some of the unfocused color using either a light yellow filter (a #8 Wratten is good) or one of a variety of so-called minus violet filters. A number of optical companies manufacture these filters – including, Sirius Optics, Baader Planetarium, and William Optics – which screw directly into the bottom of your 1.25- or 2-in. eyepiece. These work by effectively cutting off the violet end of the spectrum reaching the eye. They do work well on the Moon and planets and can indeed allow you to press higher magnifications into service with your telescope but often at the expense of introducing a moderate color cast – usually yellow or green – to the image.

Chromatic aberration is a much maligned problem, judging by the attention it receives in the astronomy forums. But for some, the chromatic aberration presented by a 3- or 4-in. F/10 refractor, say, is really a non issue. The effect is actually quite mild and doesn't appreciably affect the image of even really tough objects like Jupiter. You may not want to bother using a minus violet filter on these instruments either. Indeed, you may come to love the aesthetic effect the purplish halo imparts to your high power observations of the giant planet and close double stars. Bear in mind also that the giant refractors of the past suffered far more badly. Take the greatest of them all, the 40-in. Yerkes refractor. To achieve the kinds of color correction enjoyed by a 4-in. F/12 refractor, it would have to operate at F/120 – as long as a football field! In reality, the giant Clark objective operates at F/19! Many who have the good fortune to look through the Yerkes refractor have reported alarming amounts of color around bright planets, but under good conditions, its superlative resolution and great contrast ensures viewers always come away impressed!

Chromatic aberration is just one of a group of optical aberrations to keep under control when building a good object glass. These aberrations are known as the Seidel aberrations, after an 1857 paper by Ludwig von Seidel; the other four are spherical aberration, coma, astigmatism, distortion, and field curvature.

Fraunhofer was the first person to systematically eliminate two Seidel aberrations that can plague an image, spherical aberration and coma. Let's tackle spherical aberration first.

Spherical Aberration

Coma

Astigmatism

Curvature of Field

Distortion

The five Seidel aberrations
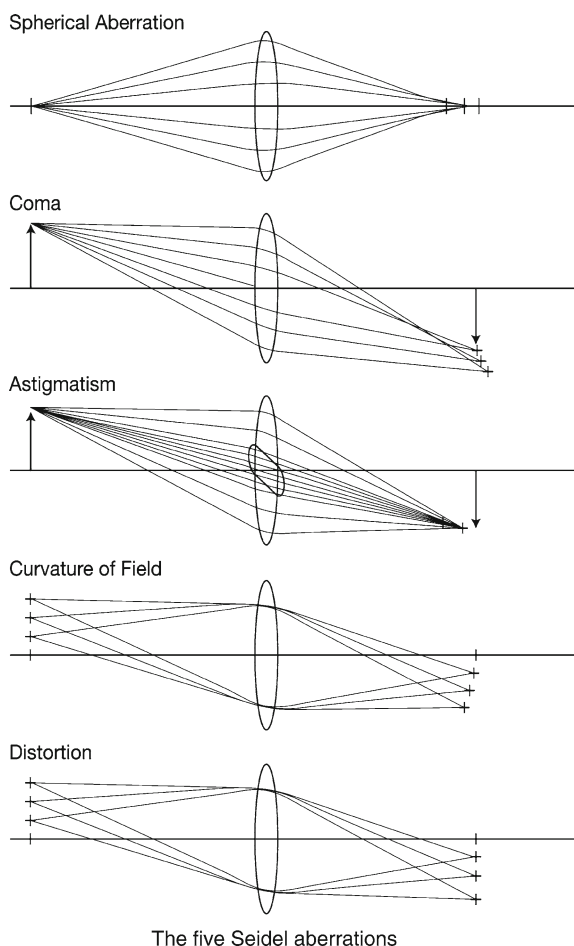
The five Seidel aberrations. Redrawn from a diagram first produced by John J. G. Savard

A perfect lens focuses all incoming light to a sharp point on the optical axis, which is usually along the center of the telescope tube. However, a real lens focuses rays more tightly if they enter it far from the optical axis than if they enter it close to the optical axis. This defect is called spherical aberration. A single spherical lens, of course, suffers from spherical aberration. However, a refractor eliminates spherical aberration by combining two lenses with equal but opposite amounts of spherical aberration. More complex refractor designs may use three or four lenses, but the basic idea is the same. These lenses must also work to eliminate a number of other aberrations, so the design process is tricky, but in the end spherical aberration – and not false color – must be the smallest residual aberration if the telescope is to provide a good image.

So how does spherical aberration impair the image in a refractor? At low magnifications, little or no effects can be seen, but as you crank up the power an instrument displaying significant spherical aberration will be very hard to focus sharply. As a result, high power views of planets and the Moon take on a slightly 'soft,' drowned-out appearance. It might not surprise you that the two aberrations – chromatic and spherical – interlink to create a new hybrid aberration. Spherical aberration actually varies with the color (wavelength) of light considered. Although spherical aberration is normally eliminated in green light (where the human eye is most sensitive), there is a slight under correction in red and a slight over correction in blue. This phenomenon is called spherochromatism and has the effect of blurring the definition of the diffraction rings on one side of focus more than the other. Though usually of only minor concern to the visual observer, spherochromatism may be more of a nuisance to the astrophotographer doing tricolor imaging with filters. Spherochromatism can be reduced by increasing the focal ratio of the objective and by increasing the separation between the crown and flint components. This was, in fact, the method used by the late American astronomer James Gilbert Baker (1914–2005) in the design of his refractors.

Coma is an off-axis aberration. By that we mean that stars in the center of the field are not affected, but the distortion grows stronger towards the edge of the field. Stars affected by pure coma are shaped like little comets (hence the name) pointed toward the center of the field. The effect is particularly common in reflecting telescopes, but, thanks to Fraunhofer, it is rare in modern refractors. That said, there is one type of refractor that can suffer from slightly more amounts of coma compared to the Fraunhofer model described thus far. The majority of high quality achromatic objectives manufactured today are air-spaced. But some small aperture scopes have cemented doublets, that is, the lenses are not separated by air but by some kind of transparent adhesive. Because a cemented objective has the same curvature on the inside surfaces of

the lenses (the second and third optical surfaces) it eliminates two more degrees of freedom from the design and so makes it more difficult to correct for coma.

Another aberration to look out for is astigmatism. This occurs when a lens is not symmetrically ground around its center or, more usually, by misaligned optics. Most of the time, when such a system is misaligned or badly reassembled, slightly out-of-focus stars take on an oblate appearance. What's more, when you flip from one side of focus to another, the oval flips orientation by 90°. In focus, images appear distorted, too.

Both distortion and field curvature were never hot topics of conversation in the age of the classical achromat. That's because these aberrations only manifest themselves to any appreciable degree in refractors with short focal lengths. Field curvature is easy to spot. First, focus the star at the center of the field and slowly move it to the edge of the field of view. If you have to refocus it slightly to get the sharpest image then your telescope is probably showing some field curvature. Distortion is usually seen when using wide-angle eyepieces on short focal ratio scopes. It comes in two flavors – pincushion (positive distortion) and barrel (negative distortion). These are best seen during daylight hours by pointing your telescope at a flat roof and looking for bending of the image near the edges of the field. Distortion is very hard to correct completely, and only the best (i.e., most expensive) eyepieces seem to be able to correct for it adequately. The good news, especially if you're a dedicated sky gazer, is that it will have little or no effect on the quality of the nighttime images your telescope will throw up and so for the most part can be ignored.

Other Virtues of Focal Length

There is one all-important lesson to be learned from our discussion thus far. All the Seidel aberrations fall off rapidly as focal ratio increases. Below is a table showing the various aberrations in scale with focal ratio.

Aberration	How they scale
Spherical	$1/F^3$
Astigmatism	$1/F$
Coma	$1/F^2$
Distortion	$1/F$
Field curvature	$1/F$
Defocus	$1/F^2$

As the focal ratio decreases, the severity of *all* of the aberrations that affect a refractor have the potential to increase. So even a well-configured 80 mm F/5 achromatic objective will almost always display more in the way of optical defects – particularly false color and spherical aberration – than even a mediocre 80 mm F/10 instrument. That's borne out by ample testament in the field. For instance, if you desire a good, high magnification view of Saturn's rings, the 80 mm F/5 will almost always produce noticeably inferior views to an 80 mm F/10 used under the same conditions.

We have not mentioned the last item on the list – the so-called defocus aberration. This measures how easy it is to find and maintain a sharp focus. This aberration is more commonly referred to as "depth of focus." Depth of focus (ΔF) measures the amount of defocusing that can be tolerated before the image looks noticeably impaired to the eye and is calculated using the following formula;

$\Delta F = \pm 2\lambda F^2$, where λ is the wavelength of light and F is the focal ratio of the telescope.

Note how depth-of-focus scales with the square of focal ratio. Thus, a F/5 refractor will have $(10/5)^2$, or four times less focus depth than an F/10 scope. This means that, using green light (550 nm) for an F/10 telescope, you need only focus within an accuracy of ± 0.11 mm. The F/5 scope, in contrast, exhibits a much lower tolerance (± 0.028 mm).

What this means in practice is that short focal ratio scopes are more difficult to focus accurately compared with longer focal ratio scopes. Photographers, of course, have long been familiar with this effect. Let's illustrate the result here using a digital SLR. The following two images were taken of the view out a front door. The first picture shows an image of when the lens was opened to F/5.6; note that the privet hedge in the foreground is sharply focused but the background is much fuzzier. Next, the lens was stopped down to F/11 and another picture was taken. Notice this time that the foreground hedge and background trees are much more sharply defined.

To see how defocus aberration affects the telescopic image, think of a bout of bad seeing. During such moments, you'll find it very difficult to find the best focus position. Telescopes with a shallower depth of focus will be more affected by this focussing inaccuracy than instruments that enjoy a greater depth of focus. When the bad seeing subsides, the short focus scope will be found to require more corrective focussing than the long scope. So a F/5 refractor will have to work four times harder to 'chase the seeing,' as it were, compared to a F/10 instrument of the same aperture. As will be explained in the final chapter, depth of focus is a

Image captured @F/5.6 (top) and Image captured @F/11(bottom)

greatly overlooked aid to attaining a steady, comfortable viewing experience, especially when observing the Moon, planets, and double stars. We shall have more to say about this interesting result in the last chapter. The downside of having a long focal length refractor is that it becomes less portable and more difficult to mount. Nevertheless, as we shall see, long focus achromats have been championed by an army of loyal fans the world over who savor their clean, crisp views.

Coatings of Many Colors

Take the cap off your telescope objective and examine it in a well-lit room or the great outdoors. Chances are you'll notice a purple, blue, or green tint (or a mixture of these colors) from the surface of the lens. Indeed the color reflected also depends on the angle from which you view the lens. Your binocular and camera lenses will also show this effect. This lens 'bloom' is due to the presence of so-called anti-reflection coatings deposited onto the surface of the lens. What do they do? Uncoated glass surfaces reflect about 4% of the light shining on them. And if light is reflected off a lens surface it can't help but form the image delivered to the eye. By using an ultra thin anti-reflection coating on the surface of the lens, typically only a few millionths of an inch thick, this light loss reduces to less than 1%. Scattered light from an uncoated lens also degrades the daylight image by reducing contrast. On spotting telescopes that have multiple optical surfaces – lenses and prisms included – images would appear noticeably dimmer and lower in contrast if left uncoated.

The simplest anti-reflection coatings take the form of magnesium fluoride (MgF_2), which can reduce reflections at a surface by a factor of four compared to uncoated lenses. Nowadays, multiple layers of different coating materials are used to reduce reflectivity by another factor of four, so total light loss can be reduced to about one quarter of a percent. Multi-coatings can reduce reflections so effectively that they can make the lens almost disappear when viewed from a certain perspective.

It's important to appreciate the terminology behind lenses using anti-reflection coatings. Coated lenses have a single layer, usually magnesium fluoride, deposited on the lens surfaces. Multicoated lenses have multiple layers of coatings deposited on their surfaces. Fully multicoated lenses (now a basic industry standard) have multiple coatings applied to all lens surfaces. An uncoated lens examined in daylight shows a bright white reflection. In contrast, the reflection from a coated lens will be a more subdued, faint blue color. A multicoated lens shows a faint blue, green, or purple tint when looked at from different angles. As we'll see later in the book, multi-coatings are also very important in multi-element eyepieces, especially when observing bright stars. That said, a single MgF_2 coating applied to the objective can improve light transmission very significantly, so much so that other coatings by and large are designed to improve transmission at wavelengths other than visual wavelengths. This will also be welcome news to CCD imagers, of course, but it is still not proven as to the utility of multi-coatings in visual applications. Some of the finest views come from objectives with only a single MgF_2 layer applied. The term fully multicoated

Antireflection coatings can vary dramatically from scope to scope. (Image by the author)

is somewhat misleading and has been abused by unscrupulous marketing hype. Truth be told, there are any number of different coatings that can be used on a newly crafted lens, and in some cases, depending on the type of glass, a single layer coating can actually have a lower reflectivity than a multi-layer. Indeed, let us go so far as to say that a well-executed single layer MgF_2 coating will perform better than a shoddily executed multi-coating.

Baffled by Baffles?

A good refracting telescope is not simply a high quality lens. The tube it's mounted on is equally important. Even the best lens can give poor results if the optical tube is not well designed.

The purpose of a good refracting telescope is to collect as much useful light as possible and prevent extraneous light from reaching the eyepiece. This is why all quality refracting telescopes are baffled. Baffles are not devices used by makers of cheap department store refractors to limit the aperture of their scopes in order to hide the bad quality of their optics. We should really refer to them as 'diameter restrictors.' In fact, properly designed baffles never reduce the useful diameter of the telescope. Quite the contrary: they allow all light from the observed object to reach the eyepiece, but block light coming from other sources to prevent degradation of the image. By increasing image contrast, baffles will give you a feeling that your scope is "bigger" than it was before; fainter objects will be easier to observe and more details will be visible.
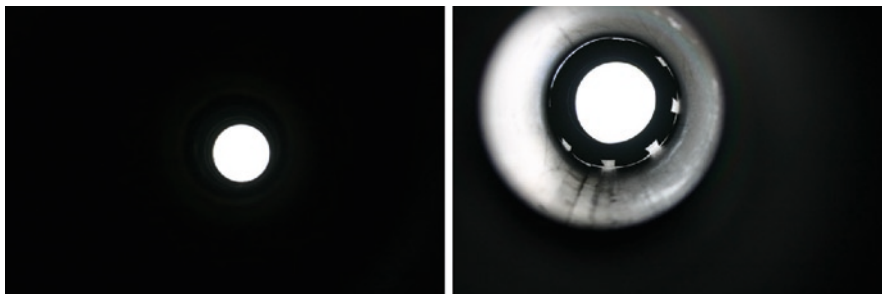
Looking through the tubes of left, a well baffled scope and right, a poorly baffled scope. (Image by the author)

TeleVue telescopes use simple, flocking material to absorb stray light. (Image by the author)

Manufacturers have come up with several different designs to ensure their refractors keep out as much stray light as possible. Most baffles consist of a series of concentric, matte black rings – sometimes called knife-edge baffles – placed at precisely calculated positions along the optical tube and using optical ray tracing. Another approach is to roughen up the inside surface of the telescope tube and dew shield, thereby creating millions of tiny baffles. TeleVue, for example, doesn't really baffle its scopes at all! Its high-performance refractors make do with a simple, dark flocking material that is surprisingly effective at dampening down stray light.

Optical Quality and All That

So how good are the images served up in your telescope? Good? Mediocre? Superlative?

One way of measuring optical quality is to specify how well the objective lens is figured. Because the difference between a good objective and bad objective can be minute, it simply isn't convenient to express errors in everyday units. Instead some opticians prefer to express the error in terms of the fraction of the wavelength of yellow green light the objective deviates from that of a perfect optic. This color of light has a wavelength of 550 nm. One nanometer is one billionth of a meter. A mediocre objective will be figured to an accuracy of ¼ of a wave; that is, the microscopic irregularities in the shape of the lens cannot be more than about 140 nm in order for it to operate satisfactorily under most conditions. Such an objective is said to be diffraction limited, which means that the optics are constrained by the wave nature of light itself and not by any flaws in its optical figuring. Who conjured up this idea? That goes to the nineteenth-century physicist Lord Rayleigh, who reckoned that an image distorted by anything more than ¼ wave of yellow green light would appear obviously degraded to the eye. This is called the Rayleigh limit. Of course, it stands to reason that an objective corrected to an accuracy of say 1/8 of a wave has an even better figure, but would you notice the difference in the field? Careful observers would definitely say yes. A refractor that is corrected to an accuracy of ¼ of a wave will show some nice detail on the planets but not nearly as much as an identical refractor corrected to say 1/6 or 1/8 of a wave. That said, there is a limit to how much the human eye can discern. In typical tests, most people are not likely to see a difference between an objective corrected to 1/8 of a wave and one that is corrected to a 1/10 wave accuracy.

Surface accuracy is all well and good, but it doesn't tell the whole story. Errors in the figure of the lens surfaces making up the objective can lead to increased spherical aberration, coma, distortion, field curvature, and astigmatism (the five Seidel errors), but even a well figured achromatic objective will still display false color, especially at shorter focal ratios. To this end, optical engineers have an even better way of expressing optical quality, which also takes into account how well the objective is color corrected – the Strehl ratio.

To understand this quantity better, picture again the image of a tightly focused star seen at high power through the telescope. The star will not be a perfect point but will instead be spread over a tiny disk of light called the

Airy disc surrounded, in ideal conditions at least, by of series of diffraction rings. This is what opticians call a diffraction pattern. In 1895, the German mathematical physicist Karl Strehl computed what the diffraction pattern of a perfectly corrected lens (or mirror) would look like, with a central peak intensity (representing the Airy disc) surrounded on either side by a series of peaks of progressively less intensity. A *real* lens, on the other hand, will have some optical aberrations that will leave their mark on the diffraction pattern observed. For example, a short focal length achromatic lens will display some false color (chromatic aberration) and so some of the light never gets focused tightly inside the Airy disc, resulting in a decrease in the peak intensity in its diffraction pattern compared to a perfect lens. Other optical errors, such as spherical aberration and astigmatism, for instance, also leave their mark on the diffraction pattern. And yes, it inevitably reduces the peak intensity of the Airy disc.

Strehl suggested that the ratio of the peak diffraction intensity of a real lens (aberrated diffraction pattern) to a perfect lens could accurately predict optical quality. Put even more simply, the Strehl ratio is a measurement of the amount of light put into the peak of the image spot (the Airy disc) in an *actual* telescope, compared to that put in the spot of a *perfect* telescope. It is also noteworthy that the Strehl ratio varies with the wavelength of light used (see figure below). For convenience, most Strehl ratios quoted are measured using green laser light (0.550–0.587 µm). This is called the peak Strehl ratio.

To that effect, some of the higher-end telescope manufacturers routinely quote these ratios as an indicator of how well crafted their optics are. A perfectly corrected telescope has a Strehl ratio of 1.0. A telescope that is diffraction limited (and no better) has a value of 0.8. But some of the best long focal ratio achromatic refractors can have Strehl ratios as high as 0.97 over much of the yellow-green region of the visible spectrum. In contrast, some inexpensive rich field refractors – the short tubes – designed for low magnification observations (such as sweeping the Milky Way at night) can have Strehl values as low as 0.67.

Of course, all of this is merely academic if you already own a telescope and enjoy the views it serves up at the eyepiece. Indeed, it pays to remember that even a 'mediocre' scope used by the modern amateur is optically quite comparable to the very finest available to the nineteenth-century amateur and look where their adventures led them! In the end, it pays to remember that *the eye is the ultimate arbiter of optical quality*.

That brings us to the end of our general discussion on achromatic refractors. Much that has been mentioned in this chapter is generally true of the other type of refracting telescope on the market today – the

Strehl Ratio Vs Wavelength for a 75 mm F/15 Achromat
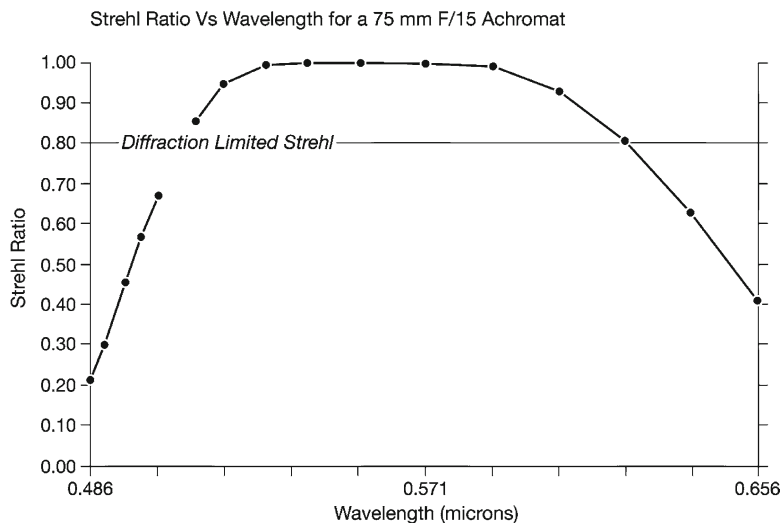
Redrawn from an image produced by Matt Considine

apochromat – which we'll dedicate time to in Part 2 of the book. You can now better understand why your scope behaves as it does and what to look out for in terms of the defects these instruments sometimes carry. For those who wish to dig deeper I can highly recommend Vladimir Sacek's superlative website dedicated to telescope optics: www.telescopeoptics. net. You'll find everything you want and more in there.

Our next port of call is the so-called rich-field achromats – relatively inexpensive instruments that have given thousands of enthusiasts extraordinary views of nature, by day and by night.