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Choosing and Using a Refracting Telescope

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Springer

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Preface

Four centuries ago, a hitherto obscure Italian scientist turned a home-made spyglass towards the heavens. The lenses he used were awful by modern standards, inaccurately figured and filled with the scars of their perilous journey from the furnace to the finishing workshop. Yet, despite these imperfections, they allowed him to see what no one had ever seen before – a universe far more complex and dynamic than anyone had dared imagine. But they also proved endlessly useful in the humdrum of human affairs. For the first time ever, you could spy on your neighbor from a distance, or monitor the approach of a war-mongering army, thus deciding the outcome of nations. Stoked by virginal curiosity or just the chance to make money, men of great skill and patience championed the cause to perfect the art of making and shaping ever finer lenses for an increasingly demanding public.

The refracting telescope – that which uses lenses to form an image – is distinguished from all other telescopic designs by its unique pedigree. Seasoned and perfected over several human generations, the refractor has blossomed into a magnificent array of endlessly useful optical tools. Opera glasses, gun sights, spotting scopes, binoculars, and periscopes all derive their power from the basic designs used in instruments perfected for astronomical investigation.

Although the Galilean telescope enjoyed a healthy future with the general public, astronomers who followed Galileo soon began looking for ways to perfect it. First they made the telescopes long. Then, in the early decades of the eighteenth century, a way was found to make them much shorter and thus more convenient to use. This tendency to downsize, which was instituted nearly 300 years ago, shows no signs of abating in the twenty-first century, when small, ultraportable instruments continue to drive the market. Historically speaking, that's the long and the short of it!

The refractor is without doubt the prince of telescopes. Compared with all other telescopic designs, the unobstructed view of the refractor enables it to capture the sharpest, highest contrast images and the widest usable field. No other telescope design can beat it on equal terms. From a practical point of view, refractors are the most comfortable and least troublesome telescope to observe with. They require little maintenance and cool down rapidly to allow you to observe in minutes rather than hours. Because a refractor has more back focus than almost any other form of telescope, it can accept the widest range of accessories, including filters, cameras, and binoviewers.

A generation ago, small astronomical refractors came almost exclusively in the iconic form of a long tube with a doublet lens objective – the so-called achromatic telescope – made from flint and crown glasses, a prescription that had been frozen into place almost 150 years before. These little backyard telescopes, ranging in aperture from 2 inches up to 6 inches, produced images of the heavens so splendid they kept their owners happy for many years. They had to be made with long focal lengths to counteract the principal flaw inherent to the design – false color (or more technically, chromatic aberration). Simply put, the achromatic objective lens acts like a weak prism, spreading the different colors of light out and causing them to reach focus at slightly different points, some nearer and some further away from the eye. This had the effect of degrading the definition of the image, especially when high powers were employed. And although telescopes could be made to reduce false color to an absolute minimum, the length of the telescope had to increase to keep it entirely at bay.

The first glimmer of a breakthrough came at the very end of the nineteenth century, when British optical engineer H. Denis Taylor produced a triplet objective made with new types of glass to reduce this false color by an order of magnitude or more. These photo-visual triplets represented the first truly apochromatic forms, or refractors that exhibit little in the way of false color around bright, high contrast objects. Although the new Taylor photo-visual triplets found their way into many astronomical observatories, their great expense meant that they remained beyond the reach of all but the most well-to-do amateur astronomers, and that's more or less how the situation remained until the 1970s, when a few intrepid optical designers, experimenting with new and improved types of glass, gave way to a new wave of refractor building the likes of which we have not seen in over 300 years. New kinds of artificially grown crystals, fluorite especially, could be fashioned into objective lenses that could eliminate the spurious color thrown up by traditional achromats. Yet these early "Apos," meticulously assembled by such illustrious manufacturers as Zeiss, Astro Physics, and Takahashi, were still prohibitively expensive to most amateur astronomers and thus remained dream 'scopes for the majority of us.

In the last decade, though, the tide has finally turned in favor of the amateur, with the introduction of a wide variety of high quality Apos available at affordable prices. Ranging in size from ultra-portable (2-inch) 50mm to 8-inch (200mm), there's one to suit everyone's budget. This, together with a wide range of traditional achromatic refractors and spotting 'scopes being sold across the world, means that there's never been a better time to own a refractor for nature study, astronomy, or photography. And that's what this book is all about – how to choose and use a refracting telescope, both astronomical and terrestrial, to suit your purposes.

After briefly delving into the long historical pedigree of the refracting telescope, we'll continue Part 1 of the book by taking a closer look at all aspects of the design and manufacture of both traditional achromats and their various forms (short-tube, medium-, and long focus), as well as looking at some celebrated classic 'scopes from the past. In Part !!, there is more of the same thing, only this time round it's with Apos. By first exploring the very nature of apochromatism, we then provide a comprehensive survey of the various genres of Apo refractors currently being sold, including doublets, triplets, and four-element designs, and discuss the meritorious aspects of a selection of popular models used by amateur astronomers. In addition, there is a a chapter in Part II of the book dedicated to sports optics, those small, highly portable models used by nature enthusiasts and astronomers with a passion for travel. An exploration of the relative merits of buying a dedicated spotting 'scope to the new range of economically priced ultraportable Apos marketed at the amateur astronomy community comes after this. Is an ultra-expensive Leica or Swarovski really in your future?

Maybe you already own one or more refracting telescopes. Then you may find Part III of the book of considerable use. What kinds of accessories might be beneficial to your viewing experience? You'll find some advice in the chapter dedicated to kitting out your refractor. Does your telescope deliver the goods out of the box? We'll be looking at some simple daylight and nighttime tests that can be performed on your telescope to assess its quality. Enjoying your refractor depends a lot on how well mounted it is. Accordingly, there will be a brief survey the types of mounting – alt-azimuth and equatorial – available to skygazers to give you an idea of what best suits you. The well-corrected, unobstructed optics of refractors has made them popular choices for astro-imagers and wild life photographers alike. I'll be sharing some pearls of wisdom that I've learned from some experienced astrophotographers, who routinely use their refractors to create some of the most awe-inspiring celestial portraits ever made.

The refractor has enjoyed an illustrious career spanning the entire history of modern astronomy. But where does its future lie? What's more, now that synthetic ED glass is available cheaply, is it just a matter of time before the humble crown-flint achromat disappears off our radar forever? In the last chapter of the book, we've canvassed the opinions of a number of people who share a passion for the refracting telescope, as well as describing an instrument that helped change the author's own views on the matter irrevocably.

The units discussed in the book are a mixture of the old and the new. Aperture is in units of inches, as this seems to be the way the overwhelming majority of amateurs choose to characterize their instruments. There are also some metric conversions for those few who seem to prefer metric (Do you really prefer 102mm to 4 inches?). In all other matters, standard units are assigned to physical quantities (such as wavelengths of light expressed in nanometers). Technical language has been kept to a very minimum, because it is largely unnecessary to understanding the crux of many of the optical issues discussed in the book. You can always have a look at the glossary and the various appendices if you feel inclined to dig a little deeper.

This book could have been twice as long, so rich and diverse is the history of the refracting telescope. Only a few models within a given genre are discussed. If your telescope has not been mentioned, we apologize unreservedly.

The making of this book was an adventure in discovery, the likes of which I did not expect and I have thoroughly enjoyed the experience. I knew refractors were going to be popular, but I was quite unprepared for the pure, unbridled passion people of all creeds and cultures have for their refracting telescopes. Failing that, if you're just plain curious and would like to know why so many people express such boundless enthusiasm for these instruments, then pull up a seat and enjoy the ride!

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I found this book to be an extraordinarily challenging undertaking, attempting as I was to summarize the current state of affairs in the constantly evolving world of the refracting telescope. Such a task, naturally, could not have been pulled off in isolation. It simply wasn't possible to look through every telescope discussed in the book. And I have a great many individuals to thank for taking time out from their busy lives to answer my questions. Very special thanks are extended to Vladimir Sacek, author and creator of that marvellous online resource www.telescopeoptics.net, to Christopher Lord of Brayebrook Observatory, Cambridge, and to Es Reid, for their many helpful discussions on the refracting telescope. I would also like to acknowledge the wonderful help of Richard Day, founder of Skylightelescopes.co.uk for providing high resolution images of some fine refractors of every vintage, and to Bill Jamieson, who kindly provided his time to reproduce some images for me. Special thanks also to Barry Greiner of D & G Optical for a useful discussion on the future of the achromatic refractor. I'd also like to thank Antony McEwan, Kevin Berwick, Seigfried Jachmann, Clive Gibbons, Brian Grider, Doug Sanquenetti, Bill Drelling, Phil Gulvins, Dave Tinning, Chris Beckett, Ted Moran, Josh Walawender, Stuart Ross, Ian King, David Stewart, Jim Roberts, John Currie, Karl Krasely, Robert Ayers, Pollux Chung, Lee Townend, Ron Laeski, Ted Moran, Nathan Brandt, Frank Bosworth, Geoffrey Smith, John Cameron, J.D. Metzger, and Dennis Boon. Special thanks is also extended to Robert Law of Dundee Mills Observatory for taking the time to show me round the 10-inch Cooke refractor. Finally, I'd like to say a big thank you to Maury Solomon and the editorial team at Springer for a job well done.

Contents

PART ONE

The Achromatic Refractor

CHAPTER ONE

The Refracting Telescope: A Brief History

The history of the refracting telescope is an extraordinarily long, rich, and complex one. Indeed, it was beyond the scope of this book to recount all the contributions made by the many individuals that shaped the long and distinguished history of the refracting telescope. Truth be told, this book could have been dedicated to this end alone!

What follows is an overview of the key players that helped shape the evolution of the refractor over four centuries of history. Those wishing to dig a little deeper are encouraged to consult some of the reference texts listed at the back of the book.

Nobody knows for sure where the telescope was invented. One thing is certain, though. Ancient human societies – the Phoenicians, Egyptians, Greeks, and Romans – were quite familiar with the remarkable properties of glass. Historians inform us that the telescope was first discovered by Hans Lippershey, a spectacle maker from Middelburg, Holland, in 1608. Apparently, he or one of his children accidently discovered that by holding two lenses in line with each other, distant objects appeared enlarged.

However, there is circumstantial evidence that the principle of the telescope was elucidated significantly earlier, maybe as early as the middle part of the sixteenth century. Whatever the truth of the matter, it is clear that by May 1609, the basic design features of the spyglass – using a convex lens as an objective and a concave eye lens – had reached the ears of a

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fiery Italian scientist, Galileo Galilei, while visiting Holland. Despite not having a prototype in his possession, he was soon able to duplicate the instrument, mostly by trial and error. He also managed to increase its magnifying power, first to 9, then to 20, and, by the end of the year, to 30. Moreover, rather than merely exploiting the instrument for practical applications on Earth, he started using it to make systematic observations of the heavens to learn new truths about the universe.

Within 3 years Galileo had made several startling discoveries. He discovered that the Moon had a rough surface full of mountains and valleys. He saw that innumerable other stars existed in addition to those visible with the naked eye. He found that the Milky Way and the nebulae were dense collections of large numbers of individual stars. The planet Jupiter had four moons revolving around it at different distances and with different periods. The appearance of the planet Venus, in the course of its orbital revolution, changed regularly from a full disc, to half a disc, to crescent, and back to a half and a full disc, in a manner analogous to the phases of the Moon. The surface of the Sun was dotted with dark spots that were generated and dissipated in a very haphazard fashion and had highly irregular sizes and shapes, like the clouds above Earth. While they lasted, these spots moved in such a way as to imply that the Sun rotated on its axis with a period of about 1 month.

Many of these discoveries were also made independently by others; for example, lunar mountains were also seen by Thomas Harriot in England before Galileo reported them, and sunspots were seen by the German astronomer Christoph Scheiner. However, no one understood their significance as well as Galileo. His telescopic adventures heralded a revolution in astronomy, providing crucial, although not conclusive, confirmation of the Copernican hypothesis of Earth's motion.

Galileo's instruments, as revolutionary as they were, must have been very frustrating to use. For one thing, the usable field of view was prohibitively narrow, and the design was limited in the range of magnifications it could use. That much was clear to the German astronomer Johannes Kepler, who received a Galilean telescope as a gift from a friend in 1610. Within a year, the great scientist had made significant improvements to Galileo's telescopic design. Kepler replaced the concave lens of the eyepiece with a convex lens. This allowed for a much wider field of view and greater eye relief, but the image for the viewer is inverted. What's more, considerably greater magnifications could also be reached with the Keplerian design, allowing higher power views of the Moon and planets to be made. Another bonus was its ability to project images – very useful for making solar observations.

The Keplerian modification was a good step forward from its Galilean counterpart, but the refracting telescope was still far from the perfection it would reach in the centuries ahead. Simple glass lenses act like weak prisms, bending, or refracting, different colors (wavelengths) of light by different amounts. Blue is bent most and red least. This means that each color has a slightly different position of focus. If you choose to focus on one color, all the others appear as unfocused discs. Indeed, were Galileo able to see in only one color or wavelength of light, the performance of his telescope would have been considerably improved.

The reality for the observer, however, was that bright objects were surrounded by obscuring rings of color; a phenomenon known technically as chromatic aberration. Now, although these color fringes might have delighted a child filled with idle curiosity, they were downright annoying to anyone wanting to see fine detail in a magnified image.

It wasn't long before men of ingenuity devised a panacea of sorts. Optical studies by the French mathematician René Descartes demonstrated that the image quality of convex lenses could be improved my making the curvature of the lens as shallow as possible, that is, by increasing the focal length of the lens. This strategy increases the depth of focus so that the eye can accommodate the spread of colors with an improvement in performance. There was a caveat, however: modest increases in aperture had to be accompanied by huge increases in focal length, making such telescopes less and less manageable.

One of the first individuals to build really long refractors was the wealthy Danish brewer-turned-astronomer Johannes Hevelius (1611–1687) of Danzig, whose instruments reached 150 ft in length. By 1647 Hevelius published his first work, the *Selenographia*, in which he presented detailed drawings of the Moon's phases and identified up to 250 new lunar features. The *Selenographia* influenced many of the great scientists of the emerging Europe, not the least of which were the brothers Constantine and Christian Huygens in Holland. Dejected by the shoddy performance of the toy-like spyglasses offered for sale by merchants, they set to work grinding and polishing their own lenses for the purposes of extending the work initiated by Hevelius. Between 1655 and 1659, they produced telescopes of 12, 23, and finally a 123-ft focal length. Instead of using a long wooden tube to house the optics, as Hevelius had done, the Huygens' brothers placed the objective lens in a short iron tube and mounted it high on a pole. Then, using a system of pulleys and levers, the eyepiece was yanked into perfect alignment with the objective. Christiaan Huygens used a more modest instrument (with a 2.3-in. objective and 23-ft focal length) to elucidate the true nature of Saturn's ring system, as well as its largest and brightest satellite, Titan.

Christiaan Huygens not only built long refractors, he was an innovator as well. Not satisfied by the standard single convex lens that formed the eyepiece of all refractors of the day, Huygens designed a much better prototype, consisting of two thin convex elements with a front field lens having a focal length some three times that of the eye lens. The result was an eyepiece – the Huygenian – which yielded sharper images and slightly less chromatic aberration over a wider field of view than any eyepiece coming before. Curiously, Huygens also hit on the idea of lightly smoking the glass from which his eyepiece lenses were fashioned, so as to impart to them a yellowish tint. This cunning trick further suppressed chromatic aberration, much in the same way as a light yellow filter does when attached to a modern refractor. Huygens also appreciated the benefits of proper baffling in designing his telescopes. Placing circular stops along the main tube, these prevented stray light reflected from the sides of the tubes from entering the eyepiece, thereby greatly increasing contrast. Constantine and Christiaan Huygens produced some monster lenses, too. The largest recorded had an aperture of 8.75 in. with a focal length of 210 ft!

Seventeenth-century telescope makers tested their lenses either in the workshop but especially on well-known celestial objects. In addition, skilled opticians could get a good idea of the quality of a lens from an examination of the reflections off its polished surface. Yet, it is fair to say that these innovators improved their telescopes mostly by trial and error, since a proper, all-encompassing theory of optics was still forthcoming. For example, Hevelius, observing with his 150-ft refractor, spent a considerable length of time measuring the apparent diameters of stellar "discs" in order that he might deduce their true size. So, too, did other great observers of the age, including John Flamsteed and Giovanni Domenico Cassini. It was not until the advent of a complete wave theory of light that such discs could be explained and are, in fact, quite unrelated to the actual diameter of a star.

Soon, the art of fashioning long focus refractors moved south to Italy, where Eustachio Divini in Bologna and Giuseppe Campani of Rome produced the finest telescopes of the late seventeenth century. Such instruments were used by Cassini to discover the gap in Saturn's rings that bears his name, as well as four new satellites of the planet. He also deduced the correct rotation period for the planet Mars, which turned out to be just a little longer than a terrestrial day. With a similar telescope, the Danish astronomer Ole Romer, witnessing a timing glitch in the eclipse of a Jovian satellite, incredibly deduced the speed of light – 300,000 km/s.

Romer is also credited for inventing the meridian transit circle telescope (usually just called the meridian circle), an instrument used for measuring precise star positions and the determination of time. A highly specialized device, the meridian circle is a rigidly mounted refractor positioned along a line passing from north to south through the zenith. A star's position is measured as it crosses, or "transits," a set of crosshairs mounted where the eyepiece would normally be. A star's transit time, measured against a celestial reference frame, provides its celestial longitude, or Right Ascension. A star's altitude can also be measured directly and in turn converted directly into its celestial latitude, or Declination. When developed further in the eighteenth and nineteenth centuries, the meridian circle could be used to measure stellar positions to accuracies approaching 0.05 arc seconds (one arc second = 1/3,600th of an angular degree). Although meridian circles are no longer used, the legacy of the measurements carried out by our astronomical ancestors form the basis of many of our star catalogs today.

Although the largest "aerial" telescopes were certainly difficult to use because of their unwieldiness, the same is not really true of smaller instruments. In a delightful article published in *Sky & Telescope* back in 1992, the planetary scientist and amateur astronomer Alan Binder described his impressions of a homemade seventeenth-century telescope. Calling it the "Hevelius," it sported a 3-in. planoconvex lens with a focal length of 17 ft (F/68). The objective was mounted on an elegant wooden optical tube and hoisted on an observing pole. Altitude and azimuth adjustments could be made by using a crank, cord, and pulley system. Binder also constructed some seventeenth-century style eyepieces of Keplerian and Huygenian design. These eyepieces delivered magnifications of 50×, 100×, and 150×.

Binder went on to study a host of celestial objects including the brighter planets, the lunar surface, and brighter deep sky objects. His conclusions were very surprising. Not only was the 17-ft Hevelius remarkably easy to use, it was comparable to the views served up by his "comparison" scope, a modern 4.5 in. F/7 reflector. False color was remarkably suppressed and only prominent around bright stars and Venus, while spherical aberration was also very well controlled. It had a resolution – based on his studies of tight double stars – only a notch below that of a basic, modern refractor. Indeed Binder goes on to claim that these aerial telescopes were actually better in many ways than the early achromatic refractors (to be discussed shortly) and reflectors produced up until the mid-eighteenth century. Focal length, it seems, was the magic ingredient needed to correct for optical imperfections. Because they possessed enormous depth of focus, the eye was more easily able to accommodate the aberrations inherent to a single lens objective. That said, some scientists were already thinking of ways of downsizing these telescopes into more manageable packages. For instance, in 1668, Robert Hooke suggested using a system of mirrors that, by successive reflections, could "fold" a 60-ft focal length telescope into a box only 12 ft long. His idea, unfortunately, never caught on, not least because of the poor quality of flat mirrors of the day.

Newton's Error

Long focus refracting telescopes were standard equipment at all the major observatories of Europe when Isaac Newton was performing his first experiments in physical optics. Why glass focused blue light closer to and red light further away from the lens was still a profound mystery. Most of the great scientists of Europe at this time considered white light to be pure and all colors to be contaminations of white light. Newton, however, considered an alternative idea – that colors are primary qualities and white light is our perception of their combination.

Beginning in 1663, the great genius, then in his early twenties, began making grinding and polishing machines in order that he could investigate for himself the aberrations of lenses. By 1666, after having performed many artful experiments with prisms, he became satisfied that white light was in fact made up of a rainbow of colors. What is more, Newton despaired of ever finding a glass lens that could bend light without causing the colors to disperse. In other words, Newton came to the firm conclusion that refraction through a glass objective *always* involved dispersion.

It was this conclusion that led him in the end to his reflecting telescope:

> Seeing therefore the Improvement of Telescopes of given length by Refractions is desperate, I contrived heretofore a Perspective by Relexions, using instead of an Object-glass, a concave metal.

Newton's enormous status in the Enlightenment did much to stunt the development of the refractor for many decades to come; a reminder that intellectual brilliance is no guarantee against being dead wrong! But one of Newton's contemporaries did beg to differ. In 1695 James Gregory, then the Savillian Professor of Astronomy at Oxford University, refuted Newton's conclusion that dispersion of light always accompanied refraction. Gregory's inspiration was the extraordinary human eye:

> Perhaps it to be of service to make the object lens of a different Medium, as we see done in the fabric of the Eye, where the crystalline Humour (whose power of refracting the Rays of Light differ very little from that of Glass) is by Nature, who ever does anything in vain, joined with the aqueous and vitreous Humours (not differing from the water as to their power of refraction) in order that the image may be painted as distinct as possible upon the Bottom of the Eye.

Gregory believed, erroneously as it turned out, that the human eye provided sharp images without chromatic aberration. Perhaps it was just such reasoning that led to the next momentous breakthrough in refractor design. For in 1729, the English barrister and amateur optician, Chester Moor

Hall, having experimented with prisms made from two types of glass, one flint and one crown, elegantly showed that one could achieve refraction with little or no dispersion. Moor Hall followed this up by commissioning the construction of the first doublet objective consisting of a concave element made from flint glass and a matching convex element fashioned from crown glass.

Moor Hall was no businessman, however, and thus he never pursued the idea on a commercial basis. Although he kept the design hidden, the secret of the crown-flint doublet was reverse-engineered by a nosy lens maker – George Bass – who happened to be subcontracted to work on both lenses at the same time. News of Moor Hall's marvelous lens spread slowly among the opticians of London, where for the most part, its significance was largely unrecognized. However, all that changed in 1750 when the design was made known to John Dollond, a London instrument maker. After conducting his own – and largely unique – set of optical experiments, he was able to produce a variety of crown flint doublets, which he dutifully presented to the Royal Society in 1758. Meanwhile his son, Peter Dollond, applied for a patent. Moor Hall twice attempted to challenge the patent on the grounds that he was the inventor. The core of Dollond's challenge was predicated on the fact that his firm was the first to demonstrate it to the public and thus should be the first to profit from it. Dollond won his day in court and the rest, as they say, is history.

The name "achromatic" (meaning color-free), however, was first coined by the amateur astronomer John Bevis, who claimed that one of Dollond's 3-ft focal length telescopes "could now produce the same quality image as a non-achromatic telescope of 45 ft focal length." Statements like that make powerful advertising, and soon orders came flooding in from all across Europe to purchase these new achromatic telescopes.

The elder Dollond died in 1761, and the business was re-structured and expanded by his son Peter. While the elder Dollond was a tinkerer and adventurer in optics, the younger was more entrepreneurial in outlook. It is said that he assembled his achromatic objectives largely by trial and error. If a crown-flint doublet didn't meet with his personal standards, the combination was discarded. What's more, we know next to nothing about the methods he used to work his glasses. It seems Dollond preferred to keep his techniques to himself and a few select opticians in his employ – justifiable enough, given his endeavors to establish a major business for a world market. Needless to say, over the next few decades Dollond made a fortune. In 1780 he introduced the "Army telescope" with a mahogany brass bound body and brass-collapsible tubes. Dollond also introduced small "Achromatic Perspective Glasses" and even prism kits (with crown and flint elements) "arranged to demonstrate the principle of the achromatic objective."

Although many of Dollond's telescopes were fine terrestrial and astronomical instruments, residual color, though greatly reduced, was still present, especially around bright stars, planets, and the lunar surface. Dollond's best achromatic doublets were relatively small in aperture (between 2 and 4 in.) and had a fairly long focal length. Unfortunately, as we shall explore in more detail in the next chapter, the precise way in which a crown glass disperses light is always slightly different from a flint. And so the flint does not have the capacity to perfectly nullify the crown's chromatic aberration. This lack of perfection leaves, in all lenses, a residual color error of greater or lesser extent.

Grandfather of spotting scopes, a Dollond terrestrial telescope (Image credit: Richard Day)

John Dollond, pioneer and adventurer in optics, was well aware of the deleterious effects of small amounts of spherical aberration in the images his achromatic doublets threw up. We'll get to the meat of this and other aberrations in the next chapter, but for now suffice it to say that spherical aberration has the effect of rendering high contrast details on planetary and lunar subjects a bit 'soft' and ill defined. Dollond set to work contriving ways of reducing it in new ways that didn't involve extending the focal length of the telescope. Dollond imagined a kind of "modified" flint glass, with the right refractive and dispersive properties to mate with the crown glass in order to reduce spherical aberration still more. Being severely limited in the types of glasses available to him, he hit upon an ingenious idea – what if you use crown glass to “tweak” the dispersive powers of the raw flint so that it mated better with another crown element? In other words, the “triplet” objective uses the natural differences between the refractive (bending) powers of the two types of glass to reduce both chromatic and spherical aberration even more. Largely by trial and error, he managed to create a prototype triplet objective that saw first light in 1757, creating considerable interest from some of the most illustrious astronomers of the age. The then Astronomer Royal Neville Maskelyne was so impressed by one of Dollond’s triplets – a 3.75 in. instrument – that he had it mounted in a small room all by itself. James Short, better known for his contributions to the development of the reflecting telescope, having looked through a similar Dollond triplet at 150× remarked that it “gave an image distinctly bright and free from colors.”

But Dollond’s early triplets, promising though they appeared, never gained much headway in the bustling eighteenth-century telescope industry. Because of their greater optical complexity, they were expensive to make to a consistently high standard. Worse still, the difficulty of crafting large, optical-grade glass blanks meant that their small sizes (5 in. or smaller) prevented them from competing with other telescope designs gaining popularity at the time.

Dollond telescopes slowly replaced the long and awkward simple refractors of the observatories of Europe. Their much greater portability meant that they could be installed on heavy-duty clock-driven mounts and were far easier to operate. But unlike later adventurers in refractor optics, Dollond wasn’t motivated by building larger and larger aperture telescopes. Even by the beginning of the nineteenth century, flint glass discs of flawless quality greater than about 4 in. in diameter were as rare as hens’ teeth. Unless some way could be found to cast large, high-quality glass discs, the refracting telescope would have to stay relatively small.

The Dollond business, centered as it was in England, might well have continued to be the epicenter of refracting telescope innovation were it not for a short-sighted policy of the government. An exorbitant duty was placed upon the manufacture of flint glass, and as a result, the English trade was almost entirely stamped out. Necessity is the mother of invention, and the lack of large high-quality flint glass blanks led some opticians to device novel approaches to the design of the achromatic refractor. One such adventurer was Albert Rogers who, in a paper to the Royal Astronomical Society in 1828, described a Dialyte refractor. Instead of having a full aperture crown and flint objective, Rogers proposed placing a smaller crown element further back on the tube. That would mean that a full-sized flint lens need not be made. The problem with this design was that it introduced significantly more optical aberrations, which made the device impractical to manufacture. The only way around the problem of building large refractors was to solve the problem of producing high-quality glass blanks. And that evolutionary step came from the heart of Europe.

In 1780 a Swiss bell-maker turned optician, Pierre Louis Guinand, began experimenting with various casting techniques in an attempt to improve the glass-making process. After 20 years in the wilderness, Guinand finally hit on a reproducible way of casting flawless glass blanks with apertures up to 6 in. in diameter. Moving to Germany, he was to later team up with some of the most prolific telescope makers of the era, especially the young Bavarian Joseph Fraunhofer. Under the aegis of Guinand, Fraunhofer carefully studied the Dollond doublet objective and introduced significant changes to its design. Fraunhofer made the front surface more strongly convex. He then made the two central surfaces slightly different in shape and introduced a very small air gap between them. The innermost optical surface was nearly flat. Such an objective – the Fraunhofer doublet – was able to bring two colors of light to a precise focus, greatly reducing false color as well as virtually eliminating an optical flaw known as spherical aberration (this renders images a bit "soft" or drained of detail at high powers). Fraunhofer's so-called aplanatic refractors became the new standard by which all future refracting telescopes were measured for more than a century to come.

To get the high-quality glass his telescopes demanded, Fraunhofer also had to develop better grinding machines that depended less on the manual skill of his opticians. He improved the furnaces from which his glass was annealed, thereby removing defects – usually in the form of tiny bubbles – from its intricate crystalline structure. But the crowning glory of Fraunhofer's genius is exemplified by the great 9.5-in. Dorpat refractor, which saw first light just 2 years before his tragic death in 1826 at the age of 39. The famous Russian astronomer and director of Dorpat Observatory, F.G. Wilhelm Struve, commented that upon seeing the instrument, he was unable to determine "which to admire most, the propriety of its construction… or the incomparable optical power, and the precision with which objects are defined." Struve and other astronomers used the telescope with extraordinary high magnifications to survey over 120,000 stars. Equally impressive was the beautiful equatorial mount designed to allow the great refractor to track the stars with hitherto unequalled precision. A slowly falling weight provided the energy to drive the telescope mount, which completed one revolution in a single day. The Great Dorpat refractor remains to this day a monument to human engineering. Indeed, his 9.5 in. refractor compares very favorably to the finest achromats built over the last two centuries.

Model of the Great Dorpat refractor designed by Fraunhofer (Image credit: Institute of Astronomy Cambridge Archives)

Fraunhofer's instruments quickly established themselves as the finest available in the world, and German optics became the standard by which all other rivals were compared. The successors to Fraunhofer's business – Merz & Mahler – used Fraunhofer's blueprint to build even larger instruments. In 1839, they produced the 15 in. (38 cm) refractor at Pulkovo Observatory, Russia, and a twin instrument for the Harvard College Observatory in the United States. It was this instrument that William Bond and Henry Draper used to make the first crude photographs of stars around 1850.

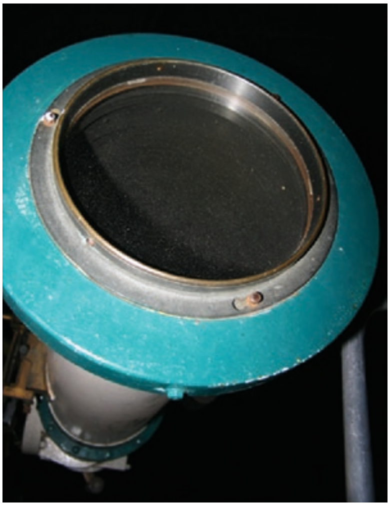
Meanwhile in England, another great telescope maker was making a sterling reputation for himself. Thomas Cooke was born in 1807 at

Allerthorpe, Yorkshire. He received only the merest of formal education, as he had to leave school early to help out in his father's business. But Cooke was bright and curious and read widely. After studying mathematics and optics he attempted to make a small achromatic telescope, and the results encouraged him to start his own optical business in York, crafting instruments and selling them to friends. Inspired by optical giants such as Fraunhofer and Mahler, Cooke invested his time constructing medium aperture equatorially mounted telescopes between 4 and 9.5 in., which found their way into some of the great observatories, first in Europe and then in North America. Cooke's rapid progress was due in good measure to his being able to obtain large discs of optical glass from the nearby city of Birmingham.

The fine 10-in. Cooke refractor at Mills Observatory, Dundee, Scotland

Cooke's largest instrument, the 25-in. Newall refractor, was, for some time, the largest in the world. It took 7 years to build, and some say it was the death of him, for the elder Cooke passed away in 1868, a year before it was completed. This instrument was commissioned by a wealthy amateur, Robert Stirling Newall. The 29-ft optical tube was mounted astride a 19-ft high cast iron pillar on a German-type equatorial mount on the grounds of his private garden in Gateshead. Unfortunately, the great instrument couldn't have had a less favorable position; the sky was seldom if ever clear and steady enough to take full advantage of the telescope's superlative aperture. Writing in 1885, Newall said of the 25 in., "I have had one fine night since 1870! I then saw what I have never seen since." Today, the 25-in. has found a new home at Penteli Observatory, just north of the city of Athens, Greece. It's been there since 1958.

Progress in telescope making in the New World was slow to take off. Indeed, the largest telescope in the United States before 1830 was a 5-in. Dollond achromat. The paucity of public observatories across the nation in the early nineteenth century is evidence enough that the country had not yet fully exploited her latent talent for astronomical adventure. America needed a great lens maker, and it found its answer in a Massachusetts portrait painter named Alvan Clark.



This mid-nineteenth century Cooke achromat had an uncoated lens

An amateur astronomer, Clark tried his hand grinding small mirrors and lenses. As anyone who has performed such a task knows, it's a time-consuming activity. But his patience paid off. Unlike Cooke and Fraunhofer, Clark's approach to practical optics was more intuitive than theoretical. That much became clear when he was first granted an opportunity to look through the great 15-in. Harvard refractor. It was a moment that was to change the course of his life. In his memoirs, Clark wrote,

> I was far enough advanced in the knowledge of the matter (optics) to perceive and locate the errors of figure in their 15-inch glass at first sight. Yet, these errors were very small, just enough to leave me in full possession of all the hope and courage needed to give me a start, especially when informed that this object glass alone cost $12,000.

And start he did, closing his art studio to master the art of figuring old lenses. His first instrument had a 5.25 in. aperture, followed by an 8-in., both of which were as good as any of European origin. Naturally, being an unknown, he at first found it hard to sell his instruments. What he needed was someone with great astronomical gravitas to champion his cause. If the astronomers didn't come to his telescopes, then he'd have to bring his telescopes to them. In 1851, Clark wrote to the prominent English amateur astronomer the Reverend William Rutter Dawes, describing to him the close double stars he had observed with his 7.5-in. refractor. Impressed, Dawes sent Clark a more extensive list of close binary stars for him to split, together with an order for the same object glass!

With his Clark refractor, Dawes later wrote that he had enjoyed the finest views of Saturn he had ever seen. Clark's reputation in England spread like wildfire, and he soon received another order from a certain William Huggins, who had used the lens as the centerpiece for his pioneering work in astronomical spectroscopy. In the summer of 1854, Dawes invited Alvan Clark to London, where he was introduced to Lord Rosse (of Leviathan fame) and Sir John Herschel. These meetings did much to cement Clark's reputation as an instrument maker of the highest order.

A nicely restored 9-in. Clark refractor made in 1915 (Image credit: Siegfried Jachmann)

To this day, very little is known regarding Clark's methods for producing his lenses. Like the Dollonds of the previous century, they left no records of their procedures. But nothing was done in secret, either. The factory often welcomed curious visitors. One snooty caller quipped that the methods employed were crude and inferior to those used by European standards. But Alvan Clark never professed himself to be an optical theorist. He apparently had a very fine intuition for crafting some of the finest refractors in the world. He could apparently detect tiny irregularities on the surface of the lens and often retouched it using his bare thumbs while examining the image at the eyepiece. We do know that polarized light was often used by many nineteenth-century makers – the Clarks included – to inspect their optical glass and the finished lens. The test was as simple as it was telling. Inhomogeneous glass would usually reveal streaks or splotches, whereas a well-made optic would not.

As news spread of the incredible discoveries the Clark telescopes were making in the hands of these astronomical evangelists, it wasn't long before orders for Clark telescopes came flooding in. His first major commission was an 18.5 in. refractor for the University of the Mississippi. Such was the confidence in his own abilities that Clark sold his home to invest in new premises – at Cambridge, Massachusetts – to build and test the new object glass. Accompanied by his two sons, George and Alvan, he constructed a 230-ft long tunnel to evaluate the optical prowess of his objectives on artificial stars. But it was while testing a tube assembly prototype of the same object glass that Clark discovered the faint and elusive companion to Sirius; the white dwarf star we know today as Sirius B. The Clarks went on to build the largest and finest refractors the world has ever seen, the finest of which are the 24-in. refractor at Lowell Observatory used to divine the Martian "canals," the 26-in. instrument at the U. S. Naval Observatory used by Asaph Hall to discover the asteroid moons of Mars, the 36-in. Lick refractor in California and the largest still in existence, and the 40-in. at Yerkes Observatory, Wisconsin. For the record, a 49-in. lens with a focal length of 187 ft was also made by the Clarks, but subsequent tests revealed it to be rather poor optically. The enormous weight and extreme difficulty in casting, figuring, and polishing such large lenses meant that refractors had reached their natural limit in terms of size. Reflectors would go on to win that prize.

No text on the refracting telescope would be complete without mentioning the great Pennsylvanian optician John Brashear (1840–1920), who hand-built excellent instruments ranging in size from 4 to 30 in. in aperture. From school he became an apprentice to a machinist, and at the age of 20 became a master of the trade. At age 21, he went to Pittsburgh and spent the next 20 years there working as a millwright. In his spare time, Brashear educated himself in optics, astronomy, and telescope making. By 1870 Brashear had built his first telescope in his South Side home and immediately opened his doors to neighbors, friends, and strangers to observe the sky. Dr. Samuel Pierpont Langley, the director of the Allegheny Observatory, encouraged him to establish a workshop for astronomical instruments. The workshop became the John Brashear Company, an internationally established maker of superb optics. Dr. Brashear died in 1920, leaving a legacy of craftsmanship and astronomical instruments still treasured and used today. Incidentally, Brashear was the first of the great nineteenth-century opticians to meticulously record his work for others to follow.

Just as the great refractors at Lick and Yerkes saw first light, the era of the super large aperture dawned on the world's stage, and interest in creating still bigger lenses dried up. The technical challenges associated