Acknowledgments

We must thank most especially Mr. Jean Texereau for his advice, support and encouragement.

We wish to thank warmly the people who, through their help and their work, have enabled us to bring this project to fruition: Sébastien Debruyne, Simon Fabre, Gino Farroni, Jean Funel, Richard Nowak, Romuald Oumamar, Gauthier Philippon, Michel Sarrazin, David Vernet, Frédéric Auchère, Georges Beaume, Claire Bigot, Nicolas Biver, Mourad Cherfi, Etienne de Foras, Jean-Bernard Emond, Arnaud Gaillon, Renaud Goullioud, Madani Khezam, Daniel Pasquelin, and the Melles Griot Company.

We would like to thank the Société Astronomique de France, in particular Elisabeth Sablé and Michel Laurent, as well as all of the members of its Commission on Instruments.

For this new edition, we also thank all of the amateurs who wrote to us to tell us their experiences with the first edition. Finally, we are most appreciative for the efforts of our English translator, Christopher Bechtler and our technical reviewer, Harold R. Suiter.

KARINE AND JEAN-MARC LECLEIRE

Preface

Amateur telescope-making literature always has been a kind of swamp through which one must hack and trudge to find the occasional sunny clearings. For every good article or book there seem to be ten that teach the reader only enough to be dangerous. There are many manuals giving decent instructions on mechanical assembly, but for mirror making the information is very thin. One good collection was the original *Amateur Telescope Making*, edited by Albert Ingalls. It introduced novice amateur telescope makers—called "ATMs" long before the money-dispensing machines—to the unfamiliar optical world of pitch and grits, together with the unlikely process of achieving perfection by haphazardly rubbing two disks of glass together. However, even the most reverent admirers of this old book would freely admit that its strength is not in testing. For that, English-speaking amateurs had to wait for Jean Texereau and the translation of his landmark *How To Make a Telescope*.

For the first time, the English-speaking amateur was led systematically through the mathematics and—more importantly—the *practical use* of the knife-edge test, including the time-saving technique of the varying reference curve. While this information had been obscurely implied in earlier works directed toward the amateur, it was either presented at an extremely theoretical level or at a cookbook level, with nothing between. Texereau straddled the gap.

Before Texereau, amateurs often struggled for hours trying to correct a perfect mirror. Their entire reduction technique was predicated on the assumption that the hard-to-measure central zone was exactly accurate. A trivial error here resulted in the rest of the wavefront appearing out-of-tolerance. Still other books used no wavefront reduction at all, relying on the raw longitudinal aberration measurements and the relative insensitivity to error of the slow reflectors being made at the time. After Texereau, amateur telescope-making improved a great deal. Aperture ratios came down and the test-reduction techniques that would enable the large, fast reflectors of today became more commonplace in the amateur world.

It seems exceptional that this first comprehensive mirror-making manual in many years (almost the next after Texereau) should also be a contribution of the French, but perhaps it's not so strange. The French have always delighted in exquisite telescopes and other fine astronomical instruments. Perhaps the excellent seeing at Pic du Midi had something to do with it. Maybe the early 20th-century optical geniuses represented by the great names of Lyot, Couder, Duffieux, and Maréchal influenced the French origin of this work.

In any case, this book by Karine and Jean-Marc Lecleire may look superficially like an updated version of Texereau. Nothing could be further from the truth. The basic knife-edge testing method suggested for slower mirrors may resemble Texereau's, true, but that is just reluctance to interfere with something that works. Where this book really shines is in the extensive corrective measures suggested to cure optical difficulties encountered during figuring. It deals more thoroughly than previous books with figuring the kind of mirrors used today with fast Newtonians or Cassegrain primaries. The Lecleires discuss tests less cumbersome than the Foucault test in figuring these very fast instruments, namely the wire and caustic tests.

Actual images using modern physical-optics theory have been added to provide an air of conviction to statements that have in the past been a sort of received wisdom. Most interesting of these to me is the progression of successively more curved diagonals, showing just when this curvature becomes detectable. I recalculated some of these star-test figures to provide more reproducible digital images, but they existed in the French original.

Lately, there has been a movement toward the Strehl ratio as a statement of quality rather than the peak-to-valley Rayleigh tolerance. Although people argue with good reason that the Strehl ratio is a much better way of specifying the wavefront than the somewhat arbitrary Rayleigh limit, a possible degree of duplicity exists in some manufacturers' preference in barely meeting a Strehl ratio = 0.8 criterion. For example, astigmatism can be as large as ⅜-wavelength peak-to-valley and still satisfy the criterion. One can use the Zernike polynomial expansion[1] to show that the ¼-wavelength Rayleigh tolerance is always a tighter tolerance than Strehl ratio = 0.8.[2] In short, using the minimum Strehl ratio allows manufacturers to make sloppier mirrors than heretofore. Commercial makers should bump up their Strehl-ratio criteria to a little higher than 0.8 if they want to make substantially the same mirrors as they did when they met the ¼-wave Rayleigh limit. Several honest makers won't release an optic unless its Strehl ratio exceeds 0.9, a move of which I heartily approve.

Other than a sidebar discussion of just how the Strehl ratio is calculated, this book does not deal much with it, sticking instead with the Rayleigh limit. Some would argue that this omission is a flaw, but I don't think it is much of a defect. We must differentiate between measures useful in specifying finished optics for contractual arrangements, such as a university buying an expensive mirror for an observatory, and measures useful in actually making a high-quality mirror for personal use. Relying on the Strehl ratio to write a purchase agreement prevents the customer from making unreasonable criticisms against a perfectly good mirror,

[1] M. Born and E. Wolf. *Principles of Optics, 6th ed.*, Pergamon Press, 1980.

[2] Some highly artificial wavefronts can be imagined that do indeed creep below a Strehl of 0.8 for a peak-to-valley of ¼ wave (e.g., such a wavefront from a rectangular-trough diffraction grating has a Strehl = 0.50), but a linear combination of lowest-order Zernikes describes most wavefronts where an effort to fabricate good optics has been made. For these, Strehl = 0.8 occurs for refocused wavefronts deformed at or more than a quarter wave.

such as complaining about the interior of a tiny pit exceeding the ¼-wave limit. Still other customers might carp about a turned edge that has been pushed right to the perimeter, still theoretically breaking the ¼-wavelength limit but in practice having no effect whatsoever. On the other hand, when making a personal mirror, there is very little difference between the utility of either method. You can always refocus the best peak-to-valley wavefront to the minimum Strehl ratio wavefront, or vice versa. After all, you don't need to delude yourself using either tolerance; you are your own customer.

In fact, inferring the Strehl ratio from any measure across a diameter or independent diametric measurements is probably a form of speculative fiction. Any test across a diameter leaves vast areas of the disk unsampled, and it is those areas that are most heavily weighted in the Strehl calculation. The Strehl ratio is only reliable when the testing technique has been generated from the whole mirror, such as from interferometry or the two-dimensional Hartmann wavefront test. In a perfect world, it would seem an excellent practice to *require* all tests across the diameter to use peak-to-valley specification, and to only permit the Strehl ratio to be quoted when a whole-mirror test has been used. That way, we would know not only the tolerance but have some idea of the measurement technique employed.

Likewise, the Lecleires will undeservedly attract criticism for using what is known in English—through Texereau—as the Danjon and Couder criterion number 1 (here the authors abbreviate this as the Couder criterion). Various internet pundits have summarily stated that all slope or, equivalently, transverse aberration criteria have been "superseded" by the Strehl ratio. This conclusion is overstated. There is unique information in the transverse aberration of the zones not contained in any one number wavefront-amplitude criterion, including the Strehl ratio and the Rayleigh tolerance. Surfaces can produce acceptable Strehl ratios and still have objectionable features; not until we used measures like the modulation transfer function do these differences manifest themselves numerically. The most common case: a surface with a rolled edge might meet a given Strehl ratio and still distribute an ugly aura around a bright image. Just because transverse aberration does not predict the diffraction shape of the image does not mean mirror slope as a function of radius is not extremely useful in making a superior optic. Again, the Strehl ratio is a convenient and uniform standard of minimum acceptability, but to deliberately throw away the extra information contained in the transverse-aberration perspective is worse than foolish; it is reckless.

The Lecleires also introduce a test for polish quality and high mirror slopes to the American telescope maker. If you replace the lamp on a standard Foucault tester with a super-bright halogen source, widen the slit somewhat, and move its image until it is just covered by the knife, you see only those small-scale errors with enough slope to throw some light beyond the knife. Even though it uses the same apparatus as the knife-edge test, it is actually an inexpensive variant of the Lyot test, which replaces the knife edge with an attenuating phase plate. Because it is not quantitative, this test gains utility with experience, and only by comparison with good optics. Still, it is a handy tool to add to your bag.

Thus, I come to the end of my comments. I wish you joy at reading what is the first thoroughly new amateur mirror-making manual in forty years. My final bit of advice is directed at those who might want to ask me which manual I recommend, Texereau's or the Lecleires'.

Don't be silly; read both!

Harold R. Suiter
Panama City, Florida
March 2003

Foreword

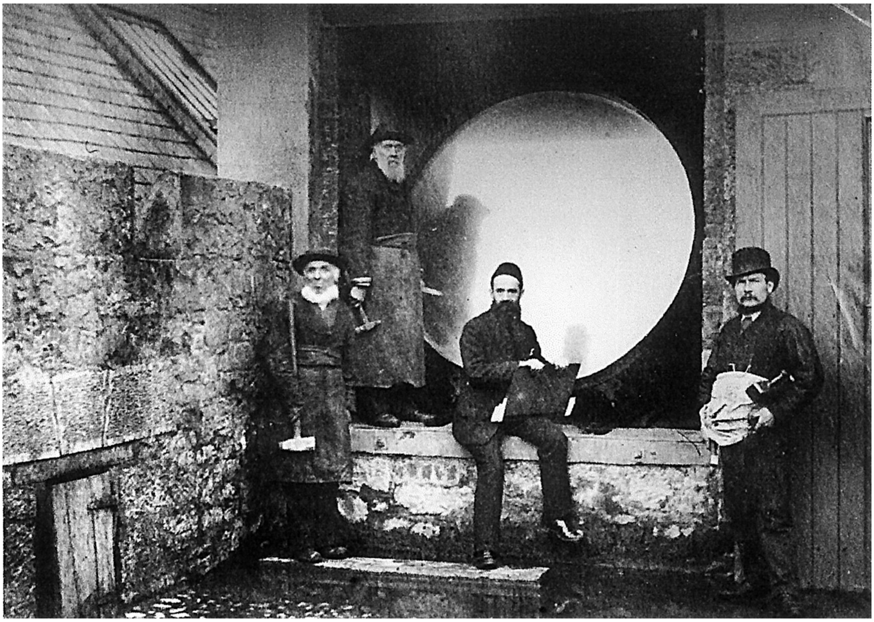
The image of mediocrity usually associated with the work of amateurs is a misconception. On the contrary, amateurs, by the strength of their motivation and dedication, have many chances to stray from the beaten path. Their passion takes them into the realm of productive research and enriches their lives. It is perhaps superfluous to remind those already engaged in astronomy of this; but what is little known, and deserves to be discussed, is that the science of astronomical optics was essentially created and perfected by amateurs.

The English, often more attuned to the concrete than the abstract, have played a dominant role in this development. To begin, we must mention Newton—yes, Isaac Newton. It is not the grave, wigged character, master of the Mint of London, that I wish to evoke here; nor the mathematician of binomials and fluxions; nor the founder of celestial mechanics; and especially not the gawky youth, with his relentless pursuit of mystical subjects like biblical chronology and alchemy. It was Newton, the optician—not only the theorist but, especially, the practitioner—who made the first practical astronomical mirror. This first reflecting telescope, the objective of which measured merely 1⅓ inches in diameter, was considered in 1672 to be superior to long refractors with simple objectives, and it marked the beginning of a fruitful era in the history of astronomical optics.

Artists and professionals, jealous of their secrets, share none of their information with us; but amateurs, sometimes famous ones, make decisive contributions. We know their famous astronomical discoveries very well, remembering here only how they created the indispensable tool, the fruit of patient experiments.

William Herschel was at first an organist and composer. In 1774, helped by his sister Caroline, he began to cast metal mirrors (called *specula*) and to research the best alloys; he eventually made more than 300 mirrors, each one more perfect or larger than the last. He discovered Uranus in 1781 with a simple 16-cm Newtonian *f*/13, and conducted a systematic study of the sky with a variety of instruments, culminating in 1789 with the famous 122-cm telescope that probably required as much effort to use as it did to make.

Lord Rosse was a great landowner who had a large workforce at his disposal in his Irish estate at Parsonstown. Look at the photograph on the next page, of some of Rosse's craftsmen before his colossal 182-cm speculum. Despite the chisel and hammer, he is not about to do any local retouching! The carpenter with the bowler hat has a trying plane under his arm, and the astronomer Boeddicker is holding his portfolio of drawings. This mirror—cast after several attempts, made of a poorly reflective copper/tin alloy, and difficult to polish—was never really



Lord Rosse's 182-cm speculum, photographed at Parsonstown about 1845.

satisfactory; it would have taken a new Herschel to get good results from it. Still, we owe to Rosse the visual discovery of the spiral structure of several galaxies.

William Lassell, a merchant who retired and sought better observing conditions by moving to the island of Malta for three years, constructed the last successful large telescope with a bronze mirror, which he mounted on an equatorial fork. The mirror was 122 cm in diameter and had a focal length of 11.30 m; access to the Newtonian focus required a rather dizzying three-level tower. Lassell was the first to have the idea of supporting the mirror with an astatic lever, one of the best systems still to this day.

The modern era of telescopes employing glass mirrors silvered on the front face opened in 1856 with the work of Léon Foucault. The director of the Paris Observatory at the time was the famous Urbain Leverrier, who was probably less of a pure theoretician than he is normally pictured. He recognized Foucault's genius for experimentation and entrusted the modernization of the observing instruments to him.

Foucault not only introduced glass mirrors, he figured the first 10-cm glass one himself. In 1858, he published all the details, notably the marvellous method of the knife-edge test. This test allows the mirror maker to see the smallest defects, almost to feel them as if he could manipulate them and—for the first time— to retouch them. With the collaboration of two firms, Secrétan and Eichens, he built equatorial fork telescopes of 20- and then 40-cm aperture, and an 80-cm one for the Marseille Observatory.

It is thus the great English-speaking amateurs who first profited from Foucault's contribution. Henry Draper abandoned metal mirrors in 1860; his best instrument was just 39.5 cm in aperture, but he opened the doors to astrophotography, overcoming the disadvantages of his alt-azimuth mounting with a sliding plateholder driven by a water clock to track throughout the shot.

A. A. Common made metal specula, and he was perhaps the last great amateur to do so. After making a good 45.7 cm mirror in 1876, he went on to a 91.5-cm one in 1879. In France, he obtained a plate-glass disk 152.5 cm in diameter and 15.2 cm thick. He tested the surface of this mirror by zonal measurements, and his equatorially mounted telescope went on to become the forerunner of the large photographic telescopes of Mount Wilson that would dominate astronomical research through the first half of the twentieth century.

The origin of the more modest activity of many amateurs can be traced to about 1880 in the journal *English Mechanic,* in which subscribers discussed amongst themselves such diverse topics as the construction of organs, tricycles of unusual design, and telescope mirror making. From 1881 to 1886, a suite of articles by H. A. Wassell brought much information to light; these were reprised in 1909 by C. D. P. Davies and, most significantly, served as the basis for the book by another pastor in 1920: *The Amateur's Telescope* by William F. A. Ellison.

In the United States, the movement grew largely thanks to Albert G. Ingalls, associate editor of the prominent magazine *Scientific American*. He stumbled onto a 1921 telescope-making article by the extraordinary Russell W. Porter, a man of many talents: polar explorer, artist, engineer, optician; a sort of latter-day Leonardo DaVinci. From their collaboration came, beginning in 1926, the famous *Amateur Telescope Making* books, which included the basic articles, magnificently illustrated by Porter, text and figures from Ellison's book, and many other contributions. This first *ATM* was followed in 1937 by *ATM-Advanced* and then by *ATM-Book 3* for the most avid in 1953. From that point on, American amateur astronomy magazines have had regular columns on telescope making.

But in France? Well, in France craftsmanship is not as highly valued as in the English-speaking world, and it is definitely secondary to the contemporary hegemony of literature and the media. In the eighteenth century, the monumental *Encyclopedie* or *Dictionnaire raisonné des Sciences, des Arts et des Métiers* (Encyclopedia or Dictionary of Sciences, Arts and Trades), published between 1751 and 1780 by Diderot and d'Alembert with the assistance of the Chevalier Jaucourt, was a brief success, but it was known more for its theological and philosophical polemics than for its industrial articles, though these were magnificently detailed and illustrated. The Enlightenment remained in darkness when it came to technology. Foucault, despite a popular republication in *Classiques de la Science* in 1905, remained almost unknown by amateurs, although there were already 4,000 members in the Société Astronomique de France (SAF), which was founded in 1887 by Camille Flammarion.

It was not until the 1930s that a new Foucault advanced things: André Couder's 1932 thesis revealed the fine physicist who, along with André Danjon, gave us the admirable *Lunettes et Télescopes* (Refractors and Reflectors) in 1935. The work, of which only 1,800 copies were published, quickly went out of print, and was never reprinted during the authors' lifetimes. Though it did not treat mirror making, it was a bible for the amateur; it answered simply most of the questions asked by its readers.

Things began to progress quickly. At the S.A.F., the idea of making one's own telescope was mentioned in a few isolated articles. The first gathering of the Society's Commission on Instruments was held in November of 1945, and the appearance, in serial form, of *How to Make a Telescope* began in the May 1948 issue of *l'Astronomie*. These articles, once assembled and published, constituted the first edition of *How to Make a Telescope* in 1951, and with additions, its second edition in 1961. It would not have been possible without the gentle but determined pressure of André Danjon—a great astronomer, a great professor, and a great teacher who loved his students as well as the most modest amateurs, because he was always one of us. His death in 1967 left a void, but the seed had been planted and strong roots remained. First, Gauthier Philippon manned the craftsman's workshop. Now, Jean-Marc Lecleire gives us this new book, a modern transposition of my *How to Make a Telescope*.

Jean-Marc, with good reason, presents three separate plans for telescopes of increasing difficulty. I would here underscore the importance of the most modest, the 130-mm Newtonian with a spherical mirror, which many ambitious amateurs would perhaps think they could overlook. Learning first to produce a sphere or a weak parabola, smooth and without zonal defects, is an essential step, the revealing test that allows one to master mirror figuring. One must absolutely resist the premature desire to retouch faulty zones or a turned-down edge; he must find what is wrong with his strokes and, moreover, his polisher, which must be remade when necessary with a mixture of pitch, whose hardness is tempered with turpentine, to yield perfect squares that quickly take the shape of the blank and adjust gradually during the work.

Be careful with the λ/n measurements, because they will be meaningless if the measurements and calculations are not done with great care. Finally, be wary of articles espousing "new methods" of mirror testing; much experience is necessary to understand the sophistication often present in those articles and to arrive at a correct evaluation. In short, bear in mind the spirit of George Bernard Shaw's adage (from *Man and Superman*, 1903): He who can, does. He who cannot, teaches.

Méaux, August 1997 JEAN TEXEREAU

Jean Texereau is the author of the standard reference work on the construction of telescopes and the figuring of astronomical mirrors, How to Make a Telescope.

Part 1: Introduction

1 About this Book

This book details the making of mirrors and the construction of telescopes. It describes the optical and mechanical parts of a telescope and guides you through making a complete instrument. There are complete, step-by-step plans for three telescopes, from the simple to the complex, so that you can make an instrument that suits your desires and needs.

This book also gives important advice on the use and maintenance of telescopes and on the technique of mirror alignment. It is therefore useful to amateurs who are frustrated after having bought an instrument that is complicated and difficult to use.

1.1 Why Make Your Own Telescope?

In our day, when everything is manufactured, what is the use of making your own telescope? Why not just buy one?

Making your own telescope allows you to understand it and its capabilities more fully, and thus get the best performance from it. It is possible to improve the performance of your instrument constantly, to add new accessories to it, and to refine its optical and mechanical alignment.

Making a telescope is exciting. It enables you to discover (or rediscover) manual work and gives you the opportunity to make high-quality optical pieces with your own hands. The mirror is the most important and complex part of a telescope; it is the eye of the instrument. The figuring of mirrors is a very enriching challenge, and it sometimes reveals hidden talents.

Making your own telescope also saves you money. You can make a telescope yourself, without skimping on its quality, for as little as a quarter of the price that you would pay for a commercial instrument. You can make telescopes that are superior to commercial models. The secret to success lies in a good understanding of mirror making and, more importantly, mirror testing.

The qualities most useful for telescope making are patience and carefulness. You must like to do things yourself, have some capacity for doing things with your hands, and—above all—take your time. It is not important for you to know a lot about optics; the formulas you will use in this book are quite simple. Chapters 1 though 5 will give you the background necessary for planning an instrument to

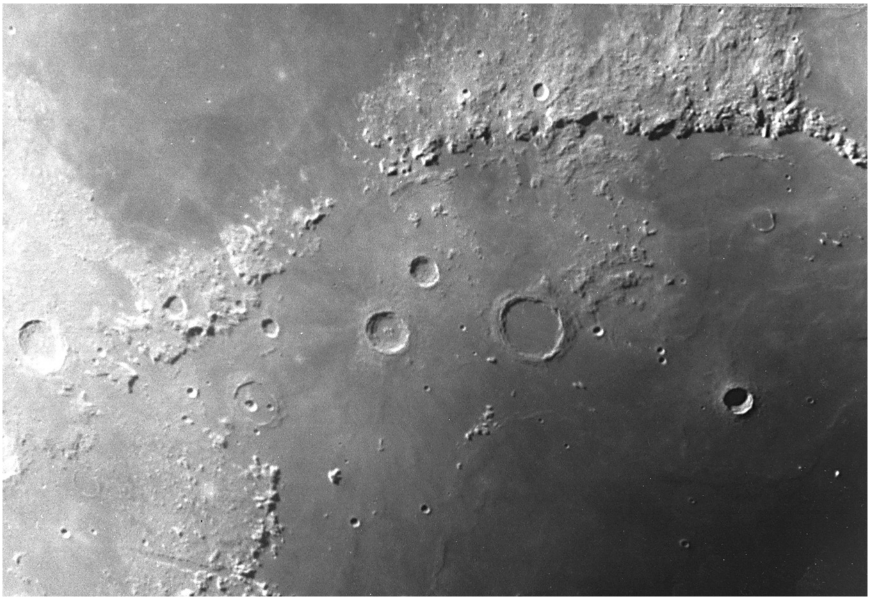


Fig. 1.1 The 130-mm telescope reveals the beauty of the lunar landscape. Here, a photograph of the Archimedes crater region, the Montes Apenninus and Mare Imbrium.

meet your own unique needs and interests. Telescope making is something many people can do; it is not reserved only for scientists. There is no age limit for building a telescope—from children in summer camp to retired persons, anyone can make his or her own telescope.

1.2 What Use Is a Telescope?

A telescope inspires dreams and fantasy. Seeing the stars through a telescope expands the limits of our world and our imagination. A telescope permits you to survey the Moon's mountains like an astronaut, to contemplate the majesty of the rings of Saturn, and to follow the ballet of Jupiter's moons or the phases of beautiful Venus.

To possess a telescope is to have a powerful instrument at your disposal with which to make sketches or take pictures, keep an observation notebook, follow the changing appearance of a comet, detect the presence of sunspots, or observe the polar caps of Mars. A telescope is a window open to the planets, the stars, nebulae and galaxies. Thanks to these instruments, we can examine the universe first hand and try to understand our place in it.

Observing telescopes are tools for research and discovery. In our day, professional astronomers scour the skies in quest of a new supernova, a distant galaxy, or an invisible quasar. They use their giant instruments to concentrate on very small portions of the firmament. Most of the sky remains unexplored, and amateur

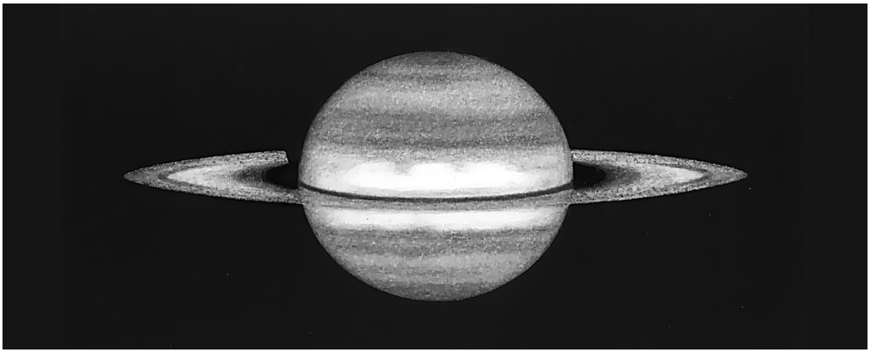


Fig. 1.2 Saturn, observed August 26, 1996, with a 250-mm telescope. Drawing © Nicolas Biver.

astronomers can fill this void. Amateurs are building more and more powerful instruments and search for undocumented celestial phenomena like undiscovered asteroids and comets.

1.3 The Instruments Described in this Book

1.3.1 A Beginner's Telescope

The first instrument described in this book is designed for beginners. It is inexpensive and easy to make. It will familiarize you with mirror making and optical testing methods.

The beginner's telescope is a Newtonian with a 130-mm diameter primary mirror and a 1200-mm focal length. It is comprised of a concave, spherical primary mirror and a small, flat secondary mirror placed at the top of the tube.

This instrument can detect stars about 650 times dimmer than you can see with your unaided eye, down to magnitude 13.5—there are over ten million stars brighter than that. It will reveal details on the order of a kilometer and a half on the Moon. You can begin to resolve globular clusters into stars, observe hundreds of diffuse nebulae and galaxies, go on comet hunts, and travel the spirals of the Milky Way. The 130-mm telescope will unveil the rings of Saturn and the cloud belts of Jupiter, and it will distinguish the phases of Mercury and Venus.

1.3.2 The Standard Amateur Astronomer's Telescope

The second instrument in this book is a Newtonian reflector with a 250-mm objective and a focal length of 1000 mm. The primary mirror is paraboloidal (popularly called parabolic); the secondary mirror is flat. This "all purpose" telescope reaches stars of magnitude 14.5 and gives beautiful images. At the eyepiece, the Orion Nebula shines an electric green with pale pink stripes, planetary nebulae appear emerald green, and the bands of Jupiter swarm with details. The Moon unveils the finer details of her topography, revealing valleys, hills and small craters.

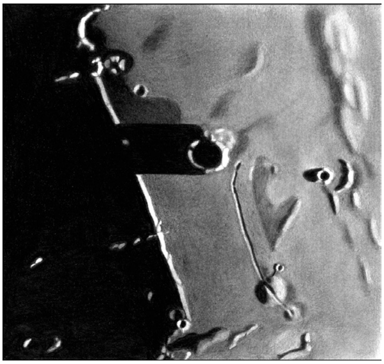


Fig. 1.3 Drawing of the Moon, region of the **Straight Wall**, made August 19, 1995, from 3:40 to 5:05 Universal Time, through the eyepiece of a 200-mm telescope. Magnification 476x. Drawing © Nicolas Biver.

Fig. 1.4 The Orion Nebula, M42, at the focus of a 300-mm telescope. Photo © G. Beaume.

This telescope can be equipped for astrophotography, either at the eyepiece (by projection) for planetary imaging, or directly at the focus to record the dim glow of galaxies. With its focal ratio of 4.3, this high-resolution instrument is particularly well suited for astrophotography; with it, you can obtain beautiful photographs of the sky in color or black and white.

This 250-mm reflector is the standard instrument made by amateurs and is a good springboard to the construction of a larger telescope.

1.3.3 The Telescope for the Experienced Amateur

This is a 300-mm *f*/12 instrument in a Cassegrain-coudé (or Nasmyth) combination. Its round tube fits the equatorial mount for the 250-mm telescope described above.

This project gives you the chance to make several things: a long-focal-length mirror, a convex secondary, and a telescope window. It also introduces you to advanced testing methods such as the wire test or the caustic test.

This long-focal-length telescope reveals the major details of Saturn's rings and will send you to the cores of globular clusters and colorful planetary nebulae. In photography, its versatility lets you capture planets and relatively bright nebulae and galaxies.

The methods detailed in this book are useful for other sizes of instruments. The techniques described for making the mirror and the mechanics of the 130-mm model are usable for smaller mirrors up to that diameter. Those who would like to make a 200-mm telescope can take their inspiration from the method for the 250-mm. Finally, the figuring and testing techniques used for the 300-mm mirror can be applied in the making of 375- to 500-mm mirrors.