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Wilson Wall

A History of Optical Telescopes in Astronomy

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Book Summary

Preface

The importance and pivotal position of the optical telescope in moving astronomy into the modern era. The way that the telescope became simultaneously a vital tool and a source of disbelief and illusions, as it seemed able to alter the way the world was perceived.

Chapter 1: Astronomy as a Science in Need of a Tool

The limitations of unaided vision in determining the nature of the universe. Early ideas of the Solar System limited by parallax and problems of scale.

Chapter 2: The Invention of the Telescope

The combination of spectacle makers and good fortune. How Galileo became essential to the development of the telescope, although he had probably never seen one before he made his own using written descriptions. The first astronomical observations using a telescope that we can be sure of were made by Galileo. This includes some details illuminating his understanding of telescopes from his 1610 publication *Sidereus Nuncius* (The Starry Messenger), where he describes his work in some detail.

Chapter 3: Developments in Optics and the Newly Invented Telescope

Developments in optics as applied to telescopes improving the value of them as astronomical instruments. Closing the gap between theoretical optics and the makers of lenses working empirically, a reflection of the social differences between artisans and gentleman academics.

Chapter 4: Aerial Refractor Telescopes and the Development of Reflectors

Development of refractive aerial telescopes alongside Kepler's understanding of the need for reflective telescopes to produce higher magnifications with reduced spherical and chromatic errors.

Chapter 5: The Ascent of the Mirror Lens and Reflecting Telescopes

Some of the finest examples of telescopes and the ascendance of reflecting telescopes and mirror lenses. The development of the builder/pioneer individuals who made massive strides by indulging their hobbies.

Chapter 6: Industrial Life Creating Fine Instruments and Polluting the Skies

The modern phenomenon of pollution affecting optical telescopes. Industrial pollution and later light pollution putting telescopes into ever more remote regions at high altitude.

Chapter 7: Moving Observations off the Planet

Understanding the limits to ground-based telescopes looking through an unreliable climate and thoughts of working above the atmosphere. The role that the crystal clear photographs of Earth taken from the Moon had in changing public attitudes to impossible dreams of telescopes in space.

Chapter 8: The Hubble Space Telescope

The Hubble Space Telescope. From idea to production of the greatest telescope that had ever been built. This telescope has created a resurgence in optical astronomy and changed so many attitudes towards the universe and the search for life. A chapter will be devoted to it alone.

Chapter 9: The Future: James Webb and Beyond

The optical telescope in the future. James Webb and beyond. Handling huge volumes of data.

Chapter 10: Timeline of the Optical Telescope

A timeline of astronomical and general events happening worldwide, from the year 3000 BC up to 2008 AD.

Chapter 11: People in the Text

An alphabetized list of all the names appearing throughout the text, including background information and relevant details.

Preface

There are few occasions where it can be clearly stated that the invention of an instrument has changed the way we view the world. The microscope and its effect on biology is one example, but there was a great deal that could be done without it.

For the telescope, the position is different. Until its invention around 1600, astronomy had stalled. Looking at the skies was limited by the capacity of the human eye, and even the very clearest eyesight is limited. The telescope changed all of this at a stroke. It became possible to see what had never been seen before. So remarkable was the transformation of the night sky that Galileo began to describe stars as visible and invisible; the visible could be seen with the naked eye and the invisible which could only be seen with his telescope.

Part of the change wrought by the invention of the telescope was a disruption of the classical concept of nature. Being dependent on what could be seen with the naked eye, it was possible to create an explanation of the universe that fully explained everything that was visible. However, once more celestial objects could be seen with telescopes, prevailing explanations needed to be revisited, some of them cast aside in favour of new hypotheses. As Thomas Kuhn pointed out in *The Structure of Scientific Revolutions* (1962), even when anomalies appear in testable hypotheses, adherence to the old ideas—often imbued with a verisimilitude of ancient authority—causes a collective refusal to accept the new data as true. Only when the anomalies mount up and they can no longer be ignored does the old give way to the new. A case in point is the Catholic Church's inability to adapt to the heliocentric model over the geocentric model of the Solar System until they were the only people left apparently believing the unbelievable.

Although we can be fairly sure about both when and where the telescope was invented, the who remains a source of debate. It is all part of human nature that we feel an invention should have a specific point and source of origin, but in science, this is not always easy to pin down. Telescopes came out of a time and place, in Holland in the 16th century, where a spectacle-making industry had grown that put pairs of lenses into the hands of individuals. This is important because the cost of making a lens was such that up until then, owning two lenses was rare indeed. The spectacle makers, of which there were many, would communicate with their colleagues and pass information back and forth. At the same time, they were men of business, so when word got around—as it inevitably would—that two lenses, one convex and one concave, could be used to bring distant objects close, the hunt was on for precedence in the invention and patents for profit. The first to file a patent was a man named Lippershey, but he may not have been the very first constructor of a useable telescope. He is generally credited with the invention, even though we cannot be absolutely sure he originated the idea.

What we do know for certain is that these early spyglasses gave an upright image and were presented not as instruments of astronomy but as devices suitable for use by lookouts. This was a time of exploration: the further you could see land, the better. It was also a time of political turmoil—an enemy's ships may be just far enough not to be visible to the naked eye and yet seen with a spyglass. Thus, the nascent telescope initially had a far more terrestrial use than was destined for it.

Within a very few years of the first Dutch trunke, as they were originally called, the instrument came to the attention of the scientific community. This marked a grand change in fortunes for the telescope, as the uses to which it would be put would require far better optics than telescopes started with. Although the earliest astronomical observations were made with the image as we would describe it "the right way up," the first major development would be when Kepler changed the eyepiece lens from concave to convex. This had two immediate results. The first was that the image was now upside down, and the second was that the instrument achieved a far greater magnification. While the value of increased magnification was significant, the inversion of the image was not. Just as in microscopy, there is no up or down, neither is there in astronomy; it does not matter which way the image is oriented.

Throughout this period, refracting telescopes were dogged by spherical and chromatic errors. Spherical errors were due to the shape of the lens giving different focal points across the width of the lens. This is a direct consequence of the lens section being spherical; the smaller the radius of the sphere, the more pronounced it becomes. Chromatic errors come about from the diffraction of light through the glass causing colour fringes in the image. It was a simple matter to correct chromatic errors by using a mirror. As there was no diffraction through glass, there would be no splitting of light and so no colour fringes. The production of suitable mirrors was a technical feat that would take some time to come to fruition. Design of reflector telescopes took many forms depending on the types of mirror being used, but they all were broadly based on two mirrors giving a very much longer focal length than the containing tube would indicate.

Spherical aberrations and the blurriness associated with it for both refractor and reflector was only really cured when the community moved away from the spherical section lens or mirror and towards a parabolic section. This ensured that all rays reflected from the mirror focused at a single point, and all rays refracted across the entire width of a lens focused at the same point. At the same time, the production of achromatic lenses by using two different glass types, refracting by different amounts depending upon the wavelength, more or less solved the problem of chromatic errors.

In the 21st century, we take for granted that glass is a clear, aberration-free product, but this was not always so. For early astronomers, it was a major problem to gain access to lenses that were up to the mark. Throughout the 17th century, the search was on to make bigger and better telescopes for astronomy. These began having bigger objective lenses with very long focal lengths. The focal length increases as the square of the objective diameter in these telescopes, which helps to reduce chromatic errors that soften the focus and gives coloured fringes to high-contrast edges. For astronomers, the most obvious problem of this sort is when looking at the Moon against a dark sky. The urgency of trying to make more advanced telescopes was fuelled by the knowledge that there were unseen stars out there still to be found. There also existed the possibility that if telescopes were powerful enough to map the surface of planets, it may even be possible to see cities and animals. This belief that other planets in the Solar System were so much like ours that they harboured life helped propagate the many myths and fantasies surrounding Mars.

While Galileo had first made serious astronomical observations on Jupiter, a planet much further away than Mars, it is our nearer neighbour, the red planet, which has stimulated the most speculation. During the 19th century, Schiaparelli in Italy produced maps of the surface of Mars showing *canali*, suggesting the presence of active water. This was picked up later by Lowell, who suggested that the canals were not natural and represented evidence of civilisation. It was much later before these observations were shown to be misinterpreted artefacts of observation, but by then the idea of Martians had become established. This was reinforced by H.G. Wells in his story *The War of the Worlds*.

To this end, very long telescopes were devised that were of such a long focal length that they were unstable in wind. In fact, collapse of ridiculously long telescopes was reported. The solution was both novel and well thought out. Since astronomical observation was made at night of light objects against a dark background, one could do away with the supporting tube altogether. Thus was created the aerial telescope. This was made up of a long focal length objective and an eyepiece, usually tethered together by a cord. There is a replica of one such aerial telescope at Leiden Observatory with a 4-m focal length. Even when using this instrument, one must remember that the glass is modern and uniform in shape, which hand-polished lenses would not always be. Aerial telescopes had a relatively short existence, as they were unwieldy and needed as much skill to use as to make. As a consequence, their productivity in astronomical research was quite limited, and as soon as reflector telescopes became useful, aerial telescopes were replaced.

The introduction of reflectors did not, however, spell the end of the refractor. A major step forward came with the design of the achromatic lens. This seems to have been invented in England, probably by Chester Moore Hall, but remained unexploited until John Dollond patented the product in 1758. By matching crown and flint glass lenses together without a gap, the twin element lens could correct for chromatic errors at two wavelengths, usually in the red and blue section of the spectrum (either end of the visible range). All of a sudden, the use of refractors of manageable size for astronomy became possible again. Later on Peter Dollond, John's son, developed the apochromatic lens correcting for chromatic errors in red, green and blue at the same time, green being more or less midway in the spectrum between the other two. By simultaneously moving away from spherical section lenses, spherical aberration was also removed. From this point onwards, the use of refractors and reflectors developed together, both of inestimable value in moving astronomy along. Eventually, it became possible to produce lenses of astonishing diameter. But as they became larger, they became disproportionately difficult to polish accurately and were very heavy, so the supporting frame needed to be progressively larger. Interestingly, you might still read on the Internet that very large lenses "sag"—well, they do not. This is based on an old urban myth that glass flows. It does not. It is not a liquid, it is a non-crystalline solid, and once set stays set. If you doubt this, consider the Lycurgus Cup in the British Museum, deeply incised with relief figures. It dates from the 4th century AD and has not yet sagged!

Manufacturing large lenses has many associated problems, and by the middle of the 19th century, there were few glass makers who were capable of carrying it out. For some, like Chance Brothers in the UK, additional problems came in the form of government taxes on the smelting of glass. This is sometimes erroneously called a window tax, but that was completely separate and associated with the rateable value of a property. There is no doubt that while astronomical telescopes were essential to the development of astronomy beyond describing a few constellations, we should recognise that in the wider world telescopes also had a value. This is epitomised by a quotation from *Homage to Catalonia* by George Orwell, published in 1938, talking about his time in 1937 in the Spanish Civil War:

A cylindrical object in a leather case, four feet high and six inches in diameter, was leaning against the wall. Obviously the machine-gun barrel. We dashed round and got in at the doorway, to find the thing in the leather case was not a machine-gun but something which, in our weapon-starved army, was even more precious. It was an enormous telescope…

Later on, Orwell reiterated his regret at not being able to carry away the telescope as a vital military aid. Apart from the optical developments of lens production that allowed a tripod-mounted telescope of the sort described by Orwell to be made, technical issues meant that reflectors could be made bigger, with a longer focal length and lighter construction.

The progress of telescopes as instruments of exploration seemed to have no limits, until it was realised that at sea level, there were always going to be problems looking through the atmosphere. It became normal to plan powerful telescopes on top of mountains, initially above cloud and pollution in the significantly thin atmosphere of high altitude. Later on, these high-altitude observatories coincidently became a haven from light pollution spilling from our cities. But this was never going to be enough: telescopes needed to be above the atmosphere. Once the imagination of humankind settled on the idea of sending a telescope into orbit, out of the way of the atmosphere and the light pollution of our civilisation, it was natural to plan a reflecting telescope to do the job. They need not be the most powerful telescopes, as they work in the vacuum of space, unencumbered by atmospheric effects, both natural and manmade.

Even now, the optical telescope can hold its own as a tool for astronomy. We are creatures of the visible world as much as anything. The beauty of the night sky really does have to be seen through a clear telescope to be fully appreciated in all its glory.

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Contents

Chapter 1
Astronomy as a Science in Need of a Tool

Before the telescope, astronomy was a floundering science. It had moved as far as it could, based upon sightings made with the naked eye. There were many deductions that could be made using sightings and timings, but there was no doubt the field was in need of a tool, which was not going to be available until 1600. Before this date, many speculations and calculations were made that would be added to or nullified when telescopes finally became available.

In philosophical terms, the range of the human imagination when viewing the untouchable stars far outstripped the range of the observer's eyes. This is a perfectly obvious thing when you consider that looking at the sky with the naked eye gives an image that is to all appearances in two dimensions. It was reasonable, therefore, to assume the world was enveloped in a shell upon which stars and planets were fixed, apparently moving together across the night sky. It did not go unnoticed that some of the stars seemed to move independently at different speeds; these became known as wandering stars long before it was realised they were planets. It also seemed that the Moon was a disc, since it only ever presented a single face to us. This sat comfortably with the idea of a dome upon which the stars and the Moon were attached.

From these straightforward interpretations of simple observations made by the naked eye, there came two motivations for the detailed analysis of any changes that could be observed. The first was the most human of all: curiosity. The second was rather more prosaic: economics. Curiosity was by far the most important in the long term, but initially, most of the systematic observations were associated with defining the year for the benefit of accurate tax collecting. It is sometimes suggested that early agrarian cultures needed to know the time of year for their husbandry, but this is not so. Planting and harvesting depends exclusively upon the weather and the state of the crops. That this falls within certain dates of the year is irrelevant to the farmer, as when the day length changes and crops ripen, is the time to harvest, just as when temperatures increase, it is the time to plant. For the governments of the time, however, knowing the date in terms of its position within a solar cycle became important for collection of taxes. Making sure that taxes are collected at the right time of year every year required a reliable calendar. For these reasons, calendars

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became significant at a local level. But it was not always easy to create a calendar from scratch. Although many places had the mathematics and observational ability to create a calendar based on the passing of the Moon and planets, there were many more places where the information was used and implemented without considering the original calculations.

It was reasonable, given the human memory of the annual cycles of the seasons, to correlate celestial events with specific times of the year. In this way, the Babylonian calendar was created. Its first implementation immediately demonstrated the difficulty in relying upon a single astronomical cycle for a calendar, in this case the phases of the Moon. They based their annual calendar upon lunar months, which is about 11 days shorter than a solar year. This discrepancy between the lunar and solar calendars required the insertion of additional days from time to time to make up the difference. The exact number depended upon the gap between the insertions. Without this process, key dates would move through the year. This is why the Islamic calendar, which has no inserted days, has Ramadan moving position annually.

The workings of these older calendar cycles are well reported and make an interesting study in themselves, but in astronomy, they represent the earliest proper use of observations on a routine basis. The most interesting aspect of these is the point at which either the month is regarded as starting, or when the year starts. We tend to think that the year has always begun on January 1, but until the move to the corrected Julian calendar (normally referred to as the Gregorian calendar), the start of the year was different in different jurisdictions. It could in fact be anywhere—there is no profound reason for starting it in one place rather than another. This is also true of months. They can be started at full moon or at the first sighting of the crescent moon; the start is arbitrary and of no consequence so long as the entire cycle ends at the same point.

Once these cycles were clearly recognised, it became possible to mathematically define celestial events and develop a better understanding of the observable sky. It is the use of the phrase "observable sky" that is important here, as without a tool such as a telescope, observation is quite limited indeed. Some of the questions that had to be answered by early cosmologies included apparently simple ones, such as why the Moon does not fall to Earth, since every other observable object does. With its rotation being synchronous with its orbit around the Earth and therefore always presenting the same face to the observer, was the Moon a disc? By eye, there is no clue from perspective at such a distance, so it would be natural to assume that it was a flat disc rather than a sphere.

These questions regarding the Moon epitomise the state of early astronomy, in that as long as a hypothesis could explain naked-eye observations, it was perfectly valid to hold that it was correct. This was because in the ancient world, it was virtually impossible to test the various hypotheses by experiment, and further observation was limited in scope, since what could be observed had generally already been seen.

It is similarly true that in the ancient worlds of Babylon and Egypt, there was only a limited interest and pursuit of science. The great feats of what would be now termed engineering, such as the pyramids, were constructed empirically, and the knowledge gained was never codified. In the same way, there does not seem to have been any attempt at understanding chemistry or biology. In these cultures, it would be true to say that any pursuit of astronomy was motivated by religion and astrology. In the Mesopotamian area, the Chaldaeans seemed to have produced detailed astronomical tables that have been meticulously interpreted by Pannekoek (1947) from the original broken clay tablets. They had a clear idea of the movement of the Sun, Moon and visible planets, but no record was left regarding any speculation about orbits. Such tables would have been buttress of the calendar and consequently of great official use.

Over the next centuries, the accuracy of measurements increased as more sophisticated techniques were developed, but the number of different measurements did not alter. By the time that Greek speculation was ascending, something rather strange became evident. Speculation about the nature of the observable universe became further disconnected from day to day observation. Thus, there were flat disc ideas about Earth, originating with Thales, and various floating geometric shapes, spheres and cylinders circulating as alternative versions. Sometimes, these were suspended upon a material of known type, like air or water. These ideas seemed to try and fit the massive and unknown into the domestic and known. There was also the difficulty of explaining why the planet and Moon did not fall. They would have to be supported by something, otherwise, like everything else, they would drop. Everything else seen on the planet falls—even birds must come to the ground (Fig. 1.1).

Trying to explain the movement of the celestial bodies was difficult because of a simple idea, ingrained in both religion and education in the ancient world: the assumption that the Earth as a planet had to be central to the sky. This was regardless of gods and spirits, which had at various times been proclaimed as creators and maintainers of the heavenly vessel. The problems of creating an explanation were

Fig. 1.1 Thales of Miletus, around the 6th century BC, as depicted in the 1493 *Nuremberg Chronicle* (Michel Wolgemut, Wilhelm Pleydenwurff (Self-scanned) [Public domain], via Wikimedia)

compounded because rules and compliance to the rules could only be based on worldly concepts. Any explanation of planetary motion at this time was going to be based on preconceived ideas. Untested ideas were introduced with an air of authority, when in reality, they were all little more than idle speculation. This often became the written authority that supported later ideas, with precedence turning it into fact. This process was the stumbling block that caused such problems when more plausible, straightforward explanation at last emerged.

Both Plato and his slightly younger contemporary Aristotle (4–5 century BCE) thought that a spherical Earth worked well. This was an idea that had originated sometime earlier with the school of Pythagoras at Croton in Italy. They did not adopt this viewpoint for any particular astronomical reason, but more because they recognised the sphere as a perfect solid. From this simple point, their speculations started to depart from reality more and more. The planets were attached to concentric spheres, which needed varying levels of complexity to explain the different observations as they were introduced to the model. Somehow, they needed to reconcile the strange nature of planetary motion and the odd reversals of direction that had been observed since antiquity. Eudoxus took on the challenge and did manage to explain the limited observations in mathematical terms. The geometry involved was very complicated, involving 27 geocentric spheres. To account for the movement, four spheres had to be assigned to each planet known at the time: Mercury, Venus, Mars, Saturn and Jupiter, as well as the stars themselves. It still did not account for all observations, such as the varying brightness of the planets, which would be expected to remain constant if they were a constant distance from the Earth. The shortcomings of the model when compared to the observations is one of the reasons that we think Eudoxus was aware that this idea was a purely mathematical explanation and not real in the physical sense. Yet, others were more literal, assuming it was a true image of the cosmos. Aristotle was one such individual—he thought the spheres were real, physical structures made of an unknown crystalline material.

Aristotle believed in a spherical universe, but that going past it was impossible, as it had neither time nor space beyond. This may sound like an infinite universe, but it was on a much more human scale than that. There was nothing against which an infinite distance, or even an incalculable distance, could be measured, so a universe of conceivable scale, outside of which there was nothing, was a much more easily dealt with concept. In this theory, Earth was at the centre and motionless, surrounded by transparent spheres, the outermost one carrying the fixed stars. While Plato and the Pythagoreans had postulated a spherical Earth more on aesthetic grounds than anything else, Aristotle had a better reason for this suggestion. He noted that travellers said southern stars decreased in altitude as they moved northwards and some became invisible if you went far enough north. This was about the limit of his interest in practical astronomy; he certainly gave little value to observing the heavens himself.

Since the 4th century BC, it was assumed that the Earth formed the central point of the universe, even though there had been flirtations with a heliocentric model before this. Until the 17th century, Aristotelian cosmology backed up by religious bigotry determined that the Earth was at the centre of the universe. This was to cause no end of problems when trying to fathom the movements of stars and planets became of practical value.

Aristotle's entire cosmology was based upon a geocentric centre, itself a result of humankind's arrogance and flawed thinking. It became embedded and embellished after 250 BC with Greek science in Alexandria. The flawed thinking is epitomised in the argument for a stationary Earth at the centre of the universe: Whenever you move, the movement is sensed, whether by balance changes or wind on the face. But as you stand still on the surface of the Earth, no movement can be felt, so the Earth must be stationary. This logic was always going to cause mathematical difficulties in interpreting the movement of heavenly bodies.

One should remember that the only things that could be seen around this time were those which were visible with the naked eye. This also means that with the exception of the Moon, no details could be discerned. On the other hand, there was no light pollution, so the total number of stars visible to an observer, even in a city like Alexandria or Athens, were very much greater than can be seen in the 21st century from anywhere except the most remote parts of the globe. What did happen as a matter of scientific endeavour was the more accurate measurements of star positions and planetary movements relative to each other.

It was at about this time that measurements were starting to be made of a different type to simple star position—celestial distances. This may seem like a simple task, but without prior knowledge, it is quite difficult to make an accurate determination using parallax techniques. It was not just distances that were tackled, as once distance is known, size can be calculated and vice versa. The degree of accuracy required to make these calculations was beyond the earliest attempts, which were carried out by Aristarchus, who tried to make calculations based on a triangle of Sun, Moon and Earth. The result was based on proportions, so the distance to the Sun was a multiple of the distance to the Moon, resulting in the distance to the Sun appearing to be only one twentieth of what it actually is.

This raises an interesting problem, because there was no standard measure of distance at the time. We take for granted that a metre will be the same wherever it is referred to, but before the standardisation of length, it was a very local measure, generally based upon a biological unit such as a stride. This makes accurate assessment of ancient units of distance very difficult and the measurement of astronomical distances in any sort of way impossible. Consequently, the distance between one celestial body and another could only be referenced with any accuracy at this time by a comparison of distances—by a ratio. This in itself made for difficulty in understanding the distances involved in planetary calculations; you may know A is 2.5 times the distance of B from your position, but it does not actually tell you how far either of the items are from you. When Aristarchus made his measurements, according to Archimedes, he believed that the planets, which included the Earth, moved in orbit around the Sun. This concept of a heliocentric system was the same one that Copernicus constructed 1800 years later. Unfortunately, both the weight of Aristotle and later the church were sufficient to maintain a geocentric Solar System against the much simpler but heretical idea of a solar-centred system.

In the 3rd century BC, two well-known attempts were made to measure both the diameter of the Sun and the diameter of the Earth. The diameter of the Sun was a relative measure, but that of the Earth was calculated as a quantitative value. Perhaps surprisingly, measuring the diameter of the Sun is simpler in principle than that of the Earth. It involves what is probably the earliest Greek sighting instrument. This was a staff, most likely wood, upon which there was a scale and a round disc. By looking from one end and moving the disc until it just obscured the Sun, it was possible to ascertain a relative diameter. This needed to be carried out in hazy conditions at the very least and would have given a progressively less accurate measure as the calculation was carried out and discrepancies became magnified. Geometrically, it is an easy step to take the two measurements we know, the disc and the distance from the eye, to calculate the diameter of the Sun if we can estimate the celestial distance. This was the method that Archimedes is said to have used.

At the same time that Archimedes was working, his friend Eratosthenes, custodian of the library at Alexandria, made an attempt to measure the size of the Earth. This was a difficult task, as it is not possible to take a step back and look at the entire planet. But since it was known to have a visible curvature, using minimum shadow length at midday was one way to approach the problem. The reason for assuming the Earth might be a spherical planet was simply travellers' tales. It was generally reported that southern constellations decreased their altitude as the viewer moved northwards. The distances had to be considerable to be noticed. The regular reporting of the phenomenon was most easily explained by a spherical planet.

The technique to utilising the curvature for its own measurement is in principle simple. At the summer solstice, the shadow of a stave at modern Aswan, then Syene, disappeared, while at Alexandria, there were short shadows. By knowing the distance between Syene and Alexandria from pacing, Eratosthenes calculated the Earth's radius. If he assumed the Sun was so much larger than the Earth that it was effectively a collimated light source, the shadow length revealed the curvature of the Earth. In general terms, it looks as though Eratosthenes got quite a good result, but it does depend upon the size and reliability of his original measurement between the two cities. This particular stochastic error reflects many of the problems facing early astronomy, in that equipment was not interchangeable and the standard by which any measuring device was made affected the accuracy of the result (Fig. 1.2).

Use of graduated instruments to try and standardise measurements along sight lines was one of the reasons that Hipparchus is remembered as one of the great pre-Christian astronomers. By utilising various forms of armillary sphere and gnomon, he measured the altitude of the Sun above the horizon at the winter and summer solstice, thereby fixing the position of the celestial equator and from that the obliquity of the ecliptic, the tilt of the Earth's axis. This led to measurements of precession. Hipparchus spent some time at the library of Alexandria but seems to have been mostly based in Bythnia, now part of modern Turkey. Only a single work by Hipparchus remains; most that we know of his trigonometry is from later authors and scholars.

As he believed in the geocentric Solar System, Hipparchus was obliged to work out extraordinary methods of explaining the observed movements of the planets.

Fig. 1.2 Aswan (Assuan) to Alexandria. This is from a map of 1894 and has Assuan (marked at the bottom) as Syene. The distance is approximately 815 km in a direct line (Authors image from Stanford's London Atlas of Universal Geography 1893)

This involved epicycles, as earlier described by Apollonius earlier, where planets rotate on circular orbits that also orbit on a circular path around the Earth. There was some difficulty with the orbital calculations because the orbits were assumed to be circular, rather than elliptical. Hipparchus did acknowledge that this system did not fit the observations properly and had to move orbits. Most notably, the Earth was shifted slightly to help explain the eccentric orbit of the Sun around the Earth.

The work of Hipparchus, though sometimes overshadowed by the philosopher science of Aristotle and Archimedes, is of huge importance. Previously, astronomy had been based on speculation, trying to account for observations that were sometimes selective with pure reasoning. What Hipparchus did was to try and make science a process. Hipparchus improved his graduated instruments and created spherical trigonometry so that his data could be analysed in detail. The reliability of his observations set him apart from previous observers of the night sky, and when Ptolemy was working in the first half of the 2nd century AD, he discussed the work of Hipparchus, using his observations and calculations as reliable data (Fig. 1.3).

Ptolemy, whose work *Almagest* is the only comprehensive astronomical work that has survived from ancient Greece, lived and worked in Alexandria, although it is thought he was not born there. Ptolemy sealed the geocentric orbits of planets, stars and Sun by making the deferents eccentric to the Earth, with a point outside the deferent where angular motion was uniform. This was contrary to the current notion of planetary motion, but by careful mathematical manipulation, he reconciled the observed with the assumed. It was Ptolemy's goal to bring a mathematical harmony to the perceived circular motion of the observable skies, rather than to try and improve measurements by developing practical astronomical techniques. This apparent difference between observational and theoretical astronomy would be repeated throughout the centuries. Ptolemy did, however, suggest the quadrant could be used to far greater effect than complete circles for observing stars. Although this was never made by Ptolemy, it was used and improved in the Arab world to such an extent that the quadrant became a standard instrument in observatories well beyond the introduction of the telescope.

Ptolemy is perhaps most famous for his innovative map of the known world, which used both latitude and longitude for the positioning of towns and cities. The

Fig. 1.3 Ptolemy from a woodblock printed in 1584. There are a number of image of Ptolemy as he produced the explanation of the heavens favoured by the Catholic Church (http://www.er.uqam.ca/nobel/r14310/Ptolemy/Thevet.html)

accuracy of the Ptolemaic map was severely compromised by the lack of hard data relating to latitude, although this was easily calculated using a gnomon and his reliance on seafarers for most of his data. Nonetheless, the technique was a sound one that remained in obscurity for more than a millennium. Much of his work was picked up first when it was translated into Arabic, whereupon it returned to Europe via the conquest of Spain from North Africa by the Caliphate of Umayyad in the 8th century AD. Ptolemy's work was translated from Arabic into Latin, so this repeated translation may well have introduced differences and lost subtleties that were present in the original. It is quite common for ancient texts to have been translated into Arabic and then returned to their original nation in retranslated form, often in Latin rather than the original Greek. It should also be remembered that it is not always straightforward to translate complicated texts and potentially ambiguous ideas from an ancient language into a modern one. This requires fluency in two languages and an intimate knowledge of the subject being dealt with.

From the ancient period through to the introduction of the telescope, the methods of observation remained essentially the same. It was possible to improve the scope of observation through improved geometry and superior engineering, but the methods were unaltered. It was brought to a high level of sophistication at several sites in the Arab world. Perhaps the most interesting and spectacular is found at Samarkand, now in Uzbekistan, but before that in the USSR, and before that the Russian Empire. By carefully using large scale equipment, Ulugh Beigh (usually called Ulugh Beg) made some very skilful measurements, including a first measurement of the year as 365 days 6 hours 10 minutes and 8 seconds. This was correct to within 58 seconds, which he later reduced to an error of +25 seconds. To make such accurate calculations, Ulugh Beigh used a gnomon of 50 m and a sextant of about 40-m radius. This was constructed in the 15th century. Ulugh Beigh is celebrated in five lunar craters, A, B, C, D and M. Two hundred years later, between 1727 and 1734, another massive outdoor observatory was constructed this time in Jaipur, called Jantar Mantar, followed by four additional large observatories that allowed for very accurate local time measurement from giant sundials.

The retranslation of Ptolemy, specifically the *Almagest*, and Aristotle into Latin during the 12th century both in Spain and Sicily as well as two notable Arabic scholars, Al-Battani, sometimes Latinised to Albategnius, and Al-Farghani, Latinised to Alfragnus, was of great significance. With these collected translations there developed a degree of conflict of ideas. This was due to the apparent authority with which these scholars approached their subject. Some pursued the Ptolemaic idea of the cosmos, while the opposing view held that epicycles were not necessary, preferring the crystal spheres of Aristotle.

Trying to reconcile ideas became a feat of an almost impossible nature. Inevitably, there developed two broad systems, the Ptolemaic and the Aristotelean. The Aristotelian system was accepted as true by the Spanish-Islamic scholars Ibn Rushd (Averroes) and Nur ad-Din al-Bitruji (Alpetragius). Averroes and Alpetragius rejected the Ptolemaic epicycles and believed in the homocentric spheres, which, of course became staggeringly complicated to interpret in any physical way for simple observational reasons. An example of this clash of observation with theoretical interpretation of a philosophical idea comes from the crystal sphere, where a planet is an equal and constant distance from Earth, and yet its brightness fluctuates widely. The equally incorrect Ptolemaic description fit the observations better than those of Aristotle, but that did not affect the Church in accepting the homocentric version of the visible skies broadly as described by Aristotle. This debate was taking place in the 12th century, when it was still difficult to observe anything other than the presence or absence of a celestial body, with the exception of the Moon. There was no detail visible except by eye and no star visible that could not be seen by any observer looking up on a clear night.

The situation regarding theories of cosmology shifted towards Ptolemaic ideas quite quickly, as although both Plato and Aristotle had different notions and were greatly venerated as being Ancients, it was only Ptolemy whose ideas could explain the observations. This was still a homocentric system of extreme complexity, but it did more or less work. By the time of the Middle Ages, tables were constructed of star positions based on the work of Ptolemy. Two hundred years later, in the 15th century, more accurate attempts to measure star positions were carried out, revealing anomalies between prediction and reality.

There was a growing mathematical understanding that Ptolemy's explanation of the heavens was not always reliable, and it was certainly not an elegant explanation of a system. It is unlikely that the bigger picture of scale and distances could figure greatly in a pre-telescope era of astronomy, as it was still assumed to be more than likely, by simple observation, that all the fixed stars were the same distance from the Earth. If it was only the stars being investigated, then a simple Aristotelean explanation could work. It was only the nearer celestial bodies, where parallax was an observable phenomenon, that caused major problems. There was a slowly increasing level of doubt about the efficacy of Ptolemy's explanation of the Solar System, slow mainly because the Church still supported the Ptolemaic ideas. Into this situation, where questions were being asked about orbits and stars which were not easy to answer, came a Polish mathematician called Nicolaus Copernicus (Mikolaj Kopernik in Polish).

Copernicus was a clear thinker, an early mathematician of the Renaissance and Reformation, but he was not trying to reconcile a philosophical discrepancy. It is unlikely that he was particularly bothered where the Earth stood in respect of the cosmos; he was much more driven by the quest to find a reliable mathematical model that fitted precisely with the observed universe. Copernicus had the idea that geometrically, the universe was both simple and elegant, which the complicated description given in the *Almagest* was not. Since earliest times, the circle was seen as simple and perfect. It was after all considered the very crux of human mobility, even though neither wheel or axle are found in nature. Thus it seemed reasonable to Copernicus that circular orbits as perfect reflections of geometry must be important in any scheme of explanation. By the time that Copernicus published *De revolutionibus orbium coelestium (On the Revolutions of the Heavenly Spheres)* in 1543, it seems that the general premise of a sun-centred universe was well known, if not accepted. The idea of acceptance was significant, as in the early years of the idea, Copernicus regarded it as a hypothesis to be tested. It was only later, most notably under his student Joachim Rhectus, that it was seen as fact.

The original Latin text of *De revolutionibus orbium coelestium* was published in several editions. The second in 1566 is nearly as rare as the first. The third edition of 1617 was published in Amsterdam and for the first time gained some explanatory notes. Care was taken not to deliberately offend authorities such as the Church; the first edition was seen through publication by Andreas Osiander, who was a cleric. He added a preface that suggested that the idea of a heliocentric universe was possibly not true, but just a useful computational technique to explain the observations. By holding onto the idea that orbits were circular, Copernicus had to introduce several epicycles, making his idea both simultaneously revolutionary and evolutionary; a re-vamped Ptolemaic explanation of the heavens with the Sun becoming central (Fig. 1.4).

Throughout this period, there had been no change in instrumentation available to astronomers, and for many practical purposes the available instruments were of no use other than as sources of contentious results, as was demonstrated by one of the most significant astronomical events visible with the unaided eye to have been accurately described. This was the supernova, as we now know it to have been, of 1572 that appeared in the constellation of Cassiopeia. Various methods of measuring the parallax of the new star were tried using various instruments by various astronomers. The range of results was equivocal, and each measurement came up with a

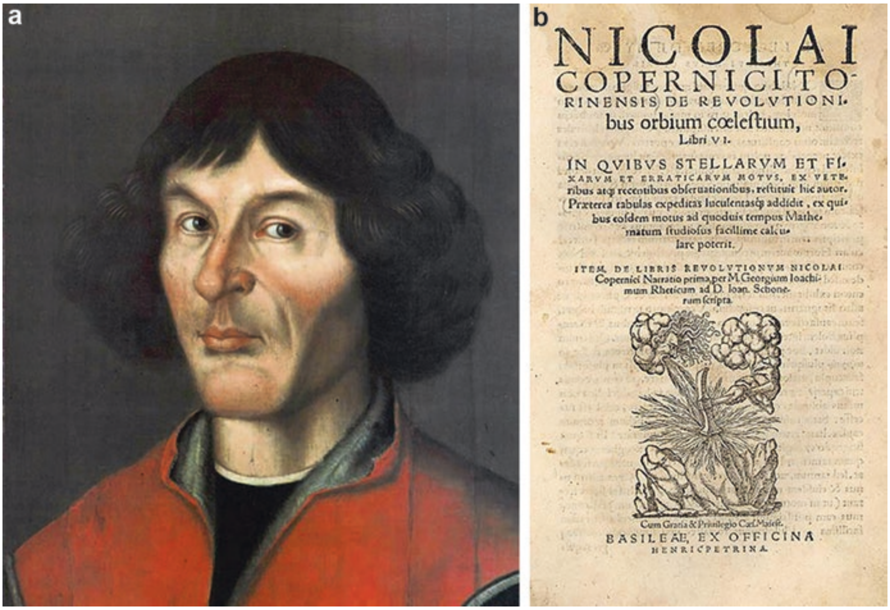


Fig. 1.4 (**a**) Nicolaus Copernicus. This is a portrait from the Town Hall in Toruń, in the north of Poland. It was painted about 1580 by an unknown artist. (**b**) *De revolutionibus orbium coelestium*. This the front of the second edition of 1566 and is considerably more ornate that the first edition, which also included a quotation in Greek (**a**, http://www.frombork.art.pl/Ang10.htm, **b**, Jagiellonian Library, Krakow)

different answer. This supernova was referred to as Tycho's supernova because of the extensive work that he published on the subject in *De nova et nullius aevi memoria prius visa stella* (Concerning the Star, new and never before seen in the life or memory of anyone), which was published in 1573. It was later reprinted in 1602 and 1610, these publications being overseen by Johannes Kepler. Kepler worked with Tycho as his assistant for a while but disliked his ideas of cosmology with the Sun and moon orbiting the Earth, much preferring the heliocentric system of Copernicus (Fig. 1.5).

This limiting lack of reliable instruments is epitomised by the work of Michael Maestlin, a Lutheran and professor of mathematics. He managed consistent measurements not by using a free-standing instrument such as a quadrant or triquetrum, but by sighting a thread in line with the nova and nearby stars. His conclusion was that there was no measurable parallax, therefore it was one of the fixed stars of very great distance.

Tycho Brahe was a young astronomer at the time of the 1572 supernova, only 25 years old (he was born at the end of 1546) but nevertheless frustrated by the apparently random nature of the astronomical measurements being made. Brahe worked to try and make observations exact. This culminated in 1576 with him receiving a grant of a sum of money and the island of Hveen by the king of Denmark. The island is now known as Ven and is Swedish, lying as it does more or less equidistant between Sweden and Denmark. Logically, Tycho Brahe thought that the best way to minimize errors was to make the instruments as large as possible. This was exactly what he tried at his new observatory called Uraniborg, built on the island (Fig. 1.6).

Fig. 1.5 Johannes Kepler by an unknown artist, painted about 1610 (Image from Wikipedia, original in Benedictine monastery in Kremsmünster)

The scale was large, but not without some intrinsic problems associated with engineering of this type. Nonetheless, considerable advances in measurements were made at the observatory. One of the primary reasons for this was the use of transversal scales, a technology that Tycho popularized at a time when accurate engraving of vernier scales and engineering of threads with little reciprocity to support them was beyond contemporary technology. Transversals had been used before on measuring instruments and involves the use of diagonal lines between alternate values on parallel scales. On a radius divided by degrees, this allows for an accurate assessment of in between values, minutes and seconds of arc. The exact origin of diagonal scales remains obscure, but does require a knowledge of geometry to construct one accurately.

In the case of the diagonal scales utilized by Brahe, one was of such complexity that it required division of an arc of 90° into concentric sectors with one less division in each down to 46. This would require alternate arcs to be divided into an odd number of sections. Although of great elegance in use, and designed by Nunez, a mathematician, this was technically a very demanding piece of engineering and was

Fig. 1.6 An engraving of Tycho Brahe by Jacques de Gheyn II, currently in the Museum of Fine Arts, Houston (Museum of Fine Arts, Houston)

only used once on a relatively small instrument. With these scales on very large instruments such as were at Uraniborg, it requires a very steady instrument with very little slack in the threads and joints. At this time, sighting exactly on a star faced the same problem as un-lensed gun sights: the target and sight cannot be in focus simultaneously. Tycho approached this by having a variable aperture sight of four pates, which worked in the same way as an iris diaphragm in photography. By adjusting the aperture and position of the line of sight simultaneously, he could target a specific star regardless of brightness.

The engineering skills required to produce a reliable quadrant, or any sighting device for astronomical use, is quite considerable and should not be taken lightly. This was a period where it was necessary for instrument makers to make all the parts, including springs and screws. As there was no standard for constructing such devices, any maker would have their own set of dies and taps for threads and methods for marking out teeth on cogs, which would be hand cut. This is particularly relevant to astronomical observations, because besides the manufacture of equipment, it was also difficult to construct a reliable clock.

There were two aspects to this problem of time. You can use a quadrant to check the time and consequently the correctness of your clocks, which as far as we can tell is the way that Tycho Brahe worked. But it is also possible, if you know the right ascension of a star and have an accurate clock, to determine the right ascension of others from the transit over the meridian. Herein lies the problem. Tycho could check the accuracy of his clock, but it was unreliable, being plagued by random errors due to temperature and humidity and the state of the mechanism. There were probably systematic errors as well, with the mechanisms of different clocks running fast or slow. The type of error was not important so much as the lack of a clear method for dealing with them.

A major part of the problem would not be solved for many years—the type of escapement used on the first clocks. They were powered by dropped weights and gravity, but the control of the clock function fell to a verge and foliot escapement. This system has two weights on a balance beam that oscillates on an axle, usually through 90°, although the exact figure depends on the clock maker. As it sits in the open (usually on top of the clock), it is easy to see where the variation in accuracy can come from.

There was an accidental detail about these very old clocks that made them unsuitable for accurate time keeping: they only had one hand. There are many reasons why the practice of only having a single hand on a clock persisted well into the 18th century, but it most likely started because clock makers were emulating the Sundial with a single gnomon. In fact, the clock at Rue du Gros-Horologe in Rouen was made in about 1389 but had no face or hand until 1409, time being kept by the tolling of an hour bell. Similarly, the clocks of Westminster Abbey, London have only a single hand, even though they were constructed between 1738 and 1745. There was little point in having two hands when errors were so large on these devices, and as a consequence, Tycho Brahe was in many ways limited by the technology of the day. Some of the calculations based on available clocks of the time created significant errors for the right ascension (Fig. 1.7).

Fig. 1.7 Painted in about 1832 by J.M.W. Turner, the clock face of The Gros Horloge at Rouen is clearly recognizable (Image from Tate Gallery, London)

One of the innovations that Tycho Brahe introduced was to have his armillae rotated through 90° relative to the Arabian versions. This meant that the structure rotated on a polar rather than equatorial axis, with the result that the circle was in the plane of the equator. So, rotating his instrument around the polar kept the star in view, which is essentially the way a modern equatorial telescope functions. By introducing other techniques and by careful use of his equipment, Tycho managed to refine the observations of stars and improve star charts, but he was limited in what he could achieve because no matter how much he tried to refine the line of sight of equipment he designed and used, there was one aspect that could not be overcome: a fixed field of view. Tycho was without doubt the last groundbreaking astronomer who worked without any additional optical help. Although the telescope was on the horizon, it was not until he was middle aged, dying at 54 in 1601, that any hint of the revolutionary instrument appeared.

It is worth considering the situation regarding naked-eye observations from a practical point of view. It is now commonplace to see comparisons between digital cameras and eyes. This is spurious and of no interest here, as it is as misleading as a comparison between a gas turbine and an internal combustion engine; the only thing they have in common is that they can move things. The eye is a complex structure, and it should not be forgotten that the retina and the optic nerve are part of the central nervous system, so they are not passive collectors and communicators of data, but rather actively participate in making sense of the world before passing the information to the brain. An example of this is that we see a moving image without apparent blur from a continuous stream across the retina; there is no shutter. The naked eye has limitations usually described around acuity and resolution, which is the ability to resolve two points at a specified distance. This, however, is slightly different when you are dealing with points of light against a dark background, so although problems of astigmatism and myopia could be major problems for the pre-telescope astronomer, it was the ability to make a very precise, measurable and repeatable alignment that was the most important aspect of observing.

When astronomical observations are made, the important aspect is the acuity of the observer, which can vary considerably depending on conditions. Being purely physiological, simple measurements using an eye test card of any sort will allow for the correction of optical defects in the cornea and lens. It will also give what is routinely described as an acuity measurement, but this is not the whole story. Perception is equally important; you have to know what you are looking either for or at, which is something that can be learnt by the observer under different conditions. In the same way, the value of familiarity with the equipment being used cannot be overestimated. It has never been as straightforward as explaining how a piece of equipment works and then being entirely equal in the capacity to use it. Such things take time and practice to make the best use of, which is why the pre-telescope observers made such strides in cataloguing the fixed stars and wandering stars (planets); they were skilled observers using their own equipment with which they were deeply familiar. There is no doubt about this, as trying to make accurate angular measurements by eye using a sighting line or a sighting tube is extremely difficult.

References

Aristotle. 2008. *Physics*. Translated by Robin Waterfield. Oxford: OUP.

Brahe, Tycho. 1573. *De nova et nullius aevi memoria prius visa stella.*

Copernicus, N. 1543. *De revolutionibus orbium coelestium*. Nuremberg: Johannes Petreius.

———. 1976. *On the Revolutions of the Heavenly Spheres*. Translated with an introduction and notes by A. M. Duncan. Newton Abbot: David & Charles.

Pannekoek, A. 1947. *The Planetary Theory of Ptolemy*. *Popular Astronomy* LV (9 November): 459. Whole No. 549.

Perry, Bruce M. 2014. *The Almagest: Introduction to the Mathematics of the Heavens*. Santa Fe: Green Lion Press.

Chapter 2
The Invention of the Telescope

> *Great, I say, because of the excellence of the things themselves, because of their newness, unheard of through the ages, and also because of the instrument with the benefit of which they make themselves manifest to our sight.*
>
> —*Siderius Nuncius* (1610)

We can with some certainty place the origin of what we now understand as a telescope to the start of the 17th century. It was soon thereafter when the nascent telescope was first pointed skywards. What was to follow was without a doubt an explosion of observations, which confirmed or disputed previously held ideas and created new hypotheses that had to be explained. These explanations made our understanding of the natural world and our Solar System far greater and developed the new science of astronomy.

Astronomy as an independent subject beyond the ancient aspects of astrology started when it became common knowledge within the European intelligentsia that it was possible to magnify a distant object. Several ideas and events had to come together to produce this step forward; it was not simply going to happen on its own. The first thing that was needed was the ability to make and polish glass. It is easy to consider that glass is fused silica and once fused is clear, but this is not automatically so. This modern perspective on glass stems from the almost complete lack of flawed glass in the modern world. It has taken a long time to be able to manufacture optically clear glass on a scale such that we all have clear windows and our cameras have unblemished optics.

As far as we can know, the first recognisable telescopes were put together by spectacle makers. This seems reasonable, as they were a group who had access to all manner of lenses of the finest quality available. Precisely which one was first is almost of no concern, since the evidence is not and likely won't be available to be wholly sure. What we do know is that it was carried out by Dutch spectacle makers. Lenses were previously available but were difficult to make and very expensive; owning two would be rare. The makers of spectacles were able to gain access to

W. Wall, *A History of Optical Telescopes in Astronomy*, Historical & Cultural Astronomy, https://doi.org/10.1007/978-3-319-99088-0_2

Fig. 2.1 Hans Lipperhey in a portrait engraving from about 1655 (http://fermi.imss.fi.it/rd/bdv?/bdviewer/bid=000000300919)

lenses by way of their business, and Holland was a place where spectacles were commonly made.

A landmark date that we can be sure of from official records is October 2, 1608. This was the date upon which Hans Lippershey lodged his patent application with the States General of the Netherlands for what we would now recognise as a telescope, although that epithet still had to be compounded from the Greek specifically for these instruments. Hans, sometimes Johann, Lippershey and sometimes Lipperhey, did not succeed with his patent application, but was still rewarded by the Netherlands Government for his design, the value of the spyglass as a tool of the lookout already being recognised (Fig. 2.1).

One of the reasons for the failure of the patent application was that there were several competing claims for original construction of these spyglasses. Other spectacle makers seemed to have worked on the same ideas at the same time. Most likely, ideas were exchanged and promulgated through social contact, much as new ideas in science often are. For example, Jacob Metius from Alkmaar also applied for a patent only weeks after Lippershey. Similarly Zacharias Jansen, a spectacle maker from Middleberg, was starting to make spyglasses at this time. Through this confusion of rival patent applications, Jacob Metius received a reward from the Dutch government for his designs, but it was Lippershey who was commissioned to produce this new instrument. This almost simultaneous production of an instrument of this sort is really not so surprising. The spectacle makers were skilled artisans with a natural curiosity regarding the products they made and sold. They would also be discussing different aspects of their activities among themselves, so ideas would naturally develop within the guild as similarly skilled individuals brainstormed along similar lines. These were men of business, keen to take advantage of any situation that presented itself. In this case, patenting such a thing as a telescope would have ensured a commercial advantage and considerable wealth.

Lipershey did not foresee the nascent optical instruments he was producing being pointed at the stars and conferring fame by having astronomical features named in his honour. As far as we can know, the first telescope Lipershey made had an approximate magnification of ×3. This implies that it was a routine spectacle lens used by lace makers, or possibly myopic readers, which formed the objective lens. This is also indicated by the very small diameter of these lenses, being small, round, spectacle-sized objectives. For this modest start, Lippershey has since been honoured by: a small lunar impact crater of about 6.4 km diameter; asteroid 31338, named Lipperhey (no "s"); and Exoplanet Lipperhey, 55cancri d.

The production of useable lenses was a time-consuming process, as well as a skilled one. This meant that for the foreseeable future, the lens makers created and maintained control of a new market where previously there had not been one. Telescopes, although still not referred to as such, were rapidly demonstrating their worth as navigational and military aids. It was going to take a very great observer to use these simple instruments to make new and novel observations in astronomy. The difference with terrestrial-based observations of ships at seas or moving armies is that you start by knowing broadly what you will see—only the broad configuration of relatively close objects being observed. Once the observer pointed a telescope at the skies for what would have been the first time, what was seen was unknown and therefore needed to be rigorously recorded. It then needed to be explained, first in the context of received ideas about the skies, and if that really could not be done, then a new hypothesis to be tested. Explanations were going to needed and tested for poorly seen celestial objects that with these telescopes seemed to be moving in a flat plane, yet by passing each other were obviously at different distances from the observer.

Into this arena there came one of the greatest of all scientists, Galileo Galilei. He has been described in many different ways, but always as the "father of…" Suffice to say that he was a genuine polymath. What made his contribution to astronomy so remarkable and valuable was that he not only thought to point his telescope towards the stars, but wrote down in meticulous detail what he saw. Galileo then interpreted the observations to create hypotheses that could be used to explain other astronomical events; this was how he turned observations into science. We are lucky that not long after having constructed his telescopes, he published his observations in some detail.

The time between Galileo hearing about the first spyglass, which he refers to in Latin as *perspicillum*, and publishing *Siderius Nuncius*, which contained his observations, was only 10 months. In an irony of translation, perspicillum is now routinely referred to as meaning telescope, although as we shall see the word telescope is a compound of Greek roots, not Latin. In 1610, the same year that *Siderius*

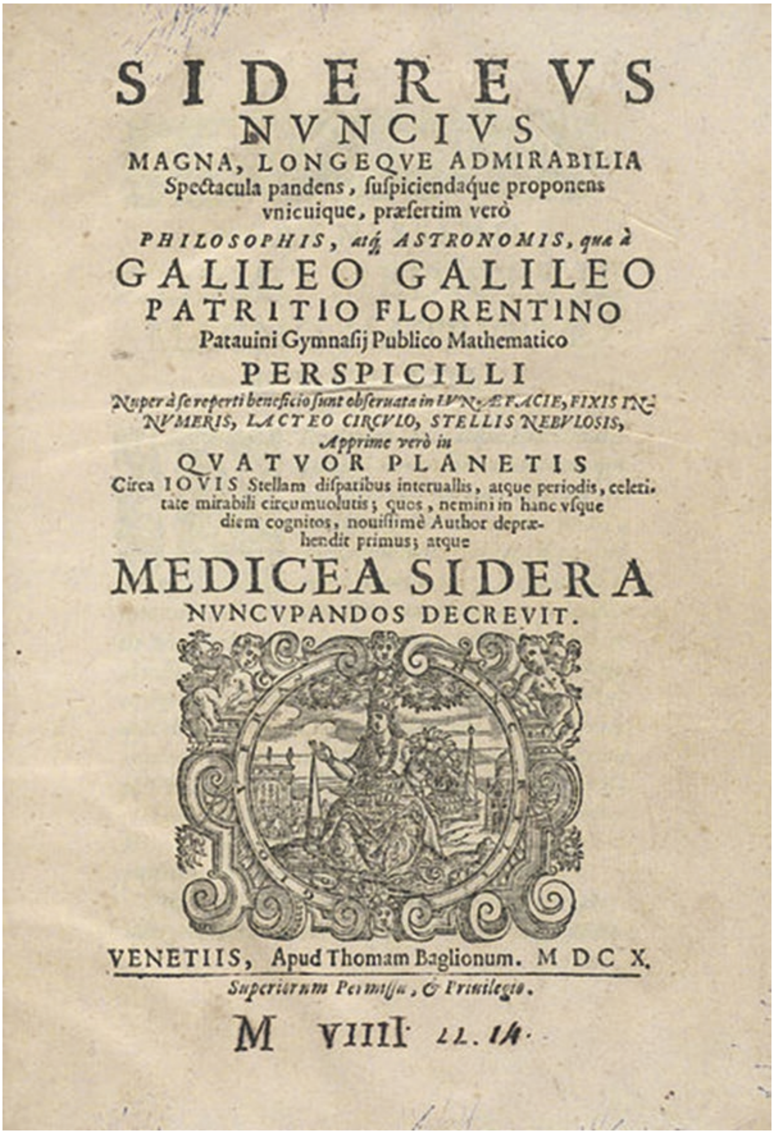

SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.
M VIIII

Fig. 2.2 Front cover of *Siderius Nuncius*. Image from Houghton Library, Harvard University (Houghton Library, Cambridge Massachusetts)

Nuncius was published, Galileo wrote a letter referring to his telescope, which is written in Italian rather than Latin. In this, he referred to his new instrument as l'occhiale, which could be used for eyewear or spectacles. At the time, this was a convenient descriptive, failing a specific name as yet settled on. On occasion, he also used *perspicillum* when we can see from the context that he clearly meant lens, in the same way that we often say “glasses” when it is clear from the context that these are either drinking vessels or spectacles (Fig. 2.2).

At the beginning of *Siderius Nuncius*, Galileo refers to having heard rumours that a Dutchman had made a spyglass. In fact the word he uses is *Belga*, or Belgian having made the glass, but the context clearly rules out our modern notion of Belgium. At the time, 1610, *Belgium* or *Belgica* was clearly used in reference to the Netherlands. The Dutch East India Company was itself known as *Belgica Societas Indiae Orientalis*. It was not until the final split brought about by the London Conference of 1830 that Belgium was constitutionally accepted as an independent country. The name of the new state came from the *Belgae*, the tribe who lived in the area when the Romans moved north under Julius Caesar.

The instrument that Galileo describes using for his observations was constructed from a lead pipe with a planoconvex lens as the objective and a planoconcave lens as the eyepiece. That there was one flat side is not relevant except for ease of manufacture; the important part is the convex or concave surface. This arrangement gives an image that is the right way up. This is important for terrestrial use telescopes. If an inverted image of a known structure is presented to a subject and then details requested, much data will have been ignored that would have been spotted if the image had been the right way up. In astronomy, up and down is not an issue in the same way, so developments made later could do away with this convention of image orientation and its associated problems.

Galileo was spurred on to construct his *perspicillum* by a letter from an acquaintance, Jacques Badovere. He had studied mathematics with Badovere in Padua and had asked him for any information about the Dutch spyglass. Badovere had responded by letter via a third party, Paolo Sarpi, with what amounted to a glowing testimonial of the new instrument and its potential. It was this that galvanised Galileo into action, aware that he could demonstrate a working, even improved instrument before the Dutch versions arrived in Venice.

The instrument he described making was composed of two optical elements, the objective planoconvex and the eyepiece planoconcave. Having the lens flat on one side made the grinding and polishing of the lenses much easier and quicker. This is because it is possible to form a blank suitable for polishing quite easily if only one side needs to be other than flat. He suggested that his first telescope was able to make things look 3 times closer and 9 times large. This would have been the best performance that he could have achieved from lenses bought from a spectacle maker. He then describes his next instrument as being able to make objects appear 60 times larger. This was the instrument, or one very like it, which he presented to the Venetian Senate after his demonstration to the Doge. Upon this success, he spared neither time nor expense to make one that made things 1000 times large and 30 times closer. At this point, Galileo recognised the “Earthly” uses of his telescope, but dismisses them and sublimely pointed it towards the Moon, now barely two diameters of the Earth distant. His delight was palpable in his writings, moving on to view the fixed and wandering stars, meaning the planets (wandering) and stars (fixed).

It is worth noting here that *Siderius Nuncius* follows a tradition of page numbering that was usual at the time, when paper and printing were expensive. The pages are numbered as sheets, so that as the book is opened, only the right hand leaf is numbered and the reverse side is counted as a continuation of that number. After this page-numbering method was discontinued, the tradition of referring to these pages as *Recto* and *Verso*, front and back, remained.

Described observations from this time were inaccurate in detail, which was at least in part a result of the equipment. We can see this in the observations Galileo makes regarding the lunar surface. On the early pages of his manuscript, he clearly describes the surface as being uneven, covered in mountains and depressions, but then approaches a problem of observation regarding the edge, which seems to be smooth and circular. The first suggestion is that there are many ranges of mountains around the edge of the visible disc, both on the visible and on the one turned away from us, giving what is effectively an average view of peaks appearing to be smooth, the depressions in between being invisible due to orientation. As a straightforward explanation based on the available information, which was basically just his own observations, this could explain what he saw. Of course we know this to be incorrect, as modern telescopes easily demonstrate the tessellated edge of the Moon. But the second of Galileo's hypotheses to explain his observation can tell us a lot about his telescope.

On page 12 (*verso*) of *Siderius Nuncius*, Galileo argued that this smooth edge to the visible disc of the Moon was due to an orb of denser substance around the Moon, in the same way as there is around Earth in the form of an atmosphere. He did not call it an atmosphere; the word was not in use at the time. But the similarity must have occurred to him, only scientific reticence stopping him from suggesting a parallel beyond that required by his explanation. This surrounding orb of the Moon would reflect and receive light, not being sufficiently opaque to impede vision, but viewing it towards the edge there is a longer passage through the orb, it being intersected obliquely and thereby hiding the details of the edge of the lunar disc. This was another very perceptive idea to explain the observation, but there is a simpler one associated with the optics of his telescope. The most probable reason for his diffuse observation of the edge of the lunar disc is the spherical aberration of his objective lens reducing the acuity of the system.

Spherical aberration is the varying point of focus of refracted light through a lens. It is an intrinsic quality of spherical section lenses and can be corrected for in one of two ways. This can be done by either polishing an aspherical lens from a single piece of glass, which is extremely difficult, or by making a compound lens. When grinding lenses, the easiest curve to make is spherical—this does not mean totally spherical in shape, just that the curvature has a constant radius. Because the point of focus varies across the lens and is dependent upon the degree of curvature, diameter and refractive index of the glass, the aberration can be quite pronounced. With modern compounded lenses, spherical aberration is eliminated as far as is practicable and for most purposes is not noticed. With a simple telescope of an objective and an eyepiece, such as Galileo made, it can be quite severe. It will tend to render only the centre of the image useable and resultantly gives a halo appear-

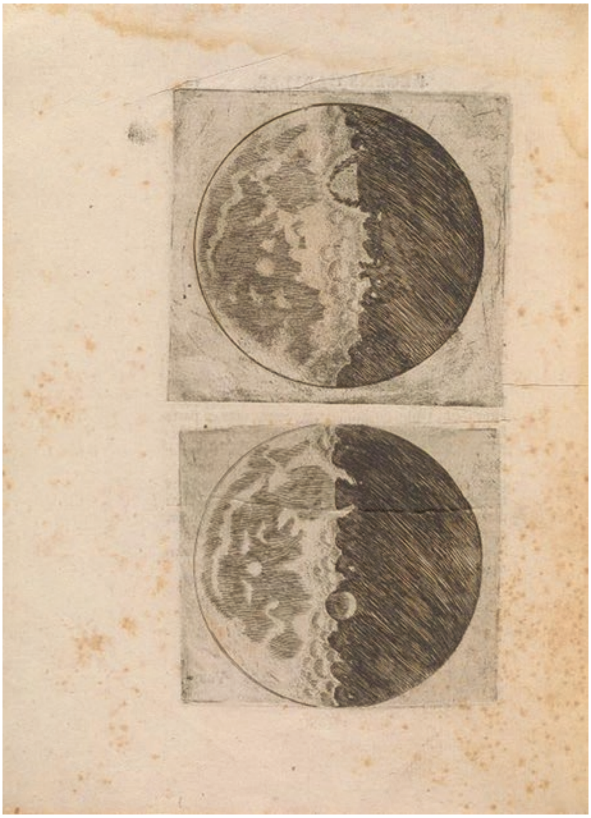


Fig. 2.3 Drawing made by Galileo of the Moon published in *Siderius Nuncius*. This was printed from a wood cut image (Smithsonian Libraries)

ance, what would often be thought of in modern photography as soft focus. This spherical aberration is quite likely to be the principal cause of the low resolution of the edge of the Moon, where the high contrast between foreground and background rendered details invisible.

Galileo continuesd with his investigation of the Moon and described the phenomenon of Earth Shine, as we would describe it, proposing different hypotheses to account for the dark part of the crescent Moon not being entirely dark. He concluded that it was most likely due to light being reflected from Earth back onto the Moon, causing the section not directly illuminated by the Sun to appear in a state of permanent twilight (Fig. 2.3).

Galileo included considerable and detailed observations regarding the Moon before going on to discuss and notarise the stars he could see and account for in the skies over Venice. These observations are of particular interest, as he made the immediate comment that unlike the Moon, the stars do not become enlarged with the telescope, but many stars otherwise invisible to the naked eye become visible. This led to a dichotomy between what he described as visible and invisible stars: those seen with the naked eye and those only visible with a telescope. The sheer scale of invisible stars put Galileo off his original intention of illustrating the whole of Orion, so he confined himself to just the stars around the three in Orion's belt and


PLEIADVM CONSTELLATIO.

Quod tertio loco à nobis fuit obseruatum, est ipsiusmet LACTEI Circuli essentia, seu materies, quam Perspicilli beneficio adeò ad sensum licet intueri, vt & altercationes omnes, quæ per tot sæcula Philosophos excruciarunt ab oculata certitudine dirimantur, nosque à verbosis disputationibus liberemur. Est enim GALAXYA nihil aliud, quam innumerarum Stellarum coaceruatim consitarum congeries; in quamcunq; enim regionem illius Perspicillum dirigas, statim Stellarum ingens frequentia se se in conspectum profert, quarum complures satis magnæ, ac valde conspicuæ videntur; sed exiguarum multitudo prorsus inexplorabilis est.

At cum non tantum in GALAXYA lacteus ille candor, veluti albicantis nubis spectetur, sed complures consimilis coloris areolæ sparsim per æthera subfulgeant, si in illarum quamlibet Specillum conuertas Stellarum constipatarum

cętum

Fig. 2.4 The Pleiades as depicted by Galileo in *Siderius Nuncius* (History of Science Collections, University of Oklahoma Libraries)

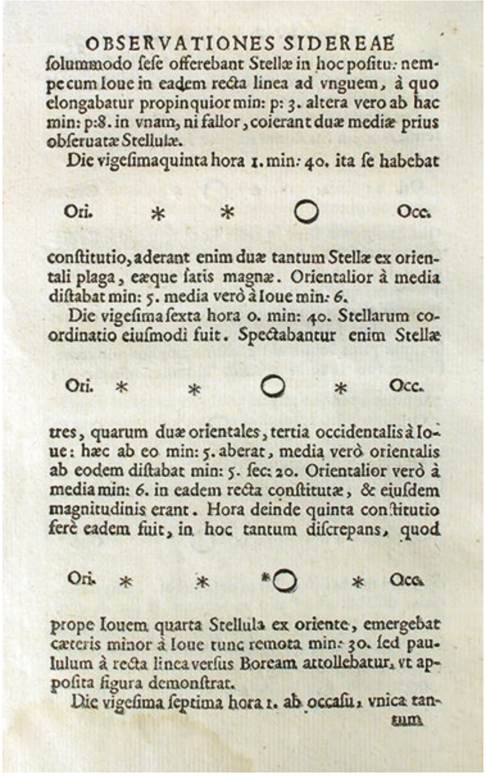
six in his sword; to these he added a further 80 stars. He performed the same exercise with Pleiades, where he saw six stars and commented that there is a seventh, though it is rarely seen. This is an odd statement, as there are six stars brighter than the fifth magnitude and altogether nine stars greater than the sixth magnitude, so usually either six or nine stars can be seen with the naked eye, depending on the eyesight of the observer. To Galileo's six stars he introduced an additional 40 previously invisible stars, separated from the constellation by not more than half a degree. Significantly, one of the previously debated ideas rapidly cleared up in *Siderius Nuncius* was the makeup of the Milky Way, *Galaxya Lacteus* as Galileo referred to it. He decided categorically that this was an area made up of stars, a conclusion by which he also came to regarding nebulous areas of the night sky (Fig. 2.4).

Probably the most well-known observations described in *Siderius Nuncius* were those of Jupiter. These took place over consecutive days and started with Galileo's apparent discovery of three fixed stars, or what he thought were fixed stars, in the background of Jupiter. When he found the arrangement of planet and these new stars were changed, his first thought was that the known calculations of Jupiter's orbit were wrong. This idea faded when 2 days later only two stars, he still thought them to be stars, were visible. Over the next few days it became obvious that the stars were not only aligned in a plane, but were in fact satellites of Jupiter. The first observation had been made on January 7, 1610, but it was not until January 13 of that year that he saw all four satellites at the same time. He describes his observations continuously until January 19, by which time he had accumulated sufficient data to convince himself and his audience that Jupiter had four satellites. He called them the Medicean planets in honour of Grand Duke Cosino II de'Medici, who became his patron. This patronage was not a surprise to Galileo, as not only had he named the Moons of Jupiter in favour of Cosino, but he had also written an introduction to *Siderius Nuncius* of five pages of oleaginous Latin constantly reinforcing the importance of de'Medici.

By choosing the names of the Moons of Jupiter himself and naming the astronomical bodies in favour of an individual, Galileo started a new process in celestial discovery that set a precedent for the following centuries, until the process was taken over by the Naming Committee of the International Astronomical Union. Previously, celestial bodies had taken titles from Greek and Roman mythology. Yet it was an age of exploration, and maps drawn of newly discovered foreign lands were labelled with the names of the discoverers or wealthy patrons who funded expeditions. An example of this is seen in what we now know as Tasmania. When Abel Tasman landed in 1642, he called it Van Diemanslandt in honour of the Governor General of the Dutch East Indies, Anthoonij van Dieman. The name only changed from honouring a powerful patron to the direct discoverer in 1856 (Fig. 2.5).

In the *Siderius Nuncius*, Galileo did not deliberately push the idea of the Copernican Solar System, even though the inference from his descriptions was obvious. This was a pragmatic action on his part, as he would have been well aware of the power of the Church and the value of patronage from political figures closely associated with it. The Catholic Church at this time was completely committed to the Ptolemaic model of the universe with the Earth at the centre and all astronomical bodies revolving around it, which carried out exotic epicyclic dances to accommodate observations.

The origins of the word "telescope" can be fairly well placed at a dinner honouring Galileo. This was held by Frederico Cesi on the election of Galileo into the *Accademia dei Lincei*, Academy of the Lynxes, in 1611. This learned academy was founded by Cesi in 1603 along with a small group of well respected natural philosophers, with the aim of studying and explaining all aspects of natural history as it was understood at the time. At the banquet, Galileo presented the academy with a copy of the instrument he had been using for his astronomical observations. In attendance was a Greek scholar and mathematician, Giovanni Demisiani. It was Demisiani who conjugated the Greek *tele* (far) and *skopein* (to look or see) to create telescope in English and telescopio in Italian. The *Accademia dei Lincei* was one of the first scientific academies in Europe, predating the Royal Society by nearly 60 years, but suffered when Cesi died in 1630 and more or less disappeared 20 years later. It was revived much later on, but under different names.


OBSERVATIONES SIDEREAE
ſolummodo ſeſe offerebant Stellæ in hoc poſitu: nempe cum Ioue in eadem recta linea ad vnguem, à quo elongabatur propinquior min: p: 3. altera vero ab hac min: p:8. in vnam, ni fallor, coierant duæ mediæ prius obſeruatæ Stellulæ.

Die vigeſimaquinta hora 1. min: 40. ita ſe habebat

Ori. Occ.

conſtitutio, aderant enim duæ tantum Stellæ ex orientali plaga, eæque ſatis magnæ. Orientalior à media diſtabat min: 5. media verò à Ioue min: 6.

Die vigeſima ſexta hora 0. min: 40. Stellarum coordinatio eiuſmodi fuit. Spectabantur enim Stellæ

Ori. Occ.

tres, quarum duæ orientales, tertia occidentalis à Ioue: hæc ab eo min: 5. aberat, media verò orientalis ab eodem diſtabat min: 5. ſec: 20. Orientalior verò à media min: 6. in eadem recta conſtitutæ, & eiuſdem magnitudinis erant. Hora deinde quinta conſtitutio ferè eadem fuit, in hoc tantum diſcrepans, quod

Ori. Occ.

prope Iouem quarta Stellula ex oriente, emergebat cæteris minor à Ioue tunc remota min: 30. ſed paululum à recta linea verſus Boream attollebatur, vt appoſita figura demonſtrat.

Die vigeſima ſeptima hora 1. ab occaſu, vnica tantum

Fig. 2.5 The Medicean planets, named in honour of Grand Duke Cosino II de'Medici. The naming by Galileo started the tradition of honouring individuals by naming a celestial body in their favour (History of Science Collection, University of Oklahoma Libraries)

During the period that Galileo was using his telescope and publishing the results in Italy for the benefit of the rulers of Venice and the Papacy, another investigator was busily at work in England. This was Thomas Harriot, an enigmatic mathematician who was a close contemporary of Galileo, being born about 1560. The details of his birth are sketchy, for both time and family. The reason that his birth year is thought to be 1560 is because the records of Oxford University state he graduated in December 1577 aged 17. This would have been on a degree day at the end of the 1577 Michaelmas term. There is no doubt that Harriot was an extremely clever and enquiring mathematician, but it is his demonstrated ability in astronomy which stands out in this context.

Harriot's astronomical studies seem to have started as mathematical investigations, trying to find a way of improving marine navigation due to the influence of Walter Raleigh. Looking for a firm financial base, Harriot became employed by Henry Percy, Duke of Northumberland, who signed over to Harriot an estate in Durham and later the use of a house on his estate at Syon, West of London on the Thames. It was here that as far as we know he started his investigations into optics in 1597. It was around 1601 or earlier that Harriot had worked out the formula that relates the angles of incidence and refraction of light passing through the boundary between two isotropic media (that is, with the same optical properties in all direc-

Fig. 2.6 Willebrord Snellius, a woodcut print showing the very epitome of a well-educated Dutch professional at the turn of the 16th century (Wikimedia Commons, Museum Boerhaave, Leiden)

tions). Because Harriot did not publish his results and simply wrote them down, this sine law of refraction took on another name, Snell's Law. This was because a Dutch Astronomer Willebrord Snellius published a complete mathematical proof of the process in 1621 (Fig. 2.6).

It was around about 1603 that Sir Walter Raleigh asked Harriot for help in his appeal against his conviction for treason, the penalty for which was death. Raleigh was shown clemency, but remained incarcerated until 1618 when he was executed. In the court judgement, Harriot felt quite badly handled, as he had strong Christian beliefs but was labelled by the judge as an evil influence. While he thought this was quite bad enough, it was about to get worse, as soon afterwards he was implicated by association with the 1605 plot to blow up Parliament and kill James I. This came about with the arrest of Thomas Percy, grandson of Henry Percy, the patron of Harriot. Henry Percy was then arrested and kept prisoner in the Tower of London, not being released until 1621. Harriot was also imprisoned in the Gatehouse, a prison originally built as the gatehouse to Westminster Abbey in 1370. The building no longer exists, but the site is marked by a stone and marble column memorial to the pupils of Westminster School who died in the Crimean War of 1854–1856 and the Indian Mutiny of 1857–1858. As there was no evidence against Harriot, he was freed from captivity by the end of 1605, at which point he returned to his optical studies.

Harriot used various telescopes over the following years, apparently starting with a ×6 instrument, which he bought in 1609 as a Dutch trunke. With this, he produced the first drawings of an astronomical object using a telescope, the Moon, just preceding the work of Galileo by a few months. These observations, carried out independently, demonstrate a phenomenon of science—that whenever a new piece of equipment or new technique becomes available, the incurably curious will start looking at ways to make the best use of it, not simply to observe or use as a toy, but to try and push forward what is known. Thus when the telescope appeared, it was natural that the same applications would be made by different people independently within a very short period of time.

By 1610, Harriot had a ×10 telescope that he also used for studying the Moon. Later that same year he had a ×20, and by 1611, a ×32. Between October 1610 and early 1612, he viewed the Moons of Jupiter. It is possible though unlikely that he had seen a copy of *Siderius Nuncius* by the time he started observing Jupiter. As it was written in Latin, he would most certainly have been able to read it if it should have come his way. Harriot himself was not good at publishing his results, so much of his original work remained unknown for many years, being recorded in personal journals and letters.

Up to this point, all of the telescopes so far as we can tell were what are now referred to as Galilean telescopes. This is of simple construction, using two lenses with the simplest of non-plane polished surfaces. It used one planoconvex as an objective and one planoconcave as the eyepiece. This arrangement would have had several advantages in the early days of telescope manufacture. The first was that it was easier to grind and polish only one curved surface (the other being simply polished flat). The second was that this arrangement has no intermediary focus, and so the image is the right way up. The polished curves, both concave and convex, would be close approximations to spherical sections.

This situation was going to change when Johannes Kepler became actively involved in the use of telescopes. Kepler started as a mathematician in Graz, Austria, where he taught at the Protestant Seminary. This was not a position he kept, being forced out due to religious persecution of Protestants. In 1600, he went to work for Tycho Brahe in Prague on a project involving the 20-year archive of pre-telescope observations. These measurements included those of Mars, which could not be fitted into a strict Copernican view of circular orbits. However, the introduction of the concept of elliptical fit the observations much better. By 1611, the year in which his wife and child died, Kepler was using a telescope himself, having moved from tabulating other people's data to making his own observations. Here, the first difference between a user of telescopes and an astronomer using a telescope becomes apparent. If you only use a telescope for astronomical observations, like Kepler, the concept of up and down cease to have any significance. It was because of this that Kepler was happy with the idea of having the image inverted for the benefit of clarity. Interestingly, the inverted image is something that microscopists also comfortably accommodate, as at the microscopical level, there is no absolute frame of reference for orientation. The Keplerian telescope was simply a case of using a convex lens as the eyepiece instead of a concave one.

In optical terms, this results in an inverted image, but there are several significant improvements available to the observer. The most important of these is that the emerging light rays are converging, which allows for a much better field of view and better eye relief. Eye relief is the term for the distance from the last element of the eyepiece to the eye at which a full viewing angle is achieved. After this point the field of view is reduced, a phenomenon easily demonstrated by slowly moving the eyepiece of a binocular, telescope or microscope away from the eye. With a two-convex lens design, it is possible to get very high magnifications with a telescope, but under normal circumstances, this also creates magnified aberrations, a limiting factor for the telescope. One can overcome the worst of these errors through a very high f-ratio. This is essentially the same as the f-stop used in photography and is the focal length divided by the objective diameter. This is normally expressed as

$$N = f / D$$

N is the f ratio (f number in photography)
f is the focal length of the objective
D is the objective diameter

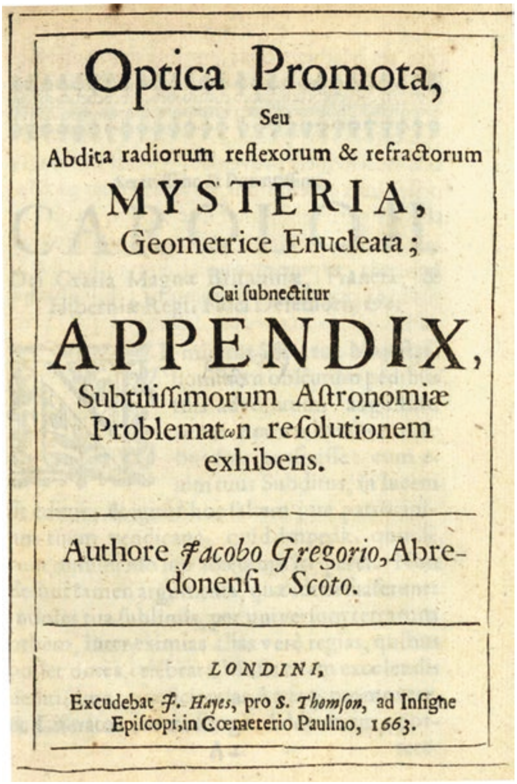
Using this formula, it is easy to see how a low-convexity lens with a consequent long focal length will give a higher value for N. This controls to some extent the aberrations inherent in the optical system, but results in a physically very long telescope. These long instruments were popular with astronomers for some years until optical improvements were made in lens design, but they were very difficult to use, as the smallest movement of the telescope would take the field of view away from the object being studied.

Even with these improved designs, the two major problems of refracting lenses—spherical and chromatic aberration—remained major stumbling blocks for many years. The reflecting telescope was a possible alternative to the refracting telescope. This is a telescope constructed using shaped mirrors. It was believed at a stroke that this would obviate the problem of chromatic error, as the light would not be split by diffraction. The first plans regarding the possibility of making a reflecting telescope came soon after refracting telescopes became readily available. One such attempt was reported by Niccolo Zucchi in Italy. He recorded that in 1616, he had tried making a reflecting telescope but had given up on the project because the result was not very good. There are several possible reasons for this and other failed attempts that would dog reflector telescopes for many years while technology caught up with the science.

The first of the difficulties lies with the method of manufacture. Zucchi had tried to make a bronze mirror, a material which for flat use has a long history, but for curved surfaces, it is a much trickier process. Bronze is generally an alloy of copper and tin, but there are many different variations on this, so although we do not know for certain what form of bronze Zucchi used in his attempt, it would most likely have been worked bronze. This is mostly copper and contains about 6% tin, as compared to the harder bronze of castings, which contains 10% tin. There is another bronze that was made up of copper, lead, nickel, zinc and bismuth, which polishes well but is unlikely to have been available to Zucchi. The bronze he would most likely have had would have been taken from an ingot and hand worked with mallets and planishing hammers until the surface was curved and smooth. This is the way a bowl would be made that was not cast, and although very good for bowls, it is very difficult to get the accuracy of curvature in all directions that would be needed for a mirror. This variation would not be immediately obvious, so although polishing unevenness from the surface is possible, it would not be possible to correct for curvature by the time the mirror was being polished. It would only be when it was finally put to use that the spherical errors would become apparent. Given this difficulty, it is not surprising that it took more than half a century before a reflecting telescope could be made that could generate astronomical data.

Designing a reflecting telescope was possible long before it could be made, which was a frustration to those interested in practical uses of instruments rather than their theoretical basis of construction. One theoretician who put his mind to design was James Gregory (1683–1675). Like many of these 17th century scientists, he is primarily remembered as a mathematician rather than as an astronomer. Even so, one of his works was titled *Optica Promota*, published in 1663. In it he describes a design for a reflecting telescope with a large primary mirror which was concave, but parabolic rather than spherical so that all points on the mirror had the same focal point, curing the problem of spherical errors. Beyond the focal point of the primary mirror there was a smaller secondary concave mirror of much longer focal length, so that the image was focused behind the primary mirror through a central hole. Unfortunately, Gregory could not find an optician to make the telescope. Whether this was for technical or financial reasons remains unclear, but it would be 10 years before a telescope to his design was made. The design that Gregory produced was the simplest possible and is very rarely used in modern telescopes, but interestingly, it is the basis of the design still used for making compact, long focal-length camera lenses. These tend to be catadioptric lenses, using a lens system as well as mirrors (Fig. 2.7).

Ten years after James Gregory published his design, Robert Hooke took up the challenge. By then, it was possible to produce a telescope. Part of the problem was that the mirrors had to be parabolic to come to a uniform focal point, and this was extremely difficult to accomplish. When Isaac Newton produced his first reflector telescope in 1668, he used spherical section mirrors, so the resolution was diminished by spherical errors. The primary mirror of Newton's reflector was about 1.3 inches in diameter and made of speculum metal. This is an alloy of roughly 2 parts copper, 1 part tin. The exact composition can vary widely, with more copper giving a yellow tint and more tin a blue one. This alloy was widely used in hand mirrors, and although prone to long-term corrosion, it took a very high polish. In a marked difference with the Gregorian design, Newton had a plane mirror positioned at 45° to the primary mirror before the focal point. This directs the image outwards through an aperture in the side of the telescope tube where the image can be viewed at the focal point of the primary mirror. This was quite useable for short periods of time and was quite influential with the Royal Society, but the optical quality of the mirror was such that it performed worse than the refractors of the day.


Optica Promota,
Seu
Abdita radiorum reflexorum & refractorum
MYSTERIA,
Geometrice Enucleata;
Cui ſubnectitur
APPENDIX,
Subtiliſſimorum Aſtronomiæ
Problematωn reſolutionem
exhibens.

Authore *Jacobo Gregorio*, Abre-
donenſi *Scoto*.

LONDINI,
Excudebat *J. Hayes*, pro *S. Thomſon*, ad Inſigne
Epiſcopi, in Cœmeterio Paulino, *1663*.

Fig. 2.7 Front page of *Optica Promota* by James Gregory, 1663 (Wikimedia Commons, St Andrews University)

The reflector telescope made by Newton predates the Gregorian telescope made by Robert Hooke, but this was a superior device with the perceived advantage of giving an upright image. Although not used universally in modern instruments, for the amateur telescope maker, this type of construction with two concave lenses has a significant advantage. It is possible to check the parabolic curvature and local defects in the mirror, as they are Foucault testable, a method devise by the 19th century physicist Leon Foucault. The constructional problem of this form of telescope was that the image from the secondary concave mirror was reflected directly back to the focal point behind the primary mirror, which to be visible needed a hole in the centre of the primary. For mirrors made of speculum metal, this was not such a problem, but when mirrors became glass, cutting the hole became a technical trial.

The third form of reflector telescope that appeared at this time was designed by Laurent Cassegrain and is now referred to as a Cassegrain telescope. This was another construction based upon two mirrors, but with a concave primary and a convex secondary lens. This design is interesting because it puts the focal point of the secondary mirror some way behind the primary mirror. This gives a long focal length and a consequent greater magnification in a physically short length. It does, of course, require an aperture in the primary mirror, and the curvature of the convex mirror is not so easy to measure accurately, unlike the Foucault testable concave primary mirror. This design was published in 1672 in *Journal des Scavans*, a journal which has gone through several iterations, ceasing publication for a while but now appearing as *Journal des savants*, specialising in the humanities. The Cassegrain design has had several changes made to it over the years, being reformed with subtle differences, but retaining the concave/convex mirror mix.

There is no doubt that using mirrors made a significant difference to the ability of astronomers to make meaningful measurements, once development of long-lasting mirrors became possible. Using speculum metal, it was possible to produce very high efficiency reflecting surfaces, but tarnishing was a problem, as was expansion and contraction with changes in temperature. The grinding and polishing of parabolic surfaces was always going to be a highly skilled process, both for polishers of lenses as well as polishers of mirrors, but mirrors do not split the light by diffraction.

The last component of the telescope that affects astronomical observations taken from a terrestrial position is the atmosphere. This also has the same effect upon terrestrial observations made by a lookout over long distances. The optical quality of the atmosphere has changed considerably since the first telescopes were constructed, with changes in transparency and ambient night time light. This has resulted in searches for places to put telescopes that are out of the way of both chemical pollution and light pollution. While these have traditionally been at the top of mountains, the second half of the 20th century saw a development that went one stage further: the ambitious idea of putting a telescope into space. There would be problems previously unthought of associated with this project, along with ground-breaking engineering solutions to solve them.

References

Galilei, Galileo. 1610a. *Siderius Nuncius*. Venice: Thomas Baglioni.

———. 1610b. *Siderius Nuncius*. Translated in to English by Albert Van Helden. University of Chicago Press, 1989. Venice: Thomas Baglioni.

Gregory, J. 1663. *Optica Promota*. London: J. Hayes.

Chapter 3
Developments in Optics and the Newly Invented Telescope

After the original flurry of activity and outstanding discoveries associated with the first two lens telescopes, frustrations started to develop as it was realised that there were limits to these instruments. To start improving an instrument, whether this is a telescope or any other device, it is necessary to describe what its shortcomings are.

Primarily (although not exclusively), early telescopes were limited by two major problems. The first of these was spherical error and the second was chromatic error. These refer to the finished product, of course, because there were many other sources of error that could corrupt the image, from colour casting in the glass to flaws and scratches when the lens was made. The difficulty of creating lenses with no obvious physical flaws in the glass was the first hurdle that telescope makers had to overcome. Early telescopes were constructed by what were essentially artisan spectacle makers. These skilled makers of small batches of glass could spend time re-melting glass until they had a suitably clear and useable blank they could then polish for clarity. This was not often difficult process when making blanks for spectacles, as these were small, but it became more of an issue when requests were made for lenses suitable for use in a telescope.

Polishing a lens is much simpler if the intention is to produce a spherical section. This was what the earliest telescopes used; a spherical section lens will magnify and is useful in spectacles. It was in fact the lens section that the spectacle makers were familiar with, and therefore the one they made for the early telescopes. Up until the 21st century, it was still a financial consideration whether to use several spherical elements that would be cheaper than designing and polishing a single aspherical element. The spherical section causes spherical errors, due to a spherical lens being unable to focus a point object to a point image, except at the aplanatic point. Consequently, the image never comes into complete focus. What is not so obvious is that the error is related to the curvature of the lens, being proportional to the fourth power of the diameter, so with small lenses it can be extremely pronounced. It also reduces the effective area of the lens that can be used, this being dependent upon the refractive index of the glass. There are two ways in which this can be overcome. The first is multiple spherical elements and the second is to grind an aspherical

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lens. This second method is difficult, requiring a knowledge of geometry so that the curvature can be measured accurately throughout the polishing process.

In broad terms, the spherical aberration is at a minimum along the mid line of the lens running through the centre, because it is not uniform across the lens, being minimal at the centre and at a maximum at the edge. The radius of the sphere making up the convex surface of the lens divided by the refractive index of the glass gives a useable area of the lens that can be used to maximum affect. While early telescopes would have been made from crown glass, to make the best use of them would require a small diameter and long focal length lenses.

When telescopes were first being made, it was normal for the adventurous astronomer to try and improve on lenses that could be bought by grinding and polishing their own. In this, Galileo was a leading exponent. During his later years until his death in 1642, Galileo was effectively incarcerated under house arrest at the orders of the Papacy. He was also troubled by failing eyesight, which may well have been due to his style of observation. Although he reportedly viewed the Sun projected onto a screen, the potential damage of direct viewing was sometimes ignored; certainly other astronomers are recorded as viewing the Sun directly and recording their eyesight as impaired for hours or days afterwards. Although we do not know the cause of Galileo's total blindness, it developed over many years, and by 1638 he was unable to see. What we do know is that he was very keen on optimising the optical performance of his lenses, and there is some evidence that he was not only aware of the aplanatic points of a lens but that he made use of the knowledge.

Galileo passed on his techniques of lens polishing before he became completely blind. It is not known in detail what the techniques were, but they do not seem to have been very different to those of other lens grinder except in one primary way. Galileo did not use the entire width of the glass blank to make his final lens but stopped them down; it is this that indicates that he had an understanding of spherical aberration. By only using the central area of the lens, he sacrificed both field of view and brightness of the image but gained image definition.

It may be imagined that the stopping down was an accidental effect of mounting the lens, however, the edges of some lenses were not polished—a deliberate reduction in optical useable area. The reduction in area was also quite large, indicating a knowledge of what was required for clarity of image and also how to go about it by stopping down. In this way, one of the telescopes of 5.1-cm-aperture is stopped down to 2.6-cm diameter. Other telescopes are also stopped down in similar proportions to improve image clarity.

With the associated problem of chromatic aberration, the single lens, planoconvex or biconvex, has a very limited resolving power, with longer focal lengths being better suited to observation than shorter focal lengths. It was with a spherical section lens of focal length 169 cm and aperture of 3.8 cm as the objective that Galileo discovered the satellites of Jupiter. This lens was at some point broken, but even in its day it was still recognised as of value. Consequently, it was presented to Prince Leopold de Medici, who had it mounted separately in a frame, rather than a telescope. In 1657, Prince Leopold helped to found the Accademia del Cimento (the Academy of the Daring) to promote observation using the scientific principles of Galileo.

Besides the spherical errors of these lenses, the very nature of the glass causes chromatic errors due to dispersion. If spherical errors were the only problem with these telescopes, that would alone make proper focusing impossible, but with chromatic errors as well, the focus becomes ever more problematic. Objects would have multiple images, effectively overlaid from the smallest at the extreme blue end of the spectrum through to larger ones at the red wavelengths. Monochromatic light could eliminate this, but celestial bodies, especially those reflecting the Sun, would appear to be white, reflecting a full spectrum. This would render them impossible to focus, further complicated by a surrounding halo, which in the case of planets can easily be mistaken for an atmosphere. It is not just the outer surface of the planet that has the optical disturbance, but also any features are visible on the planet, say craters on the Moon.

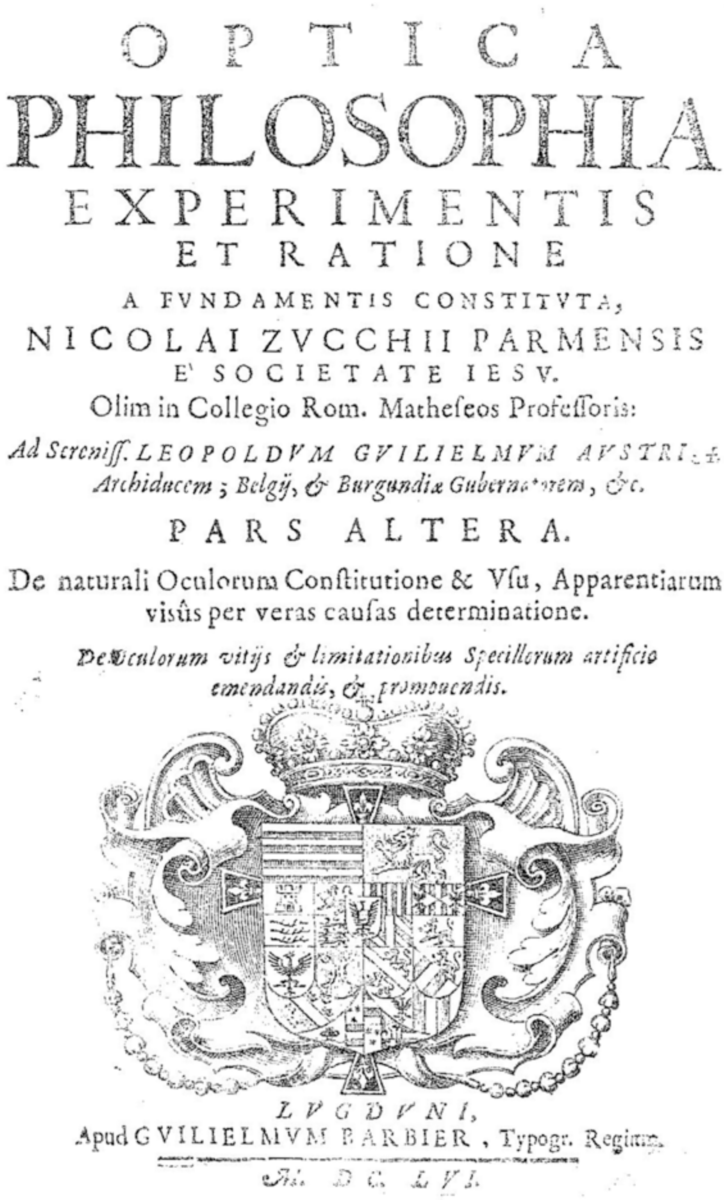
These faults were apparent to many observers and later on were addressed most successfully by the use of mirrors, as first described by Niccolo Zucchi in *Optica philosophia experimentis et ratione a fundamentis constituta* in 1652. He records that in 1616, he used a mirror found in a Cabinet of Curiosities to create a magnified image. This was usually a room that had an eclectic collection of what was broadly natural history, with oddities and unusual items of interest as well. The mirror was described as parabolic but was most likely a broadly concave mirror with considerable imperfections. The difficulties of making a metal mirror stopped Zucchi from pursuing his attempts to make a reflecting telescope, although he recognised the potential (Fig. 3.1).

Before it was possible to routinely eliminate the two major sources of error, spherical and chromatic, they had to be formulated in such a way that they could be understood. This task was taken on by Johannes Kepler when his colleague Tycho Brahe died in 1601. Taking the extensive collection of data accumulated at Uraniborg, Kepler formulated his three laws of planetary motion:

1. Planets follow an elliptical path about the Sun, with the centre of the Sun being located at one focus.
2. The swept area of an orbit is constant for equal periods of time.
3. The ratio of the cubes of the average distances of any two planets from the Sun is equal to the ratio of the squares of the periods of the planets.

Besides these laws, Kepler also established the principle of refraction as dependent upon the level of resistance of the medium through which the light travelled, rather than the nature of the object. Although not entirely correct (for example the refractive index of ice is slightly less than water, which is slightly denser) it was enough to help him obviate atmospheric refraction when dealing with the data from Tycho Brahe (Fig. 3.2).

The data Kepler used and reduced to a manageable scale was to become known as *Tabulae Rudolphinae*, the Rudolphine Tables, a gallant acknowledgement of patronage. At the time, Kepler was familiar with the court of Rudolph II, Holy Roman Emperor and Imperial Mathematician. This was a post of unreliable payment and not very well paid even when funds were available. In some ways, the title gives an insight into the difference between the skills of Tycho and Kepler. Tycho was supremely



OPTICA
PHILOSOPHIA
EXPERIMENTIS
ET RATIONE
A FVNDAMENTIS CONSTITVTA,
NICOLAI ZVCCHII PARMENSIS
E' SOCIETATE IESV.
Olim in Collegio Rom. Matheſeos Profeſſoris:
Ad Sereniſſ. LEOPOLDVM GVILIELMVM AVSTRIÆ
Archiducem; Belgij, & Burgundiæ Gubernatorem, &c.
PARS ALTERA.
De naturali Oculorum Conſtitutione & Vſu, Apparentiarum
viſûs per veras cauſas determinatione.
*De Oculorum vitijs & limitationibus Specillorum artificio
emendandis, & promouendis.*
LVGDVNI,
Apud GVILIELMVM BARBIER, Typogr. Regium.
M. DC. LVI.

Fig. 3.1 The front cover of *Optica philosophia experimentis et ratione a fundamentis constituta* by Niccolo Zucchi, published in 1652 (Zentralbibliothek Zürich, Wikimedia Commons)

Fig. 3.2 Uraniborg, the observatory set up by Tycho Brahe was sited on the island of Hven, in the centre of the map. Originally Danish, it later became Swedish, as on this map of 1913 (Authors Image from Royal Atlas of Modern Geography, W. & A.K. Johnson, 1913)

practical and skilled, while Kepler was far more comfortable handling and generating data, rather than making the instruments that could be used to collect it.

It is interesting to note that although the observatory at Uraniborg had fallen into a state of considerable decay by the 19th century, its fame and importance amongst astronomers remained widely acknowledged. This was so much so that it was often visited almost as a shrine to the work of Brahe and Kepler. One such visitor was George Forbes, an astronomer of considerable ability. He visited Heinrich Louis D'Arrest at Copenhagen Observatory in 1872, where he was presented with a brick from the ruins of the Uraniborg Observatory. By his own admission, this became one of his most cherished possessions, and after a "long absence on astronomical business", was dismayed to find it had been tidied away from his study by his cleaner. The "astronomical business" was as an observer on Kailua, Hawaii (at that time the Sandwich Islands) where he witnessed the 1874 transit of Venus.

Kepler tried to produce a law of refraction, and although he did not succeed, his designation of a refractive index of 1.5 compared to air allowed him to deal with simple lens problems. It was his work on the anatomy of the eye that suggested that a hyperboloid lens would solve the problem of spherical aberration in telescopes. His acute observation of anatomy demonstrated that it was necessary for an in-focus image to be projected upon the retina before it could be seen. We may regard this as commonplace knowledge now, but at the time that Keppler was working, the Euclidean idea of the eye was still believed. This simply held that a beam was projected from the eye onto the object being looked at. When Kepler was working, the idea of light entering the eye rather than being projected from it was not an entirely new idea, but it was he who first demonstrated of it. His anatomical work seems in stark contrast to his stated inadequacies as a practical man; by his own confession he was not a great observer and he was awkward with mechanical operations. His forte was the manipulation of data and mathematics, at which he was one of the greatest of minds.

While the definition of the two major sources of errors was clear, and the possibility of correcting one of them—chromatic error—was straightforward by the use of mirrors rather than lenses, it was going to be some considerable time before these became widely applied. Even with mirrors, spherical aberration was technically tricky to overcome. It had been known for some considerable time; in fact it had been described by Kepler that a hyperbolic lens or mirror would correct for spherical error. He recognized that the shape of the lens in an eye is not a symmetrically biconvex structure, the anterior surface being of a different curvature and shape to the posterior. Although the conclusion regarding telescope lenses was correct, the comparison is extremely difficult to take further, as the cornea acts as a focusing structure as well, and there are clear supporting liquids within the eye that all have an influence on optical performance.

Although it was theoretically possible to overcome both spherical and chromatic errors by using a shaped mirror, in the 17th century, the practical difficulties of manufacturing a complex mirror meant that interest still remained with making lenses as good as they could possibly be so that refracting telescopes could get better. There were also the large guilds of opticians made up of skilled lens makers, each one trying to outperform their rivals. When it came to making mirrors, however, no such competitive guilds were in operation, so if an astronomer wanted a mirror, they generally had to make it themselves.

The aspect that puzzled many scientists at the time was how to get rid of chromatic errors in a lens. One of the earliest references to a method of correcting chromatic aberration came in 1695. It is quite possible that this would have been addressed earlier, except for the legacy of Isaac Newton. He had investigated light in some considerable detail and had concluded that refraction and dispersion were inextricably linked. It was David Gregory who seems to have been the first to question this idea in his 1695 publication *Catoptrica et dioptricae sphaericae elementa*. He observed that humans do not have a problem with chromatic error and thought this may be due to the mixed materials of the eye (cornea, aqueous humour, lens, vitreous humour, from the air to the retina) so it would be reasonable to extend this idea to lenses and make them of composite glasses. The technique for doing this was beyond the speculative Gregory, and so as far as we know nothing was made of the idea; certainly no lenses seem to have been constructed. As an idea, the logic was correct, but we know that the eye as an optical system is not entirely achromatic, and perception of colour is rather more complicated than a simple optical system could hope to reproduce. An example of this is the perception of brown. Although we register it as a colour, it is normally regarded as an achromatic colour. This is a contradiction in terms, but it accurately describes the complexity of perception of colour against the physics of optical wavelengths (Fig. 3.3).

In 1729, when a barrister in the City of London by the name of Chester Moore Hall, possibly either having read Gregory's work or thinking along parallel lines, decided to make an achromatic lens. It would seem that Chester Moore Hall was by nature an enthusiastic optical experimenter, regardless of his legal education and money-making activities. By 1733, he had made a preliminary design for an achromatic lens. This was of a crown glass front element and a flint glass rear element.

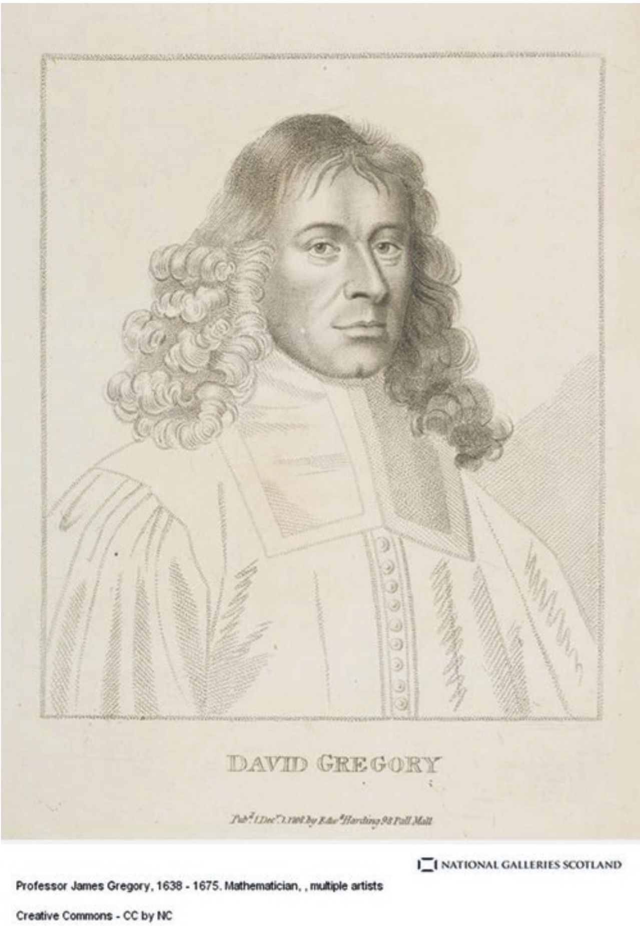


Fig. 3.3 An engraving of David Gregory, published in 1798 by David Harding, London (National Galleries of Scotland, Creative Commons)

Crown glass is mostly fused silicates with about 10% KO, while flint glass is made from high purity silicates with additional lead oxide PbO. The additional components can be used to modify the refractive index quite considerably. Crown glass typically has a dispersion of Abbe number around 60, depending on the mixture, while flint glasses vary from Abbe number 50–55, again depending on the mixture. Dispersion in this context is a measure of the change in the angle of diffraction of light at different wavelengths, being dependent on frequency. This is most obviously manifested as the dividing of uniform light into its constituent colours in the form of a rainbow.

Flint glass has an historical date of origin with the patent awarded to George Ravenscroft in 1674. He had been set the challenge of finding a useable supply of raw materials by the Worshipful Company of Glass Sellers in London for their own use, as they were disappointed with the quality of the raw materials and glass available from overseas. It was during this process that he came up with the alternative to crown glass. Ravenscroft's glass was known as "flint" because of the flint inclusions in the raw materials (Fig. 3.4).

It was not until the 19th century that the measure of dispersion became known as the Abbe. It is a composite value, being a measure of the variation in refractive index depending on the wavelength of light. It is said that by the middle of the 19th century, when Ernst Abbe specified a lens made of glass of a specific refractive index, Otto Schott could make the glass. This may be apocryphal, but it is certainly true that the collaboration between Abbe, Schott and Zeiss produced some of the very best microscopes available at the time. The relationship between the resolving distance of a lens, wavelength of light and refractive index was solved mathematically by Abbe around 1872 and was of such significance that it is inscribed on his memorial in Jena.

Fig. 3.4 The coat of arms of the Worshipful Company of Glass Sellers. This is still an active association supporting and working with the glass industry. The moto translates as "weakened by discord" (Worshipful Company of Glass Sellers)

At the time that Chester Moore Hall was interested in the construction of an achromatic lens, there was only a generic type of glass, crown glass, and flint glass of varying quality. These were known to have different refractive indices, although the dispersion was unknown. Moore Hall decided that using these two glass types might be advantageous in constructing a telescope lens. He did not grind his own lenses, which is understandable, as it was both time consuming and a skilled job. Instead, he had them made for him using his design.

Throughout 1729 and 1730, Moore Hall worked on the project in the laboratory he had built at his Essex home. He described his experiments on controlling "refrangibility" of lenses for use in refracting telescopes to his friend Addison Smith, who was himself an optician in St. Martin's Lane in Soho. When Moore Hall was ready to construct a composite lens in 1733, he approached two different opticians to make the two different lenses, one of flint glass and one of crown glass. One of these was Edward Scarlett of Soho, and the other was James Mann of Ludgate Street. Ludgate Street is no longer there under that name, having been widened and renamed Ludgate Hill in the middle of the 19th century. Both of these were well respected opticians, having both served as Master of the Worshipful Company of Spectacle Makers which had been running as a guild since 1629. Beyond this, Edward Scarlett is credited with inventing "temple" spectacles with sides that held them against the side of the head. Until then, spectacles had been held in place by hand.

These two practiced glass grinders inadvertently thwarted Moore Hall's attempt at secrecy by subcontracting the grinding to the same man, George Bass of Bridewell, a short walk for both of the spectacle makers from their places of work. The blanks for grinding and polishing came with the notification that they were both for Mr. Moore Hall, a consequence of which was that Bass may have put the lenses together as a pair and tested their optical clarity. However, it is said that Bass did not have an understanding of optics sufficient for him to have deduced the significance of the matching lenses. This first attempt at an achromatic lens was 2½ inches in diameter with a reported focal length of 20 inches. This was apparently a great improvement on single lens constructions, so Moore Hall had Bass grind several more. When he was quite satisfied that these dual lenses were a consistent improvement on single lens constructions, Moore Hall gave written instructions to his two friends, John Bird and James Ayscough, who had been an apprentice to James Mann and introduced folding sided spectacles. Ayscough became very well known later on for his microscopes rather than spectacles or telescopes. Moore Hall, having successfully solved the problem, did not bother with either widespread communication or patent; he simply went onto his next project, which was a marine quadrant. It would appear that Moore Hall was entirely motivated by curiosity and his desire to solve a perceived problem. It was most definitely not financial.

This lack of appetite for greater acclaim on the part of Moore Hall resulted in the newly invented lens languishing as an idea for many years, as both Bird and Ayscough stopped any further development while they grew their optical business along the most profitable lines. As a consequence, commercial development of the achromatic lens and subsequent telescopes was left to John Dollond. Dollond was about to found one of the oldest businesses in England: Dollond Opticians, later Dollond and Aitchison, which only disappeared in a corporate takeover in 2009.

The story starts with John Dollond's father, Jean Dollond. He was a Huguenot silk weaver who, having prospered under the Edict of Nantes, had a reversal of fortune when the Edict was finally renounced in October 1685. The result of this effectively made it illegal to be a Protestant. Thus, along with many others, he moved to Spitalfields in the East End of London where there was a growing silk-weaving community. Dolland was born in 1706 and by 1720 would have started his apprenticeship as a silk weaver. At the same time, he was very interested in science and mathematics, joining the London Mathematical Society, which had only been formed in 1717. By 1750, Dollond had become well known in London's scientific circles for his knowledge of optics, and this was the year when Dollond heard of the work of Moore Hall from the Reverend Rew, although Jesse Ramsden claimed that it was Bass, the optical grinder, who had informed Dollond. Ramsden also claimed that Bass had advised Dollond that the colour aberrations of a reading glass could be overcome by combination of flint and crown glass lenses (Barty-King 1986).

There must have been a very specific demonstration to Dollond that it was possible to combine lenses to make an achromatic doublet, since a paper by Leonard Euler of 1747, published in Berlin, started a correspondence between Dollond and Euler in which Dollond was very sceptical of the possibility of correcting chromatic error by combining lenses. There was a change when Euler, having a logical discrepancy pointed out by Dollond, conceded that his mathematical analysis of refrangibility was based upon a law of refraction that was slightly different to that proposed by Newton. This subtle change was sufficient to allow the geometric analysis to work perfectly so that a mathematical model of an achromatic lens was possible, although by his own admission, Euler acknowledged that spherical aberration was still a problem. Adding to this work, Euler finally realised that a differential curvature decreasing from the centre to the perimeter should overcome this. Interestingly, another scientist was investigating non-spherical lenses, but less for telescopes and more for microscopes. This was Johann Nahtanael Lieberkuhn. We now remember Lieberkuhn for his exemplary histology work. The Crypts of Lieberkuhn were named in his honour. Yet, he was also very interested in optics, developing the microscope beyond its contemporary performance.

It was later communications with the Swedish professor Samuel Klingenstierna and learning of the practical demonstrations of Moore Hall that persuaded Dollond to change his mind regarding the practical construction of achromatic lenses. After several experiments with lenses separated by a film of water, he determined that it was indeed possible to make such a theoretical device. His next step was to grind and polish two complementary spherical lenses. They did correct the chromatic aberration, but being of spherical section, the aberration due to shape was prodigious. Dolland realised this was due to the spherical section of the lenses but was at the time investigating the chromatic errors. At this point the details become a little confused, but a letter to the Royal Society Jesse Ramsden, after whom the Ramsden eyepiece is named, describes what was thought to have taken place when John Dollond made a visit to the Bridewell workshop of George Bass.

Dollond was looking for a suitable reading glass for the Duke of York, and Bass gave him a selection to assess. Dollond was taken with one of flint glass due to its clarity, but Bass pointed out that the letters viewed through the edge of the lens were more tinged with colours than those viewed through an equivalent crown glass lens. At the same time, Bass passed on the information that he had worked the concave lenses for Mr. Hall from flint glass. Dollond made the necessary connection between the crown and flint glass refractions and started experimenting with the two lens types in 1757, using water as the joining medium for the two lenses. By 1758, he had amassed sufficient data to prepare a letter on the subject to James Short, who recognised the significance and passed it on to the Royal Society for publication in the *Philosophical Transactions*. It was later said that a Dollond 3-ft telescope had the performance of older, long focal length telescopes of 15 times the focal length.

By 1750, Dollond's eldest son Peter had opened an optical business in Vine Street, Spitalfields. Two years later, he was joined in the business by his father. It would seem that it was at the commercial insistence of Pete Dollond that John made a patent application for the construction of achromatic lenses. With the publication of his work, Dollond was awarded the Copley Medal of the Royal Society in 1758 as a recognition of the importance of his work, or as the citation puts it, *On account of his curious Experiments and Discoveries concerning the different refrangibility of the Rays of Light, communicated to the Society*. He did not live to see the promising development of his objective lenses, as he died of a stroke at home in November 1761. The commercial capital made out of his patent was considerable.

It was the commercial success of his invention that stirred other opticians to either ignore the patent or dispute it directly. There was some commercial motivation for trying to break the patent, whatever the stated reasons. By 1764, the social politeness that had accompanied the death of John Dolland had dissipated. There appeared open criticism regarding the grant of the patent on the achromatic lens, with some pointing out that this was previously described by Moore Hall. It was assumed that Dolland had seen and copied the flint/crown doublet that Bass had created. On the basis that it should have been acknowledged, at least in part, that the patent was based on others' work, the opticians in London took it upon themselves to flaunt the patent. Whether deliberately ignoring the work of Moor Hall, or simply being unaware of his influence, Dolland nevertheless brought the value of this remarkable discovery to the forefront of the astronomy community.

While the patent held, it generated considerable rewards for the Dollands, a fact that also would have been a source of some considerable chagrin for his commercial rivals. Even though good quality flint glass was hard to come by and it was difficult to grind and polish, the obvious advantage of this sort of lens justified the cost to customers. These were people that would otherwise have bought their telescopes from other companies. Although none of the other opticians were going out of business due to the patent on achromatic lenses, they were certainly losing business, and therefore money, and like all good businessmen, they wanted to get in on the act. This avarice even extended to a partner in the firm of the Dollands by the name of Francis Watkins. Watkins had been taken on in 1758, but later on Peter Dollond found out that he had been making achromatic lenses on his own account. The partnership was not only terminated by Dollond, but he also extracted a royalty payment of £200 from Watkins at the same time.

This confrontational approach to protecting the rights of the patent sent a message that other opticians should beware of infringement. The argument over the ownership of the practical construction of an achromatic lens peaked when 35 of the Freemen of The Spectacle Makers Company got together and created a petition in June 1764. This was not a simple set of signatories: it was a petition for George III to vacate John Dollond's patent. In this context, "vacate" means to annul the patent. It was a lengthy document, with many well-known individuals appending their names. Regardless of the arguments, the basic premise was that John Dollond had not invented the achromatic lens but had in some way gained knowledge of the device from the real inventor, Chester Moore Hall. The petition was presented to the Privy Council by their lawyer, the interestingly named Mr. Grubb. The Privy Council, however, was not easily swayed and dismissed the petition, demonstrating publicly that the patent was valid. Even here, the tale is not entirely straightforward, as one of the people who did not put their name to the petition was Jesse Ramsden. Ramsden not only joined Peter Dollond in his workshop, but he also married Sarah Dollond, who was the sister of Peter Dollond.

With the reinforced strength of the patent, Peter Dollond started civil proceedings against several London opticians who were making their own achromatic lenses. In the judgement of the case against James Champneys, Lord Camden wrote "… it is not the person who locks his invention in the scrutoire [sic] who ought to profit by a patent for such invention, but he who brings it forth for the benefit of the public." This resulted in payment of £150 damages, followed by royalties for every achromatic lens Champneys made after that time. Four more cases followed, including one against Francis Watkins, his disgraced partner, and Martha Ayscough, the widow of James Ayscough. He won every one.

It is interesting to note that it was not only worth the effort of taking so many individuals to court to protect his patent, but the infringers of the said patent realised the extreme value of being able to offer achromatic lenses for sale. This reflected a major improvement in optical performance of the telescopes on which they were fitted. The range of reasons given for infringing the patent were of two broad types. The first was that it was thought the patent ceased to hold on the death of the patent holder, in this case John Dollond, and secondly that the patent could not be valid because of suggestions of how to make an achromatic lens having been previously published, and Chester Moore Hall having designed and made one. None of these arguments held sway, and Dollond achromatic lenses were a monopoly until the patent ran out. Such was the influence of achromatic lenses that it was routine for the competitor opticians to advertise the sale of achromatic and "ordinary" telescopes. Because of the scarcity of good quality flint glass at the time, achromatic lenses tended to be smaller in diameter than plain crown glass lenses. John Bevis, a renowned amateur astronomer who was also an important electrical engineer, had discovered the crab nebula using an "ordinary" telescope in 1731, but was also keen to promulgate the achromatic telescope for general astronomy. Sadly, he was also one of the first individuals who we know off to have died as a direct result of astronomical studies. It was in 1771, only

4 days prior to his 76th birthday, that he fell from his telescope and suffered fatal injuries.

Throughout this period, the spectacle makers and opticians of London were trading from shops which were distinguished not by numbers, but by signs. House numbers started in the UK as a piecemeal activity, borough by borough, around the start of the 18th century. This was the reason for the use of hanging signs outside shops, by which not only the shop owner ship was displayed, but also the nature of trade. Thus it was that the trade card of Peter Dollond gave the address of his business as *At the Golden Spectacles & Sea Quadrant. Near Exeter Exchange in the Strand*. Similarly, John Cuff a contemporary of Dollond's gave his address as *At the sign of the Reflecting Microscope and Spectacles against Serjeant's Inn Gate in Fleet Street*. James Asycough had a trade card that gave his address as *At the Great Golden Spectacles, in Ludgate Street, near St Paul's*. There were many other similar signs and addresses, such as *Archimedes and Three Pairs of Golden Spectacles* and *Sir Isaac Newton and two pairs of Golden Spectacles* (Figs. 3.5 and 3.6).

There was a problem with the standard doublet achromatic lens as it tended to have a residual second spectrum. This was inevitable, as suggested by A.C. Clairaut in France. He correctly deduced that the two lenses were inadequately matched for dispersion. This was going to be a significant problem until it became possible to

Fig. 3.5 Optician's card from Soderberg, Optician and Musical Instrument Maker (Ephemera by Cary Goodrich)

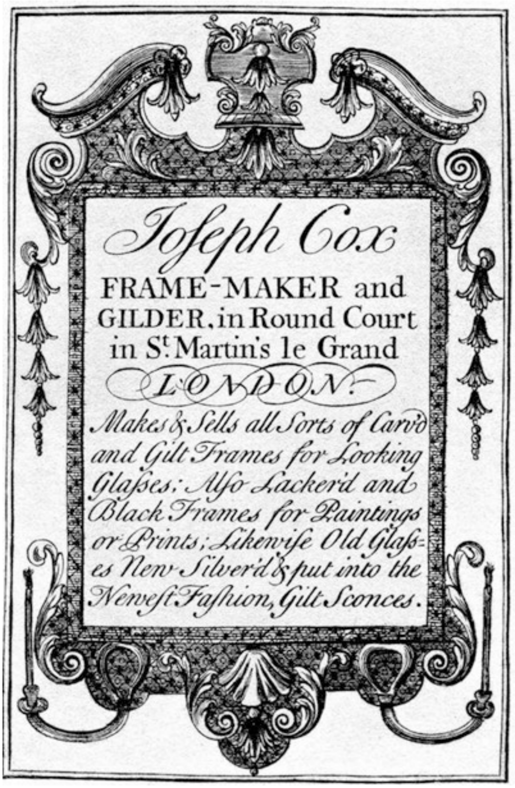


Fig. 3.6 The card from an 18th century frame maker. Frames could be made separately from the lenses, especially when expensive materials were involved (Ephemera by Cary Goodrich)

produce glass of a specified refractive index. To get around this situation, it was possible to use a triplet of lenses, at this time not cemented together and therefore inclined to cause double images if incorrectly lined up. It was in 1763 that Peter Dollond made his first functioning triple objective, although experiments were going on for some time previously, primarily by his father John. By 1764, he was offering these lenses for sale. One of the early three lens objectives that we know of was 3¾ inches (9.5 cm) with a focal length of 42 inches (106.7 cm), giving an aperture ratio just over *f*11. When reported on, this lens was regarded as very good indeed. Demand for the new triplets was considerable, limited not by price but by availability of suitable glass blanks. It was with one of these 3¾ inches triple lenses that Antoine Darquier de Pellepoix in Toulouse reported frequently seeing four of Saturn's satellites and on occasion five. The limited availability of glass blanks was an ongoing problem, as although geometric optics was advancing well, the making of glass was still an empirical and highly skilled individual activity.

The resolving power of these triplet lenses stemmed not simply by control of the secondary spectrum, but also by correcting for spherical errors, although as Fraunhofer pointed out much later that spherical errors can be corrected by two lenses. These now quite sophisticated refractors were being very favourably compared with the very best currently available achromatic telescopes. The big test for these instruments was whether they could resolve binary stars, which had been described extensively by William Herschel using a reflecting telescope. It turned out that the Dollond lenses were extraordinarily capable such that it was possible to resolve the binary system Boötis. This is a system where the primary star is a yellow/white dwarf (spectral F7V), which is just visible to the unaided eye and the secondary is a red dwarf (spectral M2V). This binary is quite close, being about 51 light years distant. In 1996, it was found to have an extra solar planet (Tau Boötis b) orbiting the primary star.

This performance of the new achromatic lenses was all the more remarkable because they were really quite small when compared with other possible mirrors able to be constructed at the same period. At this time, it was unusual for glassmakers to be able to produce glass of adequate quality in blanks greater than 4 inches (10 cm) in diameter. While crown glass was produced by several manufacturers in London at this time, flint glass was a rarer commodity. Contemporary accounts indicate that trusted opticians such as Dollond would be able to pick their own blanks before the rest were sold, either to other customers or to exporters, where they would generally be sent to Europe. The export market seemed assured at that time, because even with the efforts of Cassini, it was not possible to establish an alternative European supply of glass suitable for polishing.

For glass manufacturers in the United Kingdom, the situation was complicated for about 100 years by the implementation of a glass tax. In 1745, Parliament introduced the glass tax, sometimes erroneously mixed up with window tax, which was a method of setting a rateable value on a property. Glass tax was in fact a direct tax on all glass and a very complicated one at that. It was the complexity and interpretation of the rules that caused such severe problems for British glass manufacturers, especially in the 19th century. Broadly speaking, every glass melt was taxed, so companies such as Dollond's, who regularly had remelted the glass of failed lenses, found themselves paying tax on the same glass several times over. This situation was eased somewhat when the rules were modified slightly to exempt manufacturers of small glass ornaments and high quality optical glass. When the glass tax was finally repealed in 1845, glass manufacturers were no longer hampered in their development of new products and new types of glass, as they were no longer taxed on their failures. Glass could be re-melted until it finally made it into a product, without additional excise costs being involved. It was the removal of the glass tax that made possible the enormous production of glass by Chance Brothers in Birmingham for the Crystal Palace at the Great Exhibition of 1851 that took place in London. While the repeal of the glass tax made a considerable difference to astronomers, it had far wider consequences for the population as a whole. In the *Lancet* (1845), there was an editorial comment that began, "*In the financial scheme presented by Sir Robert Peel to the House of Commons we hail with joy the abolition of the duty on glass*". The editorial commented further that unfortunately, the other "impost on light, the window tax" remained. They claimed the glass tax amounted to 300% of the value of the glass and were vociferous in their belief that light from windows is essential for hygiene and growth.

Over the next century, with or without the interference of the revenue authorities, construction of large glass blanks was going to be a problem for all glass manufacturers, primarily due to technique and chemistry. Chemistry was required to reproduce the same refractive glass each time, and technique was required to produce a useable product. Making decorative glass such as goblets and small figurines was really no problem when compared to the manufacture of an optically clear blank for a lens. For many years after the introduction of achromatic lenses, opticians stuck quite closely to nothing larger than 4–5 inches diameter blanks. This was not an arbitrary limit; it was one set by the progressive problems of creating a disk without flaws being proportional to the area of the disc. It simply became too difficult and expensive to make larger lenses using the existing techniques.

This situation was going to take many years to rectify, but the situation was eventually alleviated by a clock case maker of les Brenets in Switzerland by the name of Pierre Louis Guinand. The results he achieved were empirical in origin, like most glass manufacturers of the time, but of considerable importance nevertheless. His interest in telescopes seems to have originated in his early twenties, when he dismantled a reflector and decided to make his own simply by copying the design. This was an early example of reverse engineering, taking apart an object to make a duplicate copy. Having already gained some idea of metal casting by way of business, he proceeded to cast his own mirrors and construct his own telescope. It was many years later, when Guinand was into his thirties in around 1783, that he dismantled a refractor with an achromatic objective with a view to making one of his own (Fig. 3.7).

Fig. 3.7 Pierre Louis Guinand started as a clock case maker but went on to become an innovator in lens making (Wikimedia Commons via Josdb at Dutch Wikipedia)

His initial attempts were based on the procurement of flint and crown glass blanks from London. It was some time later when he received some blanks, brought back by a friend, from London. The state of the glass seems to indicate that the most of the high quality glass had been earmarked for the local opticians by the glass maker; they were full of striae and of little value. This was repeated later, so the resourceful Guinand decided to make his own lenses from scratch. This was quite a decision for someone who had no formal scientific training and had to support himself with his trade, which had no common point of contact with practical optics. His initial work was involved in making glass in batches weighing around about 1.5 kg, the exact mass varying by about 500 grams. During this period, Guinand taught himself basic chemistry, although now it would be more correct to call it material science. He demonstrated that metallic lead in flint glass could be induced to come out of the glass under the influence of a steady high heat. This was a very significant observation, even though at the time the importance seemed to have been ignored. As time progressed, Guinand developed his knowledge and bought a piece of land where he built an oven that could take a very much larger charge. This was in itself a difficult system to run, as with increasing furnace size, if different techniques are employed, problems of cracking and asymmetric heating also increase. It was recorded at the time that cracking of the crucible was not unusual, with the result that spillage would cause the loss of the entire charge.

When he final achieved production of a compete block of glass, apparently without cracks, he cut part of it so that it could be polished and inspected for internal flaws. The surface of these blocks was always impenetrable to sight because of the micro scratches and aggregation of impurities on the surface. The block was streaked with "comets"—streams of air bubbles caused by the separation of lead from the mix appearing at the surface where it oxidised and started to sink, dragging air from the surface with it, into the viscous liquid glass, leaving the comet tail of air threads. By modifying his technique and allowing the glass to cool rapidly so that it fractured along its own interior stress lines, Guinand managed to produce blanks of 12–15 cm in diameter. He did this by polishing the fractured surface of his block and cutting out the largest blank he could manage. One of the practical problems that Guinand had at this time was provisioning an adequate supply of fuel for his furnace, which was wood burning. This is a relatively low energy/mass fuel compared with coal, which was not available, so it took a very large volume of wood to keep his furnace in action. At this stage, the development of larger lenses was still in the hands of individuals; techniques to make routine large lens manufacture possible were still to be developed.

In 1804, it became apparent to many people that the glass being produced by Guinand was of a very high quality. He was being courted at this time to move his works to the old Benedictine Monastery at Benediktbeuern, where there was plenty of space and, even more importantly, an abundance of wood fuel. This opportunity was brought about by the secularization of Bavaria in 1803, resulting in the dissolution of the monastery. What finally precipitated the move was that in 1805, Guinand started using a fireclay stirring rod which gave a consistently better result. This small innovation was paramount in producing homogeneous glass that could be used for lenses. The glass blanks were still cut out of a larger block at this time. Soon after the move, Guinand had effectively retired from the glass works, being awarded a pension of 800 Florins annually on the understanding that he did not continue to make glass. This undertaking was with the glass works owner, Herr Utzschneider. However, on his return to le Brenets in 1814, Guinand restarted making his own telescopes, at which point, after some acrimonious correspondence, resulted in him losing his pension. This did not stop him from developing another important innovation, along with the still-used fireclay stirrer. If Guinand had a block of good quality optical glass that was homogeneous and free of optical defects, it could be softened in a furnace just enough so that it could be pressed into a mould without being melted and developing faults. Using this technique, he provided disks for polishing of an unprecedented 30-cm diameter, and on at least one occasion, of 45-cm diameter (Fig. 3.8).

These two major improvements in optical glass manufacture—the fireclay stirring rod and the use of a mould—left a legacy to optical glass manufacturing that has had a profound effect on astronomy. At the same time, it had become increasingly clear that refractors could be challenged in their performance by the increasingly well-constructed reflectors.

Fig. 3.8 Benedictine Monastery at Benediktbeuern, where the development of new techniques of glass making by Pierre Louis Guinand took place in the early part of the 19th century (Photograph by Rufus46)

References

Bart-King, Hugh. 1986. *Eyes Right, the Story of Dollond and Aitchison 1750–1985*. London: Quiller Press Ltd.

Dollond, J. 1758. On Account of His Curious Experiments and Discoveries Concerning the Different Refrangibility of the Rays of Light, Communicated to the Society. In *Royal Society Council Minutes*, vol. IV, 202.

Gregory, David. 1695. *Catoptrica et dioptricae sphaericae elementa*. London: Oxford University Press.

Kepler, Johannes. 1627. *Tabulae Rudolphinae*. Ulm: Jonas Saur.

1845. Lancet Editorial comment 1: 214–215.

Zucchi, Niccolo. 1652. *Optica philosophia experimentis et ratione a fundamentis constituta*. Lugduni: Gillemus Barbier.

Chapter 4
Aerial Refractor Telescopes and the Development of Reflectors

Before the advent of the innovative achromatic lens, it was recognised that it should be possible to obviate the problems of spherical and chromatic aberrations by having a long focal length objective lens. This stemmed from an empirical observation that the image quality of a lens—remembering they were all of spherical section and made of crown glass—was improved by a decrease in curvature. Taken to the extreme limit, a flat piece of glass has neither spherical nor chromatic errors, but also no capacity to focus closer than infinity. By having reduced curvature and therefore a long focal length, the aperture ratio (*f*) decreases. The *f* value is created by the simple expedient of dividing the focal length by the aperture. Thus, the best images at the time were generated by long focal length lenses with a resulting very small aperture ratio (confusingly designated by a large number). Aperture ratios of 1:150 were not unknown at this time and were an inevitable result of only being able to produce long focal length lenses of relatively small diameter.

Since the dispersive power of a lens is a product of the material of which it is made, it remains constant regardless of focal length. Thus, as the focal length increases, so does the image. Consequently, the chromatic aberration has a smaller effect on the image. In a similar way, spherical aberration is reduced in proportion to the square of the focal length. The result of this is that a long focal length telescope will have a small aperture ratio, reduced spherical aberration and less intrusive chromatic aberration. The image will be large but of low brightness and contrast. Making these long focal length telescopes a productive instrument was very much a balancing act between these advantages and disadvantages.

In the 1640s, one of the longest tubed telescopes was constructed by Johannes Hevelius in Danzig. Hevelius was well travelled in his youth, having been brought up in a German speaking family and taught Polish in what was his home town of Danzig (Gdansk). He was educated in Leipzig, then went to France and England before returning to Danzig where he remained, firstly as a brewer in the family concern and then increasingly developing his astronomy. He owned (partly through marriage) a set of three joined houses, on the roof of which he built an observatory equipped with a Keplerian telescope of 46-m focal length, as well as many other

W. Wall, *A History of Optical Telescopes in Astronomy*, Historical & Cultural Astronomy, https://doi.org/10.1007/978-3-319-99088-0_4

instruments of high quality. This was quite an achievement, as the tube, made of wood and wire, was constructed by Hevelius himself. Not only was this one of the longest tubed instruments, but Hevelius was also among the first to realise that long instruments could be made that would overcome some of the practical shortfalls, spherical and chromatic, of single lens objectives.

By 1647, Hevelius had accumulated enough data using telescopes of around 3.5-m focal length to publish *Selenographia*. This was his first work and the first complete lunar atlas of the visible side of the Moon. It was illustrated with the Moon in all phases and with names to many features (Fig. 4.1).

During the 4 years in which he had been specifically investigating the Moon, Hevelius also managed to recognise and measure the Moon's libration, the apparent oscillation of the Moon as it moves through its phases. After his first wife, Katharine Rebeschke, died, he married again. His second wife, Elizabeth Koopman, was a great support and coworker, appearing in woodcuts of the time seated at astronomical instruments. It is not known for certain how much of the work was hers, but she is now recognised as the first woman astronomer. The maps of the Moon that Hevelius produced were very much better than had previously been made of the Moon but were still limited by virtue of the telescopes and of the clarity skill of the observer. One of the other ideas that Hevelius publicized was his discovery of four comets. It was his observation of these which led him to believe that these celestial bodies follow a parabolic path around the Sun.

Although Hevelius started using relatively short telescopes for his observations, word came to him of the brothers Huygens, Christiaan and Constantijn, who were making magnificent telescopes of great length. These two had apparently decided that since the available telescopes were not as good as they would like, they should

Fig. 4.1 The full face of the Moon equally illuminated, from *Selenographia*, published 1647 (http://www.e-rara.ch/zut/content/pageview/160517)

make their own. This was at the time a relatively common event for scientists of all types, as there was a limited pool of manufacturers making a limited range of equipment. Very often, the devices were ornate and embellished to appeal to the eye, thereby optimizing value and profit for the manufacturer (Fig. 4.2).

The telescopes which the Huygen brothers started making for themselves were relatively modest instruments, but in 1659 when Christiaan Huygens published *Systema Saturnium*, he included descriptions of some very long telescopes. Their initial instrument, built in 1655, had an objective diameter of about 5 cm and a focal length of 3.6 m. Although exact details of size are not available, the aperture ratio would be approximately 72. This was used first on Saturn, which at that time (March 1655) was situated such that the rings passed almost exactly through the pane of the Earth and so were impossible for them to see. With no rings to view, Christiaan Huygens looked more closely at the area of orbit and on March 25 discovered Titan, not only the largest of the Moons of Saturn but also the second largest moon of the Solar System, second only to Ganymede orbiting Jupiter. For comparison, Titan is also larger than Mercury, although only 40% as massive. By the end of 1659, the Huygens had created a 7-m telescope with which they could see an apparent tapering of the extremity of the rings of Saturn. These ansae were visible because the rings were still more or less edge on. Through both the 3.6-m and 7-m telescopes, Saturn was studied in great detail, culminating in publication of *Systema Saturnium* in 1659. As was normal at the time, scientific publications were written in Latin. This was for two reasons: the first to establish the credibility of the educated author, and the second so that it could be read by other scientists without the need for translation. This publication finally stated that the ring system was circular, not attached to the planet and also inclined to the ecliptic (Fig. 4.3).

Both Hevelius and Huygens were primarily involved in positional astronomy, although discoveries made regarding structures and features on close astronomical bodies, such as the Moon, were of very great significance to them. At the same time

Fig. 4.2 Portrait of Christiaan Huygens by Bernard Vaillant around 1686. This is unusual for the time in being pastel on paper, when the popular medium of the time was oil on canvas (Huygensmuseum Hofwijck, Voorburg)

Fig. 4.3 Constantijn Huygens, by Willem Delff about 1623 (http://www.dbnl.org/auteurs/beeld.php?id=huyg001)

that Hevelius and Huygens were working, Giovanni Domenico Cassini was also working in astronomy. Besides accurate engineering of astronomical instruments he was involved in civil engineering works, most notably in flood defenses on the river Po at the invitation of Pope Clement IX. Although not directly associated with the Vatican, River Po runs entirely within Italy from East to West, discharging into the northern Adriatic. Cassini was famous in his time as much because of a telescope he installed at the Paris Observatory as any of his other engineering activities. This telescope was so spectacular that it even attracted comment from Moliere. Cassini took up his position at the Paris observatory on September 14, 1671, starting his observations the very next day. The observatory itself was not finished when he started his work, although the building process had started in 1667. He went on to discover four new satellites of Saturn and in 1675 demonstrated that the ring system was not uniform, but divided by a dark band. Interestingly, due to political unrest and lack of interest in the observatory itself, the first four people in charge of the Paris Observatory bore the Cassini name. It was only with the grandson of Giovanni Cassini, Cesar-Francois Cassini de Thury, that the official title of Director of the Paris Observatory became established in 1771 (Fig. 4.4).

It was fitting that in October 1997, the exploration of Saturn went one stage further with the launch of the Cassini-Huygens space probe. This immensely productive system landed the Huygens probe on Titan in January 2005, and then after several years in January 2017, Cassini was flown into Saturn itself, relaying information on the way down.

It was the remarkable discoveries made by Christiaan Huygens and his publications detailing observations of Saturn, as well as rediscovery of the Orion nebula, that solidified his fame. The Orion nebula had been originally noted by Johann

Fig. 4.4 Giovanni Cassini, painted in 1879 by Leopold Durangel (http://www-history.mcs.st-and.ac.uk/history/PictDisplay/Cassini.html)

Baptist Cysat in 1618 while viewing a comet, his main area of interest. However, it was the rediscovery, which gave observational details, that gained widespread acknowledgement. Hevelius read the work of Huygens, and it was this that converted him to the idea of very long focal length lenses being used for astronomical telescopes.

Hevelius embarked upon the manufacture of very long telescopes as a means to increase his ability to observe the heavens. He was not an optician in the sense of being a lens maker, so these were either made locally or bought from dealers, while he made the tubes and mechanisms of manipulation. It should not be underestimated how complicated the process of construction these telescopes were. It was a complicated engineering project, with the fitting of the objective lens being left until the entire device was made and in position. Without modern materials, the options were few, and as a compromise between strength and weight, they had to be made of wood. Details were given by Hevelius in his volume *Machinae Coelestis* published in 1679, where the various options for construction were discussed.

By carefully making tubes in sections, Hevelius constructed telescopes of about 18.5 m, 21.5 m and finally one that was just short of 46-m focal length. The long focus lens for the 46-m telescope was made locally, others being bought elsewhere. It would seem from the point of view of Hevelius that employing a skilled lens grinder was by far the easiest part of constructing this immense telescope. The lens would be commissioned and expected to be completed while the mechanical parts of the telescope were being made.

Although making the parts were in themselves complex engineering, they were still defined by contemporary knowledge. Other parts of the process were not so clear. Mounting a lens in a tube of that length was difficult; the accuracy of alignment is crucial if the image is not going to be off centre. If it is off centre by even a fractional amount, the image loses clarity, as the centre of the lens becomes off centre in the image and all the advantages of a long focal length lens are lost. In a similar way, moving the entire telescope and maintaining the alignment with the shifting load on the telescope tube was a considerable achievement. Even with the greatest skill, this was to be a large and unwieldy piece of equipment of considerable mass. The mass in itself was a problem; strength in the supports was vital to stop flexing and allow for reliable alignment without the problem of swaying.

There are illustrations of the very long telescope that match with his description of its construction. Two flat pieces of wood were joined lengthways at 90° to each other to make a very long, straight, trough, several of these troughs were then joined to make the complete telescope length. This, then, was not an enclosed telescope: it was open on top, with the objective at one end and the eyepiece at the other. The whole construction then had to be hauled into the air by ropes and pulleys, suspended from a mast. While Hevelius makes light of the problems of controlling and using the telescope, reported details do imply that a rather more complicated technique was required than he suggested. Needless to say, it required more than one individual to accurately position the device (Fig. 4.5).

The 46-m telescope itself was open along the entire top edge and so only functioned at full performance when it was a dark and moonless night. Any extraneous light had to be shielded from the eyepiece. Along the length of the tube were a number of "stops" which limited the stray light available at the eyepiece and helped in alignment. These stops were also said to increase the rigidity of the instrument, but by virtue of its construction it is unlikely that it would have eased the twisting moment from an inadequately tensioned supporting wire. Another indicator of the complexity of operation of this telescope was that it required a large number of willing hands to hoist the telescope up the mast and to align it before observation could begin. With the structural changes due to temperature, humidity and wind, this particular long telescope, though famous and in many ways groundbreaking, did not make a significant contribution to astronomy simply because the scale of the device was beyond the available materials at the time.

The work of Hevelius was interrupted by a serious fire at his observatory on September 26, 1679, when by all accounts his books and most of his instruments were destroyed. We have two descriptions of the events and damage that took place when the fire caught hold. One was in a letter sent by D. Capellus to Peter Wyche, the British Consul, in which he describes Hevelius and his wife leaving the city for a sojourn in the country. Sending his groom back to town with his horses, his man sets a candle in the stable, which then set the place on fire. This burnt the entire frontage of the three buildings he owned and destroyed his laboratory at the front of the house. Most of his books, manuscripts and instruments were destroyed, along

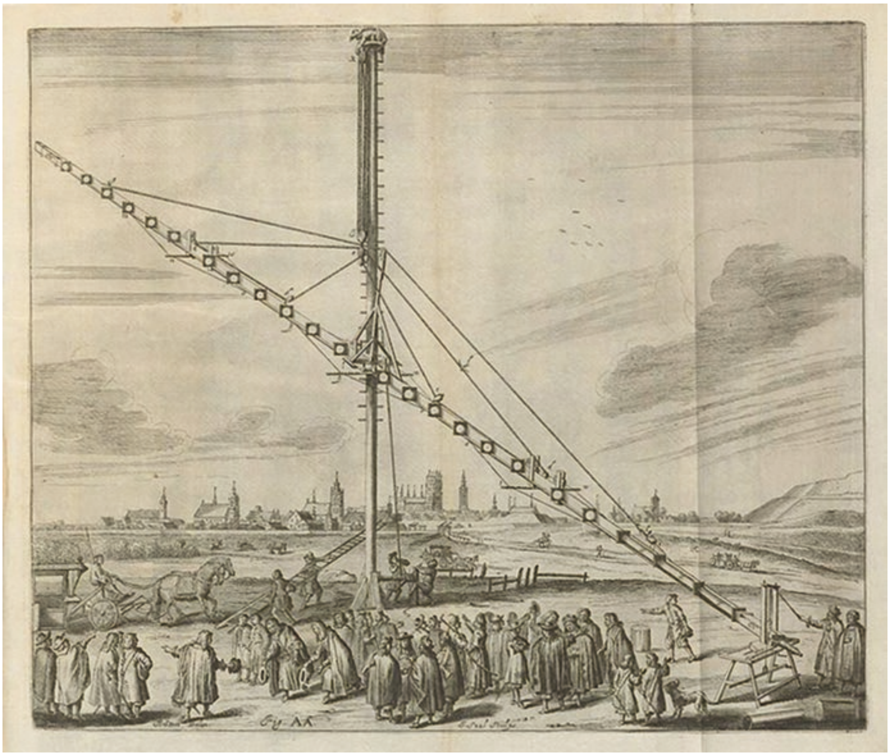


Fig. 4.5 The 46-m telescope pictured in a woodcut from *Machinae coelestis*, 1673, by Johannes Hevelius. Houghton Library, Harvard University (Houghton Library, Cambridge Massachusetts)

with the observatory. Even so, Hevelius rebuilt enough equipment to view the great comet of 1680. In 1685, Hevelius published his *Annus Climactericus*. This covered the fire that did so much damage to his equipment in a very long preface that also included a list of his observations and views of stars and planets. Interestingly, the body of the book is directed to Henrico (Henry) Oldenburg, who was not only a founding member of the Royal Society in 1660, but was also the first Secretary to the society. More than that, this was the start of the Age of Enlightenment, when science and reason were rushing to the forefront of thought in all arenas. Thus, it is no surprise that when Oldenberg founded the *Philosophical Transactions* as editor, he introduced an innovation which is still used today—peer review. Experts were called upon to spread the intellectual load of the editor in an increasingly complicated world. This is, of course, the system we now rely upon completely for testing the veracity of scientific publications (Fig. 4.6).

While Hevelius was making long and unwieldy telescopes with a partial wooden tube, Huygens realised that given dark conditions, it was quite possible to do away with the tube altogether. This astute observation was nonetheless a radical one. So it was that the true aerial telescope was born. We have considerable written

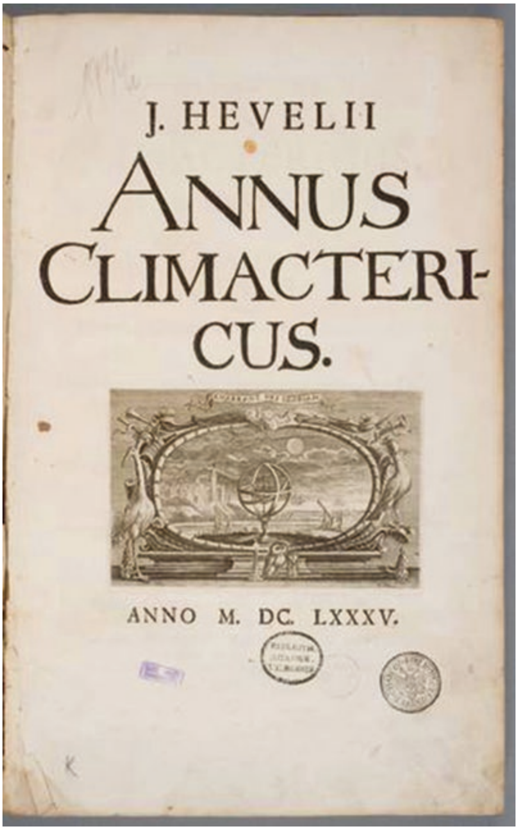


Fig. 4.6 The front cover of *Annus Climactericus* published in 1685 by Hevelius (Vinius University Library)

documentation of the Huygens aerial telescopes, as well as sufficiently detailed drawings to be able to construct a modern version, mainly from his 1684 publication *Astroscopia Compendiaria Tubi Optici Molimine Liberata* (Compound Telescopes Without a Tube). Having made the technical leap regarding the structure of a telescope, Huygens was the first astronomer to completely dispense with a supporting tube. This, of course brought with it technical difficulties of its own regarding alignment, but perhaps not surprisingly, these were less problematic than constructing and controlling an immense structure like Hevelius had done.

One of the aerial telescopes that Huygens made was 37.5 m in length, with an objective of 19-cm diameter. It was smaller than the Hevelius 46 m, but given the right conditions was just as good for celestial observation. This particular 19-cm objective was significant both for its size and its clarity, and when Constantijn visited London, he presented the lens to the Royal Society.

Although others would produce aerial telescopes of greater than 100 m in length, it was the Huygens brothers who made the greatest use of the idea of aerial telescopes, and it was them who first recognised the importance of clear skies for making observations. Christian noted that even on clear nights, stars twinkled and the edges of the planets seemed to move. It would have been easy to put this observation down to instability in the viewing system, but he was an astute observer and warned against blaming the instrument for difficulties in observation.

It is known that at least three of the lenses ground by Huygens arrived in London: the one described above; one in the possession of Newton at 51.9-m focus; and one belonging to Reverend G. Burnet, of 64-m focal length. Both of these found their way to the Royal Society as large aperture lenses, but it is the first which has a more interesting history. This 19-cm diameter lens with a focal length of 37.5 m, which is still with the Royal Society, gave the Committee some considerable problems in finding a proper place for it. They tried finding a suitable building to mount it on for zenith measurements, but they could not find one tall enough. They even considered the possibility of using the scaffolding of St. Paul's Cathedral. This was deemed unsuitable, and so it remained unused for some years until James Pound, a member of the clergy, borrowed the lens and mounted it on a maypole at Wanstead on the outskirts of London, the pole having been removed from the Strand in London. Although it was useable, the same problems attended this construction, in that although it was recognised that the lens was of very good quality, the vibration when in use made it very difficult to use and consequently limited its practical value. This problem was repeated when Henry Cavendish mounted the lens for comparison with a Dollond achromatic. Almost 150 years after the Royal Society received it, another attempt to mount the lens was made, but it was seen as too difficult and so was dropped as a project, since when the lens has been in the collection, unmounted. It should be noted that while we give measurements in metres, these are not exact values. The problem is not merely one of Huygens or his contemporaries figuring a glass to such an accurate and precise focal length, but more so one of units. In the 1684 publication by Huygens *Astroscopia Compendiaria Tubi Optici Molimine Liberata*, Huygens refers to telescopes of *34 pedo longo*, that is, 34 ft long and later 70 ft. We do not know for certain what sort foot he was referring to. Until the metric system was introduced, local units were used for weights and measures in commerce. This variation from place to place was of no particular significance when trade was local, but when it attempted to give details as Huygens did to an international audience, the value of the unit became significant. Until Napoleon introduced the metric system into the Netherlands, there was no agreed standard for what a foot was. In general, it was about the same as the English foot of the time, which makes it 30.48 cm, but this, too, is overly precise. Not having a standard length meant there could not be a standard measure, so any foot that was used would only approximate to this value. It is the standardisation of measurements of this sort that has allowed us to have pieces of equipment made by different people on different continents that fit together perfectly.

The problem of lining up the objective and eyepiece was the primary problem with these very long devices, and the longer they became, the more difficult it was. With bright objects such as planets, it was possible to project an image onto a surface that could be used to align the eyepiece. With lower luminosities, more convoluted techniques were used. These refracting telescopes were without doubt difficult to use and required a great deal of practice and learnt skill. Very often, it was only the originator of the instrument who could get the best out of the telescope, or in some cases anything at all.

Manufacturing the lenses for these very long instruments was in itself a highly skilled task, the manner in which it was done arousing some considerable interest at the time. This was primarily because they started with ordinary glass blanks but ended up with very superior lenses. This was again very much associated with learnt skills rather than a new and unusual method. It was still at this stage an artisan activity, perfected over years, with as many techniques as there were practitioners, starting with making the polishing tool to be used on the glass blank. For example, while Newton thought that putting too much pressure on the metal grinding tool while it was being polished would cause it to distort or wear unevenly, Huygens thought that great force was required to aid the tool polishing process. When the tool had been polished to a suitable finish, the glass could be introduced to the tool, which was usually more than twice the diameter of the lens. This allowed for rotation to spread the wear over the whole tool evenly, solving the problem of the tool wearing faster than the glass. Emery powder was used as the grinding abrasive, consisting mainly of aluminium oxide and other hard mineral species. This could be worked so that the larger particles worked their way to the edge of the grinding tool where they could be removed, gradually making the mixture finer and finer. Eventually, the mechanical grinding and integrated polishing could be finished off with cloth polishers. The time that this process took was considerable.

Using a slightly different technique of lens grinding, Campani in Italy produced what were recognised as some of the finest long focus aerial telescope lenses available. The way he did this was based on grinding a flat piece of glass into a concave tool so that when it was used against a glass blank it would produce a convex lens. These lenses, made and figured by Campani, were a favourite of Cassini, who used them extensively in the telescopes at Paris Observatory. It was with Campani lenses that Cassini discovered two of Saturn's satellites, Tethys and Dione, both first seen in 1684 using telescopes of 30.50-m and 41.5-m focal length.

It is interesting to note that the use of aerial telescopes declined quite quickly as shorter focal length achromatic lenses became available. Since these broadly solved the problem of spherical and chromatic errors that the long focal length aerial telescopes had tried to cure, there was no longer any need for the immense structures associated with these devices and the sheer practical problems of manipulating them. Shorter telescopes were easier to use, and the images they produced intrinsically had a much better contrast and brightness. It was the low contrast, which is inevitable from these long lens systems, which caused Huygens to note that observations could be interfered with by extraneous light. Although not significant at that time, it was going to be progressively more of a problem over time.

During the 18th century, Newton's ideas, primarily those of universal gravity and optics, became a major part of astronomy and the construction of telescopes. This new knowledge moved astronomy in two different directions. The first was trying to make sense of the movements of planets and stars as they were observed in terms of Newtonian mechanics. The second was observational, searching for new celestial bodies and making catalogues of the visible stars and planets. This was fueled by the developments in telescopes with the very large aerial instruments and achromatic lenses, and also the developments in reflective surfaces that were starting to make reflector telescopes a reality. At the same time that the production of reflector telescopes became possible and they slowly became better instruments of much simpler design than refractors, production of larger lenses was also becoming possible.

There were many issues associated with long focus telescopes, some of which as we have seen were resolved by the introduction of achromatic doublet lenses and non-spherical lenses. However, one issue remained. Stubbornly resistant to any change in optical quality and correction of aberration was the amount of light that could be collected by these instruments. The objective lenses were too small. As time went on, it became possible to construct supporting equipment and housings that could be moved on what we would now recognise as modern bearings, keeping the telescope steady and on target throughout the night. At the same time, a shift followed in the way in which the telescope was described. By the middle of the 19th century it was no longer normal to describe a telescope by the focal length of the objective. Instead, it became the practice to describe a telescope by the diameter of the objective lens. This shift in emphasis reflected the move away from trying to make detailed analysis by magnification towards detailed analysis by optical resolution. This was paralleled by changes in construction of microscopes, where many initially thought that magnification could resolve anything but then moved towards a realisation that magnification without contrast could reveal nothing about their specimen.

So it was with telescopes that the need to see further and with greater acuity resulted in a search for methods to create larger diameter lenses that could gather enough light to make the previously invisible, visible.

The advent of techniques to create glass in large enough volumes to make larger lenses opened up new possibilities. This was based on the work of Pierre Louis Guinand, who developed some of the basic techniques that helped scale up glass manufacture for lenses. Up until about 1880, it was really only possible to obtain lenses made of one of two types of glass, crown or flint. The movement into other glass types was started by the exceptional work of Otto Schott. The son of Simon Schott, a maker of window glass, he went on to study the chemistry of glass and how they could be changed by addition of other elements. So it was that he invented borosilicate glass and came to understand how it was possible to change refractive index with additions of metals. After demonstrating a lithium additive to Ernst Abbe, they set up a close collaboration in which it was said that if Abbe wanted a glass for one of his lenses of a specific refractive index, Schott could provide it. It was not long before many different glass types were available using all sorts of metal additives, such as zinc, antimony, barium and magnesium. By the end of the 20th century, so sophisticated had the chemical definition associated with the optical nature of glass become that now the exact mixture depended upon whether the lens was designed for visual use or photography (Fig. 4.7).

This was an important point, as by the end of the 19th century it was widely recognised that there were three principal instruments in astronomy: the telescope,

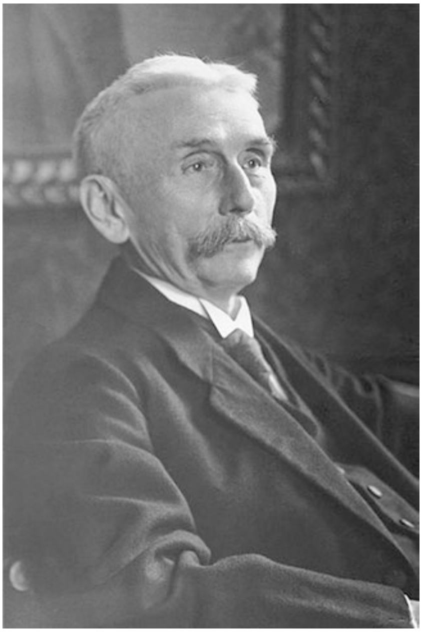


Fig. 4.7 Friedrich Otto Schott, photographed in the early 20th century. Photograph courtesy SCHOTT AG, Andrea Würzburger, Marketing and Communication, Hattenbergstrasse 10, 55122 Mainz (SCHOTT AG, Andrea Würzburger, Marketing and Communication, Hattenbergstrasse 10, 55122 Mainz)

spectroscope and camera. This changed in the following century but at the time was quite an accurate assessment of the situation. It should be noted that without the telescope, the other two instruments would be of little use. During the same century as large lenses became available, materials of sufficient strength and rigidity also appeared, so that the enormous weight of these lenses could be supported in a permanent structure.

Making large lenses is still a long and complicated business, fraught with all the problems one would expect when handling molten material at 1600 °C. In the 18th and 19th centuries, it was even more difficult and dangerous. When the lens makers art was at its peak—before the advent of computer controlled design and manufacture—there were few companies that could handle the making and casting of a uniform glass blank of high quality. The three major glass makers who could produce the volume of glass in one piece were all in Europe: Edouard Mantois in Paris, Schott Glassworks in Jena and Chance Brothers in Birmingham. Glass production at Chance has moved to Malvern in Worcestershire, but as a company they were both innovative and capable of making a large range of products from glass. It was Chance Brothers who made the glass for the Crystal Palace at the Great Exhibition in London in 1851 and the opalescent glass for the clock faces fronting the tower that houses Big Ben in London. The glass works of Mantois later became Société Parra-Mantois. In 1894, A. Clark and Edouard Mantois wrote in some detail in *L'Astronomie* how his works made the large glass blanks required for the large lenses, which were becoming objects of national pride and local competition for the largest and best.

Looking at contemporary details that are available from different sources, the systems used were broadly the same between different manufacturers. Unlike during the times of Guinand, when he and his wife controlled all of the processes and kept the details of their work secret in the manner of an old fashioned Guild, the broad techniques were no longer secret. The methods used may have been very similar, but the details were different. One thing they all had in common was that the production of large lenses was difficult and time consuming.

This technical difficulty started with the laying of the furnace. This has to be robust, as it was heated continuously on a scale of days rather than hours. Within the furnace there will be a crucible made of fire clay, this already being heated to show up any imperfections, like enclosed air, which may cause it to split in extreme heat. The crucible in the furnace was gradually heated to the required temperature. This had to be done over several days so as to obviate the problem of thermal shock causing splits and cracks.

There had been methods of measuring the temperature of furnaces available since the 18th century, when Josiah Wedgwood introduced his system of measuring thermal shrinkage. This was a simple system, where standard clay pieces were fired in the furnace to be measured, removed, cooled and tested on a tapered slope to see how far it would move down the incline before becoming wedged. As shrinkage of the clay is dependent upon temperature, the greater the shrinkage, the further down the slope the clay can move. The temperature would then be read from the side of the slope. Later developments involved matching colour, for example the colour change of a quartz crystal. The colour of the furnace interior was by far the commonest method of judging the temperature, and this was usually done by eye by an experienced furnace man.

When these first large lenses began to be made, it was generally accepted that anything up to 30 hours of steady heating was required to charge the vessel without it cracking or the furnace bricks breaking. Because a number of different components are added to the mix to make the glass, they tend to separate based on their specific gravity. This was stopped by continuous stirring with a ceramic rod, as described by Guinand. Removal of the pot when the mixture was at the right temperature (when the viscosity was just right) was a dangerous time for the workers, as the crucible was white hot and fragile. Added to this, the crucible could be stuck to the bottom of the furnace with glass spillage, so it needed working loose at the base. After careful maneuvering of the crucible, the glass was poured into a mould.

The process does not stop with the glass entering the mould; the nature of glass makes it necessary for the temperature to be controlled even as the glass cools down. The coefficient of expansion of glasses depends on many factors and is not linear across a large temperature range, so in brittle material such as glass, quite small thermal changes can result in fracture. This is true even though the coefficient of expansion may not be as great as for metals, but metals are ductile even at room temperature, while glass is not. The result of this was that the glass, now in a mould, had to be moved to a pre-heated cooling oven. This was sealed and gradually cooled over a period of 4–6 weeks, after which there was a solid block of hopefully homogeneous glass with neither flaws nor cracks. However, it was not possible to see if this was the case when the glass was first removed from the oven. The surface was milk white from slag and micro scratches, so a piece had to be removed by cutting and polished until the interior could be judged for quality. If it seemed that only a portion of the block was free of internal stress and bubbles, it was only this part that was then cut from the block. This uniform piece of glass could then be put into a crucible in the rough shape of the final objective. With very large lenses, besides the need for two objectives of different glasses to be made, it could take many attempts to achieve the uniform quality of glass that could be used to make the blank. We are lucky in having, from the works of Mantois in Paris details of the time for production of the 91-cm objective lens for the Lick Observatory in the USA, which was finished by Alvan Clark in Massachusetts. There were two lenses made to form the single objective, and the total time require was 4 years from start to finish. This was in part because the initial melt was carried out 20 times, each cycle requiring a month in the cooling oven before optical inspection for quality could start.

References

Clark, A., and E. Mantois. 1894. Les grand instruments de l'avenir. *L'Astronomie* 8: 13–31 (in French).

Hevelius, J. 1647. *Selenographia*.

———. 1679. *Machina Coelestis*. Gdansk: Simon Reiniger.

———. 1685. *Annus Climactericus*. Danzig: Self published.

Huygens, C. 1659. *Systema Saturnium*. Holland: Adriaan Vlacq.

———. 1684. *Astroscopia Compendiaria Tubi Optici Molimine Liberata*. The Hague: Arnold Leers.

Chapter 5
The Ascent of the Mirror Lens and Reflecting Telescopes

It was Newton's ideas about light and the impossibility of correcting for refrangibility by mixing complementary lenses that significantly slowed the production of achromatic lenses, as they were seen to be of no use in telescope manufacture. At the same time, his ideas did create some speculations over the value of using mirrors over lenses.

The first reported use of a mirror as a telescope comes from Niccolo Zucchi in 1652, when he described an experiment he made in 1616 constructing a mirror for use in a telescope. There are similar reports that Cesare Caravaggi made use of a mirror in 1626 as a telescope, but this device, like the one described by Zucchi was not pursued as a useable instrument. There were two main reasons for this. The first was the metal used as the mirror material. At this time, all mirrors were either metal or polished obsidian. Zucchi made use of bronze, which is copper and tin in various mixtures. As mentioned previously, there were broadly two forms of bronze in common use, worked bronze of about 6% tin and weapon bronze of about 10% tin, the remaining component being copper. This became known as speculum alloy when it was routinely used as a material for mirrors until glass was silvered in the 18th century. Using metal was a problem because of surface oxidation, which meant that the mirror needed to be re-polished on a regular basis. However, there was one major advantage with a metal mirror: it could be worked with ease when cold, so a hole could be drilled through it for viewing (Fig. 5.1).

The earliest attempts to make use of mirrors for telescopes relied on the mirrors that were available, and on viewing them from one side. This seems to be the case with both Zucchi and Caravaggi, who abandoned their early attempts, as the images were poor. This was most likely because the offset angle of the eyepiece impeded and distorted the view. It is also likely that the mirrors were of a broadly spherical section and not uniform, thereby simultaneously causing spherical errors and distortions in the final image. This was the second basic reason for early problems with mirrors for telescopes. Although chromatic errors could be eliminated quite easily, spherical errors were as bad with a spherical section mirror as a lens.

W. Wall, *A History of Optical Telescopes in Astronomy*, Historical & Cultural Astronomy, https://doi.org/10.1007/978-3-319-99088-0_5

Fig. 5.1 Niccolo Zucchi (Lithuanian Science Council, Wikimedia Commons)

The problem of spherical errors was addressed mathematically long before it was possible to address practically. This was also true of accessing the image. In 1636, Marin Mersenne produced a design with a large parabolic mirror sending the image to a small parabolic mirror, which then reflected the light back through a hole in the primary mirror. The image was then viewed through an eyepiece of a biconvex lens. This was a significant design, in that it solved the visualisation and spherical aberration problems at a stroke, but at the time it was unworkable in the details. This situation was partially remedied when James Gregory published *Optica Promota* in 1663. He used the mathematics of geometry to specify that the primary mirror should be concave parabolic and the secondary concave ellipsoid, again reflecting the image back through a hole in the primary mirror. With these mirror shapes, the telescope was free from spherical errors up to the point of the eyepiece. Other advantages to this design were that it rendered an upright image, which although not necessary for astronomy did make it very useful for terrestrial observation. Although it was not realised at the time, it is also possible to put a field stop in front of the primary mirror so that light from outside the field of view does not interfere with observations. Unfortunately, it is recorded that when Gregory approached a company of opticians, Richard Reeves and John Cox, to make a single mirror, the resulting product was just not useable. Interestingly, this was about a year after publication of *Optica Promota*, and with the associated disappointment of being unable to prove his ideas with a practical demonstration, Gregory gave up the project. It was 10 years later in 1673 that Robert Hooke made a telescope following Gregory's design.

It was another contemporary of James Gregory, Sir Isaac Newton, who introduced a further modification to the reflecting telescope and gave his name to a design. Instead of having a secondary ellipsoid mirror, Newton introduced a plane mirror angled at 45° to the incident light. This reflected the convergent beam sideways into the eyepiece at 90° to the optical axis of the primary mirror, the eyepiece being planoconvex, the plane side facing the observer. Newton made the entire telescope himself, including the fixtures and mounts for the device. It was a small telescope with a mirror of 33 mm and a focal ratio of *f*5. It seems to have had relatively little spherical or chromatic distortion, and with it Newton could see the Galilean moons of Jupiter and also the crescent phase of Venus. There were many details given of the construction and performance of this telescope detailed in his 1704 work *Opticks*. The original was in English; 2 years later it appeared as a Latin translation (Fig. 5.2).

Newton's original telescope was made in 1668 but remained a curiosity rather than a mainstream instrument of discovery. This changed somewhat when Isaac Barrow, friend and tutor of Newton, showed a second telescope Newton had made to the Royal Society at the end of 1671. This so impressive to the Society, including founders such as Sir Christopher Wren and Robert Boyle, that they were moved to demonstrate the telescope to Charles II, who had given the Society the Royal Charter only a few years previously. It was in the following year of 1672 that Newton was elected Fellow of the Royal Society, and in the *Philosophical Transactions* of that year (published in January), considerable detail is revealed as to the method he used to make his mirrors. The importance of this journal and the rarity of places for wide dissemination of scientific information at that time can be seen from there being in that same edition of the *Philosophical Transactions* an article, translated from Latin, by Hevelius, describing a cometary observation (Fig. 5.3).

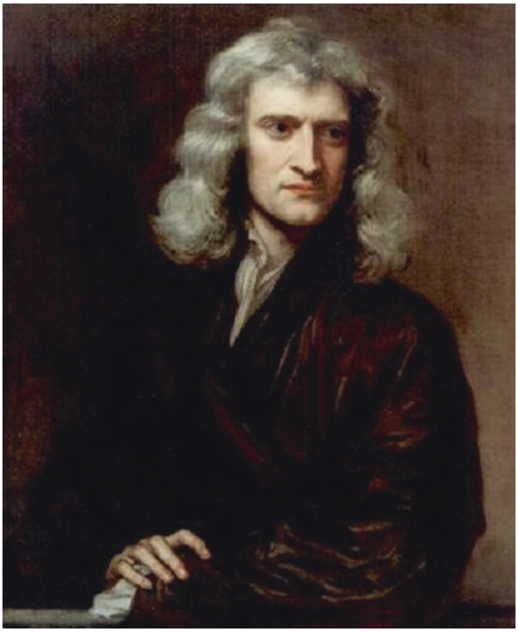
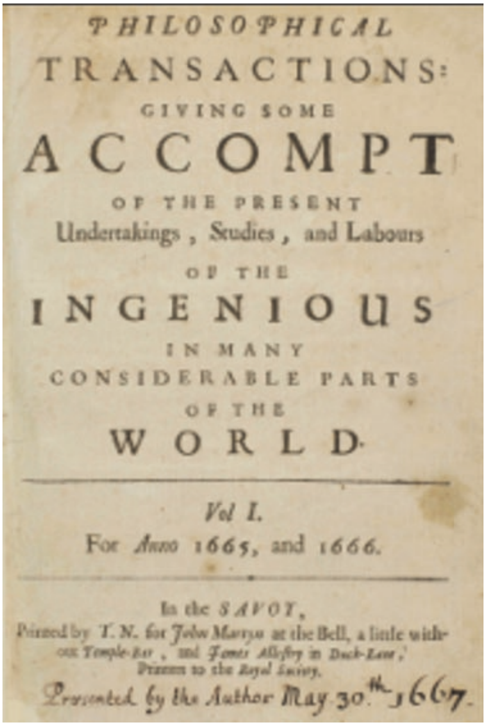


Fig. 5.2 Isaac Newton at 43, painted by Godfrey Kneller in 1689. Kneller was an almost exact contemporary of Newton (http://www.phys.uu.nl/~vgent/astrology/images/newton1689.jpg)


PHILOSOPHICAL
TRANSACTIONS:
GIVING SOME
ACCOMPT
OF THE PRESENT
Undertakings, Studies, and Labours
OF THE
INGENIOUS
IN MANY
CONSIDERABLE PARTS
OF THE
WORLD.

Vol I.
For Anno 1665, and 1666.

In the SAVOY,
Printed by T. N. for John Martyn at the Bell, a little without Temple-Bar, and James Allestry in Duck-Lane, Printers to the Royal Society.
Presented by the Author May 30th 1667.

Fig. 5.3 The cover of the first edition of the *Philosophical Transactions*, published in 1665 (Archive of the Royal Society)

One of the problems that Newton had—as all telescope makers had at this time—was the polishing of the mirrors to an accurate non-spherical profile. Besides this, there was the continuing problem of the material from which the mirror was made, the speculum alloy, which tarnished and needed repeated and careful polishing to keep it clean. This meant that although the size in comparison to performance of reflectors was very good, it did not really compete with contemporary refractors. The speculum metal of mirrors was the best that was available at the time. It was not possible to silver glass at this time, and metals that could take a polished surface to the level required, such as chromium or the alloy stainless steel, were simply not available. During the 17th century, the two most commonly available metals for general use were pewter and iron. It is interesting that until the invention of stainless steel in 1913 by Harry Brearley, the food eaten by the majority of the population was tainted by the taste of metal.

In 1721, John Hadley showed an improved Newton telescope to the Royal Society. He had solved the problem of making parabolic reflectors. His telescope had a primary mirror of 150 mm, allowing it to compare very favourably with the very best of the aerial telescopes at the time. Hadley also made Gregorian telescopes which, having two parabolic mirrors, required a considerable additional effort over the manufacture of a Newtonian telescope.

Newton's reflector telescopes suffered from the problem of coma. This is the flaring of images inwards towards the optical axis, becoming greater towards the edge of the field of view. It is interesting to note in the *Philosophical Transactions* paper of 1672, some detail is given regarding the construction and use of a reflector telescope. Newton addresses the perceived objection of trying to align a telescope of this type, where the direction in which the observer was looking is at right angles to the direction the telescope is pointing. As he pointed out, in daylight you can move the field of view relative to objects in the vicinity that can be seen. Hunting for stars was a little trickier but was cured by attaching two sights to the metal rod that supported the telescope.

Probably the most illuminating aspects of the paper of 1672 are his observations of the problems with making mirrors. These stemmed from a desire to make the mirror as white as possible, moving it away from the colours associated with copper, brass and bronze. This could be done by addition of tin-glass to bell metal. Bell metal is an alloy of copper and tin in the ratio of about 4:1 respectively. Tin-glass refers to bismuth. As Newton points out, this gives a very white metal, but it is riven with small pores due to gas inclusions that cannot be polished out because they run all the way through the alloy. His own preferred technique was to add arsenic at between one sixth and one eight the weight of copper; any more arsenic and it makes the alloy brittle. He even detailed the way in which this alloy was made. First melt the copper, add in the arsenic, "… *bewaring, in the mean time, no to draw breath near the pernicious fumes*". Into this mix Newton, added the amount of tin to make bronze, stirred them together and then poured them off in to the mould for the mirror.

Newton made a passing comment about the addition of silver to the metal, which gave a very white material but was too soft to polish. His recipe for the addition of silver was a simple one. To three ounces of metal (about 85 grams), he added a shilling. This strange unit was part of the pre-decimal coinage of Great Britain. The shilling was made up of 12 pence, and there were 20 shillings to the pound. A shilling from the reign of Charles II is silver and weighs about 6 grams. One of the better alloys he describes was made up of 1 ounce of arsenic, 6 ounces of copper and 2 ounces of tin.

Within the body of the *Philosophical Transactions* paper of 1672 by Newton, there are date references worth explaining. Year dates are marked down as $16\frac{71}{72}$, which is a reflection of the times. In Europe, the old Julian calendar had been replaced with the more accurate Gregorian calendar, which put day-to-day dates out by 10 days between the two. More than that, the start of the year on the old calendar was March 25, while on the new calendar it was January 1. The *Philosophical Transaction* was very modern, by giving the reference to dates in January within the article as being either in 1671 or 1672, depending on which country you were reading it from.

In a reply to Newton, Christian Hugens de Zulichem (sic) wrote that Newton had demonstrated in principle the very great potential of reflectors. However—and it was a great big however—it was pointed out that it was not possible for any known metal of the time to be polished well enough to compare with glass. This was going to be a repeated problem for many years. However well engineered the metals were, the standard of polish was going to be less than on glass. The situation arises from the nature of metals. They tend to cool and form a crystalline structure, which can be difficult to polish evenly. Glass on the other hand can be considered as a non-crystalline solid that has no grain or internal structure that might interfere with the level of polishing. There is more to it than simply that, for example, many plastic polymers have no internal structure, but cannot be polished reliably as they are too soft.

There was also the comment from Huygens that he, like Newton, had almost given up the possibility of making a parabolic speculum. Polishing spherical lenses, like spherical mirrors, was very much more straightforward than the parabolic lenses, which in turn was seen as easier than trying to make elliptical or hyperbolic section surfaces. Nonetheless, Newton did say that he could clearly read some of the words in a copy of *Philosophical Transactions* at a distance of 100 ft (30.48 m) with his reflecting telescope.

As we have seen, the problems of polishing a 17th century mirror, whether flat or curved in section, should not be considered in comparison with the practicalities of polishing a mirror in the 21st century. The mirrors had to be made of metal, but the manufacture of alloys was carried out empirically. We can see from the problems faced by Newton that getting a material that could be polished and was able to reflect a considerable amount of light was difficult. It is no surprise therefore that glass, which could be made without flaws and could also be polished, continued as the material of choice for telescopes. This meant that the largest and most active telescopes were refractors for many years, even though creating non-spherical lenses remained a problem of time and technology for many years to come.

The problems associated with refractors—the intrinsic errors of simple optical devices—were clearly recognised by Isaac Newton when he carried out his optical experiment of 1666. This was described in book form in *Opticks*, published in English in 1704 and then translated into Latin in 1706. It was in his description of this experiment that Newton first logged the colours of what we would now call the rainbow. He gave us red, orange, yellow, green, blue, indigo and violet. Sometimes indigo is now dropped from this list, for two very good reasons. The first is simply that while blue can be seen to shade into violet at the very edge of the visible spectrum, the intermediate colour of indigo doesn't really exist; it is at best a shade of blue. The second reason for dropping indigo is that Newton was interested in many things, including alchemy, and he was very aware of the Pythagorean concept of the music of the spheres, which were originally seven in number and by coincidence also the number of prime notes in our octave. The addition of indigo to make up a seven-colour system was seen by Newton at the time as a perfectly acceptable arrangement for the perfection of the rainbow.

Prior to the publication of *Opticks*, Newton had published another great work, *Philosophiæ Naturalis Principia Mathematica* (1687), in which he described the laws of gravitation for which he is known. Unlike *Opticks*, this was originally published in Latin.

There is an anecdote regarding the apple tree, which Newton reputedly gained inspiration from, which was told by George Forbes (1849–1936). In about 1875, Forbes was lecturing in Glasgow and showed to his audience a small box he had inherited from his father, J.J. Forbes (1809–1868), also a physicist. The box, given to him by Sir David Brewster (1781–1868) who was a physicist as well, contained a small piece of wood and a piece of paper. On the piece of paper was written:

> *If there be any truth in the story that Newton was led to the theory of gravitation by the fall of an apple, this bit of wood is probably a piece of the apple tree from which Newton saw the apple fall. When I was on a pilgrimage to the house in which Newton was born, I cut it off an ancient apple tree growing in the garden.*

The story was concluded by George Forbes commenting that the next day when he looked, the fragment of wood had been stolen.

As the development of good quality reflectors was hampered by the metal alloys being used, the quality of lenses was hampered by engineering considerations. Small objective lenses were relatively straightforward to make; it was large objectives that caused the problems. The sheer technical skill needed to make these telescope lenses can be seen in a paper written in 1900 (Faulhaber, 1900) describing the most up-to-date methods of large lens production.

It started with the production of a crucible of glass, which even at the start of the 20th century was not always of even consistency. It is easy to judge glass by our modern float glass windows that are unblemished, but consider the problems of producing a large homogenous piece of glass of considerable thickness. This is intrinsically very difficult. Once cast and checked for defects, a piece could be cut out and reheated for addition to a mould of approximately the size of the proposed final lens. This glass blank could then be ground and polished on both side prior to thorough testing. The blank was attached to an iron plate with pitch and another iron grinder plate suspended overhead on a rotating spindle. Using emery powder and water as the abrasive, the rotating plate moved across the blank in a predetermined way. Once a surface had been achieved of satisfactory smoothness, the polishing could take place. The system was the same, but the tool was covered in a cloth and the abrasive was then rouge, which was a finely powdered ferric oxide.

Once polished, the nascent lens was checked with a polariscope utilising a phenomenon described by David Brewster for internal inconsistencies. If it passed, the glass moved to the next stage, but if it should fail, it had to be returned to the glassworks to be re-melted and cooled. Before the uniformity of the glass blank was ascertained, there was little point in any other investigation being carried out. Once the glass blank was demonstrated to be fit for turning into a lens, small pieces of glass were taken from the edge of the glass, which could be fashioned into shapes suitable for determining the refractive index. With this information, the planning of the lens could begin. The important features to be calculated were the thickness of the lens and, of course, the curvature. The grinding tool for this process was usually made of metal, either iron or brass, but sometimes glass, with emery powder fed progressively onto the surface. Over time, the fineness of the abrasive was increased so that the process of grinding became slower as the lens moved towards the goal of size and shape. At the time, the grinding process was still an area of activity where great skill was required and regular measurements of curvature were made. When both surfaces corresponded to the theoretical requirements of the lens, it was released from the grinding tool. Up to this point, the lens had been static and the grinding tool had wandered over the surface in a predetermined manner to create the necessary curvature.

The lens was then attached to a lathe and centred. This process of lining up the physical and optical centres was time consuming, with the lens being moved until the axes coincide. This was also carried out by eye, making sure the reflections from the two faces did not move from the axis of rotation when the lens was turned. This allowed the lens to be turned and ground to a perfect circle of specified diameter.

Once the lens was the right diameter, it was polished on a horizontal polishing machine and tested regularly for shape, conforming to glass test pieces that fit exactly the desired curvature of the lens. These test glasses were simply placed upon the lens and note made of the size and distribution of Newton's rings. The aim was to achieve a single colour, corresponding to a uniform thin film gap between the test and the lens. As a starting position, it was more normal to have a wide range of rings, representing variation in distribution of curvature of the lens. This was another aspect of lens production which was carried out by eye and required considerable skill to interpret. It was said that a deviation of only one ten thousandth of a millimetre was achievable by the skill of the polisher. It was only possible to carry out polishing to this level when it was not rushed, and it was routinely a job that would take several months to complete to everyone's satisfaction.

Once the lens pair that was going to make up an achromatic telescope lens had been polished to a satisfactory state, they could be mounted. With large objectives, it was commonplace to fill the air gap with either turpentine or Canada balsam. This practice was discontinued, as separating the lenses for cleaning could be extremely difficult. Also, Canada balsam is not clear, but has a slight shade associated with it and is a microscopic mounting medium known for setting hard over time. Even at the end of the 19th century, not all lenses were made following a strict mathematical plan, being polished and corrected as required for use. One such is the 91-cm diameter objective of the Lick Observatory in California.

The objective lens for the Lick Observatory sited at Mount Hamilton in California has an interesting story, which demonstrates the various pitfalls that can overtake the production of such a considerable lens. The glass blanks were produced by Mantois in Paris starting in 1880, the same time that the observatory was being constructed. The two lenses took 4 years to manufacture, having to be re-melted 20 times. Each time the blank was heated it, took a month to cool it to control damage from thermal shock. The lenses were shipped to Alvan Clark in Cambridgeport, Massachusetts for figuring. From there, they were shipped by train to California and then were loaded onto a horse and cart for the last stage of the journey. Unfortunately, one of the lenses broke at this stage of the process and so had to be replaced. After all this, the lenses were not finally at Mt Hamilton until 1886.

At the same time the refractor and the industrial scale of glass production required to make the very large objective were developing, the development of mirrors and consequently reflectors was also developing.

During the second half of the 18th century, probably the greatest exponent of the use of reflectors in astronomy was William Herschel. He had been born Frederick William Herschel in Hanover in 1738. At the age of 19, Herschel came to the UK, primarily as a musician. In fact, although he was had a lifelong interest in astronomy, he would be 35 before his hobby became the all-consuming study for which he is now more famous for than his music. In 1773, besides James Cook embarking on his second voyage of exploration in *HMS Resolution* and John Harrison winning the Longitude Prize for his chronometer, Herschel's teaching commitments in Bath were much reduced at the end of term, and so he took to constructing and using a new telescope.

At this point he was still using refractors, but found the use of them difficult due to the length of the tube that was necessary to get the best out of the objective that were available. So while Charles Messier was discovering the whirlpool galaxy in the constellation *Canes Venatici* using a refractor with a 100-mm objective, Herschel, in his own words, "hired" a 2-ft Gregorian telescope. It is quite likely that the original use of refractors was at least in part because objective lenses were relatively easy to come by, there were a number of London-based opticians who would supply finished lenses suitable for telescopes. There was also the practical factor of reflectors, in that a refractor objective once installed needs little maintenance, but a mirror of the time would need regular cleaning to keep the polish from tarnishing and reducing the optical performance of the telescope.

Based on the performance of the hired device—not merely optical but also easier to manipulate in general—Herschel determined to find a more powerful telescope. This was easier said than done, as there were few mirror polishers making mirrors of the size he wanted. A practical man, his answer was simple: make one himself. There were two major things that helped him in this, the first that he bought the polishing equipment of an amateur mirror maker in Bath. The second was that he used theoretical instructions from a notable book, *A Compleat System of Opticks in Four Books* by Robert Smith, published in 1738. It should be noted that the publication date preceded Herschel's project by 35 years. In the 21st century a book of that age would be regarded as out of date or old fashioned. This does not necessarily reflect the content of the book, merely the prevailing attitude to the design and layout of the information. In the 18th century, the content was the thing, the age immaterial.

Herschel rapidly achieved success, and after abandoning attempts to produce a useable Gregorian reflector, he tried a Newtonian arrangement with far better results. The problem with the Gregorian design is getting an accurate alignment of the two concave mirrors, whereas with a Newtonian telescope, the angle of the plane mirror is very easy to adjust. With this first successful telescope, Herschel saw the rings of Saturn and became a devotee of the reflecting telescope. The year before William started his intense astronomical studies, his father died, and he and his brother Alexander encouraged their sister Caroline to join them in Bath in 1772. This was going to be significant, because while Caroline started as a willing helper to William's studies, she rapidly became an astronomer in her own right. It should be said that the initial reason for the move was so that Caroline could pursue a career as a singer, a role in which she excelled. This situation was made rather more difficult, as she would only sing when William was conducting. After William died in 1822, Caroline was bereft and moved back to Hanover where she lived until 1848 at the age of 97.

Herschel live at several addresses in Bath, starting at a residence in Rivers Street, close to where the short lived Bath Philosophical Society was set up and had rooms. This residence is still there but was unmarked as Herschel's home for several years. From Rivers Street there was a move to larger premises close to Walcot turnpike toll booth. This property had a larger garden where space could be made for setting up larger telescopes. It was this consideration that motivated the move from the Walcot area (the house is no longer there) to 19 New King Street. This was the last address in Bath where Herschel lived and is now the home of the Herschel Museum of Astronomy.

The house in Bath became progressively taken over by telescopes, with all three of the Herschel siblings involved in the various processes required to make a functioning telescope. This was not entirely to the liking of Caroline, who took charge of the household and disliked the sense of chaos engendered by her two brothers, Alexander and William. It is of interest that even though some of Herschel's telescopes were of considerable length, the problems associated with thermal expansion and contraction of the telescope, which could significantly affect the focus, were not significant. The reason for this was a by-product of making the tubes and suspension devices from wood. This material was not chosen because of temperature changes, but because a cabinet maker could make a tube specifically for an instrument without too much difficulty, especially when compared with trying to have a metal tube made.

To polish his own mirrors, Herschel used emery and then, like many before him, jewellers rouge. With much practice and the development of the practical skills required, William found that the usual technique of trying to produce a parabolic figure directly on the mirror was not always successful, and he could achieve better results by polishing as for a spherical section and then converting it to a parabolic one. This part of the manufacturing took considerably longer, since the mirror was tested for focus at regular intervals as Herschel realised that the mirror could be slowly taken to the correct shape, but if it was taken beyond that point it, was much more difficult to refigure the whole mirror.

Using his meticulous technique, towards the end of the year of 1778, Herschel completed the work on a mirror of just less than 6¼ inches, which was used in a telescope of 7 ft in length. With this telescope, he produced his very early catalogue of double stars, but rather more famously, in March 1781 he discovered Uranus. By this time, the Herschel siblings were living in New King Street, Bath. It was in the basement of this location that William took to smelting his mirror alloys. We have some detail as to what was carried out, and it was definitely not the workshop of a dilettante. In the basement he constructed a significant furnace; in 1781 he smelted 538 lbs (244 kg) of metal in one go. However, the results were rather unsatisfactory. The mould was described as being of sifted loam, which had charcoal burnt in it to harden the surface. We cannot be sure of the precise composition of the loam, but it may have had a significant organic component, which would explain its failure. The organic material could have been burnt off, either by the charcoal or by the molten alloy, resulting in tracks through the mould with the increasing mass of metal. For whatever reason, the pouring started well, but the mould then began leaking, causing a defect in the mirror shape which was then compounded as the mirror developed cracks in several places while it cooled, presumably due to internal thermal stress associated with the metal mass cooling asymmetrically across its width.

The original alloy mix had been what he regarded as ideal for a mirror at 71% copper and 29% tin, but after the first attempt at casting a mirror had failed, Herschel added sufficient copper to change the balance to 73% copper and 27% tin. It was this additional mass of metal that increased the weight to his reported 538 lbs. This time, the problems started while the mixture was being melted, as the crucible seemed to have sprung a leak that became worse as the metal went into the fire and onto the supporting stones where the thermal shock, possibly aggravated by moisture content, caused cracking and violent splitting of the flag stones. Although Herschel did not at this time make the large mirror he wanted to create a very large telescope, his care and skill in producing mirrors of quality were nevertheless going to pay dividends.

The pivotal point that allowed Herschel to stop relying on his music for a living came when he demonstrated the potential of his 7-ft (2.1-m) telescope to George III. While true that visiting the King would furnish his financial freedom, it was actually the visits prior to the Royal audience that increased his already impressive reputation amongst astronomers. His first landmark visit with his telescope was to Dr. Nevil Maskelyne, the fifth Astronomer Royal at Greenwich. Here it was that Herschel was able to directly compare his telescope to those in the Greenwich collection. By his own words, he claimed his telescopes were superior to any they had, being able to demonstrate double stars that were not resolvable using best that Greenwich had at the time. These comments were sent home in letters to his sister, and even if they contain some element of self-aggrandisement, it was certainly true that his telescopes were of a very high quality.

His second visit was to the observatory of Alexander Aubert, which was at that time out at Deptford, south of the River Thames. Later, this would be transferred to the home of Alexander Aubert at Highbury House in Islington. Aubert had bought the house, and since it had considerable grounds, he constructed what at the time was the largest and best equipped private observatory in England. Highbury House was built in 1781 and had a considerable career, at one point being converted into a school before being demolished in 1938. Where it once stood is now the site of Eton House Flats on Leigh Road, Islington in London. Aubert had a collection of superb refractors from all of the major manufacturers of the time. Once again, Herschel wrote in a letter that his telescope outperformed all of those they tried. There is no doubt that his was a very impressive telescope, able to resolve details unavailable to the large refractors, which also suffered from being rather unwieldy in comparison.

These visits were topped off by an audience with the King, after which he was appointed Royal Astronomer and given a small annual stipend of £200. Royal Astronomer is distinct from Astronomer Royal, which is a formal position associated with the Greenwich Observatory. Royal Astronomer was a separate appointment as Superintendent of the King's Observatory, based at Richmond Park. The King's Observatory was built in 1769 for George III so that he could view the transit of Venus. After that date, the building had a checkered career. It was taken over in 1842 by the British Association for the Advancement of Science, at which time it became known as Kew Observatory and in 1871 was handed over to the control of the Royal Society, then from 1910 the Meteorological Office. The site was closed in 1980 and the title reverted to King's Observatory. For many years thereafter, it had a series of commercial uses and annexes added on, but in 2014 its fortunes changed when all the auxiliary buildings were removed and it was converted into a grade 1 listed house.

The fortuitous position that Herschel found himself in allowed a move to Datchet in 1782, where he took a house not far from the river Thames. In the grounds he erected a 20-ft (6-metres) reflector for which he cast a 12-in. (30-cm) mirror. While living at Datchet, Herschel made and sold telescopes to supplement his income. It was not long after starting work that Herschel decided to introduce a larger telescope. This was christened the large 20 ft, as it was the same length but had a primary mirror of a little under 19-in. (48-cm) diameter. This became his favourite instrument, even after constructing his 40-ft (12-m) telescope. The reason given for this preference shows us just how much a useful telescope is dependent upon all of the ancillary fixtures and fittings, not just the lens or mirror. The 20-ft telescope had a system of movement both smooth and reliable, allowing for prolonged periods of observation.

Herschel devised a method of sweeping the skies to create and immense list of over 2000 nebulae. William was impatient to start his catalogue and so started before the structure supporting his telescope was completed. This meant that he would be standing on a beam high above the ground, rather than in a safe position as he would be when the device was competed. Caroline wrote that she was in constant fear of accident. This fear was not allayed by a number of accidents, some more consequential than others. Nonetheless, his major catalogue was started and continued at Datchet until 1786, when the Herschels moved to better premises not very far away at Slough.

As soon as they moved in, work started on constructing a 40-ft (12.2-m) telescope with an aperture of 4 ft (1.2 m). The King gave Herschel £2000 towards the construction and a promise of another £2000 when it was completed. This was a great construction, and the casting of the primary mirror was undertaken by a company in London. The first casting in 1785 was not perfect, as it was thinner than wanted in the centre. Polishing of the mirror was carried out and the result proved to be better than expected when it was finally installed for use at the beginning of 1787. A second mirror was started but cracked while cooling. The third attempt, however, was excellent. This was tempered by the results of polishing, which were disappointing. Herschel thought this was probably because of the large number of individuals that were employed in the grinding and polishing process, and this could be handled better by constructing a machine. So it was that Herschel designed and built a machine capable of polishing his large mirrors.

In August 1789, he had a machine that could take on the task of his 48-in. mirror and started work on the second mirror, the third casting. It took only a day to produce a useable mirror, or at least one worth testing. This was important as much to test the efficacy of the polishing machine as the mirror itself. In August 1789, testing was carried out using the now almost compete 40-ft telescope. This behemoth had a tube of about 12 m long, suspended in a triangular frame which was also about 12 m tall at the apex. The tube was made of fabricated sheet iron, reinforced with steel hoops. At the bottom end was a wooden shed in which the observer's companions, usually two, could moderate the angle and note down the position of the tube. The reason for the need of a two-man team was that observation was made from the upper open end. The observer used a chair positioned to get their head into the tube, which had to be fully 5 ft in diameter to accommodate the mirror. From the observation point, the tube could be moved very slightly, but for repositioning it required the cooperation of the person on the ground.

The mirror for testing was put into telescope base, no easy feat as this was a very heavy piece of metal. Herschel reported that despite the defects—scratches that had not yet been polished out—the mirror worked very well indeed. The remnant defects were responsible for some flare. Nonetheless on the following night, the telescope revealed Enceladus, the sixth satellite of Saturn. Herschel noted he had seen this body some 2 year before, but had not made any further observations of it at that time. It would seem that the mirror would have required a far greater exertion to remove it to polish it further, so it stayed *in situ* for many years, being used intermittently for observations. Nevertheless, Herschel appears to have preferred his 20-ft telescope, even though there were some objects visible with the larger of the two that were indistinct or not visible with the smaller telescope.

It was in 1786, during the period of constructing the 40-ft telescope and creating the mirror for it that Herschel's friend and neighbour, John Pitt, died. His widow, Mary, was reportedly a very charming woman, and in 1788 William (50 by this time) and Mary married. Mary took over the running of Observatory House on a day-to-day basis, a position Caroline had held since she arrived from Germany. Caroline remained as William's scientific collaborator, discovering eight comets and three new nebulae, and also updating and correcting Flamsteed's original star records. Caroline was recognised in her own right as a scientist and was awarded an annual salary of £50 by George III. This made her the first woman in England to have an official government appointment.

One of Herschel's notable discoveries was made in 1800: infrared radiation. His initial observation occurred when he was using an ambient temperature thermometer while splitting light through a prism. If the thermometer was placed just beyond the red end of the spectrum, the measured temperature went up. From there, it was a simple process to devise demonstration equipment that could be used to test his hypothesis of the existence of invisible rays. Interestingly, on camera lenses designed before autofocus, there was a small red spot on the focus ring that denoted the focus change if using an infrared-sensitive film.

The work of William Herschel was carried on by his son, John. William was a very versatile thinker and observer, being as comfortable with music as he was with astronomy. John shines as a scientist, one of the last great polymaths. He was a chemist, astronomer and early exponent and developer of photography; in fact in 1839, he coined the word photography. Besides a crater on the Moon, a mountain in Antarctica and Herschel Island in the Arctic, there are several villages and schools named in his honour. When he died, he was interred in Westminster Abbey. Long after the death of his father in 1822, John photographed the remains of the rapidly decaying 40-ft telescope in 1839 on a glass plate. Although the tube is missing (perhaps taken down sometime before), the frame is clearly visible in the photograph.

William Herschel's work in astronomy was of two distinct types. The first was the clear demonstration that telescopes based on mirrors were not merely a theoretical alternative to refractor telescopes. Once he had designed and built his own polishing machine, his telescopes were recognised as high-performance optical devices. Using these instruments, he made a huge impact on observational astronomy. He discovered two moons of Uranus, Titania and Oberon, and two moons of Saturn, Enceladus and Mimas. His involvement with the planets however did not stop there, as he was able to determine the rotational period of Mars and the seasonal variation of the Martian polar ice caps. The apparent similarity in so many ways between Earth and the planets we could see convinced him of the existence of extraterrestrial life. This was not concluded in an abstract way, but in a very practical description of the surface of the Moon and other celestial bodies.

William was also very keen on the study of double stars, specifically as this was seen as a method of determining parallax changes and therefore their distance from the Earth if the two stars were close together in the field of view. In his searches he was surprised to find very many more binaries and multiple stars than he had expected. Altogether, he collected more than 80, and much to his surprise, a lot of them were true pairs. These were determined by their relative movement to each other being unexplainable just by invoking the movement of the Earth. Herschel reasoned quite correctly that these were true binary pairs rather than optical ones just lining up in the same field of view, and they orbited around a common gravitational centre. During this period he also looked for nebulae, which at the time was anything of a diffuse and indistinct nature and consequently included a large number of galaxies. He published many of these catalogued nebulae, and John carried on with this work, extending the list considerably. In 1888, John Dreyer edited and produced a composite list entitled the New General Catalogue, which was shortened to NGC. This designation is still in use for celestial bodies. William was instrumental in the characterisation of infrared radiation, which in itself may not seem significant, but this was the start of astronomical spectrophotometry. The spectrophotometer is, along with the camera, one of the most important astronomical devices that can be attached to a telescope (Fig. 5.4).

The reflecting telescopes of Herschel represented just about the best that was possible using metal mirrors. It would be well into the 19th century before silvered glass mirrors became a plausible alternative to metal. Silvering was not as successful as aluminium coatings on glass mirrors, and this was not going to happen until the 20th century. These processes were going to make very large diameter mirrors a mainstay of later optical telescopes and improve the performance so much so that it

Fig. 5.4 John Herschel in a photograph taken by Julia Cameron in 1867. John was the son of William Herschel and nephew of Caroline Herschel. This early photographic portrait follows in the traditional construction and form of painted portraits of the time (Julia Margaret Cameron - John Herschel (Metropolitan Museum of Art copy, restored).png

was recognised that to use the instruments to their maximum advantage, it was necessary to site them where optical distortions due to the atmosphere could be minimised, at high altitude and dry conditions on mountains and eventually in space.

References

Faulhaber, C. 1900. Construction of Large Telescope Lenses. *Popular Astronomy* 13: 534–542.

Forbes, G. 1909. *History of Astronomy*. London: Watts and Co.

Gregory, J. 1663. *Optica Promota*. London: J. Hayes.

Hevelius, J. 1672. Extract of a Letter of Monsieur Hevelius from Dantzick Written to the Publisher in Latin, March 9. (st. nov.) 1672; Giving Some Accompt of a New Comet, Lately Seen in that Country: Englished as followeth. *Philosophical Transactions* 7: 4017–4018.

Newton, I. 1672. An Accompt of a New Catadioptrical Telescope Invented by Mr. Newton, Fellow of the R. Society, and Professor of the Mathematiques in the University of Cambridge. *Philosophical Transactions* 7: 4004–4010.

———. 1687. *Philosophiæ Naturalis Principia Mathematica*. Translation available: *The Principia* trans. by I. Cohen and A Whitman, California University Press, 1999. London.

———. 1704. *Opticks, or, a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light*. London.

Smith, R. 1738. *A Compleat System of Opticks in Four Books, viz. a Popular, a Mathematical, a Mechanical, and a Philosophical Treatise. To Which Are Added Remarks Upon the Whole*. Cambridge: for the Author.

Chapter 6
Industrial Life Creating Fine Instruments and Polluting the Skies

Although we commonly consider the positioning of astronomical telescopes on mountains as usual, this is a relatively recent phenomenon. What is not so recent is the realisation that there is something not quite right about viewing stars through the atmosphere. It is fairly certain that one of the earliest comments on this can be found in *Sidereus Nuncius*, written by Galileo in 1610. Although Galileo did not appreciate the profundity of his observation, he did make the connection between atmospheric interference and the sparkling light of stars. Up until the invention of the telescope, all astronomical observations were by naked eye, more regulated by cloud cover than any manmade pollution or atmospheric disturbances. While it is said that in some of the more densely populated cities such as London, coal burning caused local problems for night sky observers, further south this was not so obvious, as the practice of using wood to heat buildings was much more seasonally controlled and industrial use of furnaces was relatively small.

The major problem for telescope users both ancient and modern, and certainly in the time of Galileo before industrial smoke, is one of glare. This is really just a simple way of describing any unwanted light in the desired image. It can come from many different sources and for the earliest manufacturers and users of telescopes was not perceived as a particularly significant problem. The reason for this early disregard of glare was because the gains from using even a poor telescope over naked-eye observations was immense. However, it quickly became apparent that glare was an important factor, as the image through early telescopes seemed to have this aspect, while naked-eye observations did not. The earliest techniques for glare control involved stopping down the aperture so that only the centre of the lens was used, the peripheral part being most involved in optical interference. The glare in a system is constant for any given adjustment, and in the case of a telescope, the adjustment also includes atmospheric conditions part of the optical train. It follows from this that the darker the image you want to see, the worse the effect of glare becomes, as contrast is reduced.

At the very start of telescope production in the 17th and 18th centuries, tubes were made of paper, or more precisely *papier mache*, which although often

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decorated on the outside were internally plain. As telescopes became larger, the shortcomings of what is essentially a non-rigid support for individual elements became more pronounced. The answer was to manufacture tubing, but this was easier said than done. Telescope tubes need to be both strong and straight, which rules out many of the materials that would have routinely been used for pipework of a less demanding kind.

The problem was one of engineering: the range of materials for fabrication of tubes was necessarily limited until well into the 19th century. It was this lack of lightweight strong alloys that made the construction of fully enclosed, long focal length telescopes impossible, resulting in the aerial telescopes of history. To make long self-supporting light-tight tubes out of wood is size limiting, and to make one out of cast iron impossible for much the same reason. Constructing a small wooden tube was difficult but could be done by a cooper, or at least on cooper's principals. So if a light-tight tube was wanted, it would be limited in length— this was the motivation for constructing aerial telescopes.

With aerial telescopes, stray light coming in from every direction made it virtually impossible to use in any modern conurbation. Still, they reached their pinnacle of activity in the second half of the 17th century, when stray light was not a problem. During this period all lighting was based on the naked flame, which when the Sun went down was almost exclusively used inside houses. Exterior lighting was rare indeed, confined to the very wealthy on special occasions.

As there was not a great deal of light from manmade illumination, stray light from extraneous sources was not generally a problem for aerial telescopes, except on bright moonlit nights when it could become a significant issue. With large diameter telescopes, the problems of torsion and flexion of the tube were quickly understood, and any idea of constructing a self-supporting tube was soon abandoned in preference to a rigid frame that could be clad in a material both light and easily worked. With enclosed tubes, however, internal reflections causing glare always needed to be controlled. The earliest method of control of this problem was by the use of lampblack. This was nothing more sophisticated than the soot deposit that appeared on any surface in direct line with the sooty flame of an oil lamp. If this was mixed with a suitable mordant, it could be used as an easily applied paint to the inside of the telescope tube, giving a black interior. If this was carefully applied so as to be a matte surface, it absorbed the light from internal reflections within the tube. This internal colouring continued until the 20th century, when newer methods were introduced in the form of liners and true matt flocking.

The problem of glare is a relatively straightforward one to fix, and as we have seen at the time of the earliest telescopes, the question of light pollution was not a significant problem. What was a problem was transport until the 19th century and the introduction of the railways. To have a telescope and a job required proximity to the place of work. If a keen astronomer was from a wealthy family, during the early centuries of telescope observation, it was possible to have a telescope assembled on a country estate where the air was clear. For people such as John Dollond who made their living from manufacturing optical instruments, being close to potential customers as well as third party suppliers was essential. This is why early industrialisation took place in the very centre of our towns and cities. Similarly, academic workers at the great universities needed to be within an easy travelling distance of their place of employment. The result was that many early observers had their instruments sited in cities. It became apparent quite early on that during certain times of the year and under adverse weather conditions, household cooking and heating process could impede observations.

Although towns and cities were small by modern standards, they were quite densely constructed. London had a gradually increasing population, for which we have some good estimates and some accurate census data. In the *Proceedings at the Sessions of the Peace for the City of London*, which first appeared in the mid-17th century, we can say that the population of London in 1674 was roughly 500,000, By 1688, the first recognisable demographer, Gregory King, estimated the population to be 527,000. By 1715 this had risen to 630,000 and by 1760 it was 740,000. By the time of the first census in 1801, London had a counted population of 1,096,784. With the increasing population, in large part due to recruitment rather than births alone, London became a densely populated area of adults of working age. We know this in part from written records, but also because we know that between 1730 and 1760 the death rate up to the age of 2 years was 20.2 deaths/100 live births.

This population had to have fuel to cook and heat their homes, and this would have started as wood. Although this is undoubtedly a source of smoke that obscures the night sky, up until the 1600s, this was not going to be an issue. However, by the 13th century, coal was starting to be used in lime kilns and brick works. It was a relatively small amount at the start, as charcoal was still the more commonly used fuel. As the increasing cost of wood made it more difficult to afford for the bulk of the urban population, coal became more acceptable and cheaper as a domestic fuel. This marked a big change in the ability of astronomers to view the night sky. The first change to observations was, of course, the smoke production.

Coal was used indiscriminately from any source, and whereas now we categorise it based on its non-carbon content, at that time it would just have been "coal" regardless of content or origin. We cannot be sure of the nature of the coal burnt domestically, but we do know that many people tried not to use it, as they said it made the furnishings smell and covered the interior of their houses with soot. In fact, by the middle of the 18th century the London smoke plume was visible for 100 km. For most people, the smell of burning coal was also off-putting when first entering a city. This smell was also the source of the second problem for astronomers: the gas part of coal smoke. This contains a large amount of sulphur dioxide, which when dissolved in water forms sulphurous acid. This acid would very readily corrode metal mirrors. Complaints regarding smoke in the atmosphere seem to have become rather more common during the 17th century, at least in part due to the increasing use of coal as a domestic fuel. Also, because industrial use in the form of lime kilns was growing as demand for cement and mortar increased, these kilns had to be within walking distance of available workers and the cities where building was taking place. Complaints about excessive smoke in the capital had their origins as long ago as the reign of Edward I in the Calendar of Close Rolls, dated June 12, 1307. While Edward I was in Carlisle, he produced a call that read:

> To the sheriff of Surrey. *Order to cause proclamation to be made in the town of Suthwerk that all who wish to use kilns* (rogorum ministerium) *in that town or its confines shall make their kilns of brushwood or charcoal* (carbone bosci) *in the usual way, and shall not use in anyway sea-coal hereafter under pain of heavy forfeiture*.

The document went on to say this was due to complaints regarding the smell of coal burning. The town mentioned, Suthwerk, is what is now called Southwark and is on the south side of the river Thames adjacent to London Bridge. That same year, in a physically damaged document, the Dominican Friars asked that the kilns were not allowed to be rebuilt in perpetuity, the assumption being that as they fell into disuse, they would remain closed.

This was a problem of high-density living, the use of open fires and the difficulty of transporting heavy goods easily. While it might seem that these were only local problems, it became a pressing issue for both astronomers whose visibility was impaired and the general public whose health would eventually be recognised as compromised. Noxious smells and dust accumulated inside poorly ventilated houses, and the fuel clouded the skies and limited observations in towns and cities where winter heating was necessary.

In 1658, Sir K. Digby made specific comments on the problems of keeping clothes clean in London. He also made the point that this was a local phenomenon, as moving only a few miles to Richmond in the west or Stoke Newington in the east resulted in clear skies. Over the next 300 years the problems just became worse and more widespread, until acts of parliament were used to control domestic use of coal. A well-known pamphlet of 1661 by John Evelyn entitled *Fumifugium or The Smoake of London Dissipated* dealt with this issue. The problem was not long to be confined to London, as in *A Tour Through the Whole Island of Great Britain* by Daniel Defoe, he says of Sheffield in Yorkshire, "…from the great quantity of smoke occasioned by the manufactory, the newest buildings are apt to be soon discoloured".

We can see the increasing recognition of air pollution as a major problem for domestic cleanliness and health. The less recognised problem, or at least a less vocalised problem, was the obscured view for telescopes sited in areas with a high population density. Until well into the 20th century, industry was found in the centre of cities. When Claude Monet painted his pictures of Waterloo Bridge in 1900 from the fifth floor of the Savoy Hotel (Fig. 6.1), he showed us the problems of a city skyline made up of industrial chimneys.

Before atmospheric pollution became a problem, it was common wherever possible to site telescopes on building tops, but this was more about having a 360° line of sight than being above smoky rooftops. In the early days of high-performance optical astronomy, notions of atmospheric disturbance were little understood, although there had been occasional references to it in observations that stars twinkled. It should be understood that atmospheric pollution, light pollution and atmospheric disturbance are separate problems for ground-based astronomers, but the

Fig. 6.1 Waterloo Bridge painted by Claude Monet around 1900. He is looking from the north side of the river, upstream. The first large chimney is probably the flour mill, the large tower is a shot tower for the lead works, then further along, steam cranes (Authors photograph of a detail from The Hugh Lane Gallery of Modern Art, Dublin)

solution is broadly the same for all three. It is interesting that the solutions found were evolutionary rather than revolutionary, and reflected the change in observational power. This in itself was very much a function of wanting and needing to see a little bit further with every small step in telescope performance that was achieved.

With the positioning of either refractors or reflectors in areas that developed an industrial base, the problems initially was going to be corrosion of metal mirrors and dust deposits on both lenses and mirrors. As the magnification increased, it became apparent that atmospheric affects were becoming obtrusive. This is notwithstanding any problems from atmospheric pollution or light pollution, which became such a problem for amateur astronomers in the 20th century.

It is worth approaching the problem of atmospheric effects from the standpoint of what they are, although their precise nature remained almost irrelevant to astronomers who after all were not so much interested in them as interested in avoiding them. The most apparent effect of the atmosphere is to render scintillation to distant objects caused by high altitude turbulence. This scattering results in point sources such as stars getting brighter and dimmer on a millisecond scale, which is seen as a variation in luminance. With larger bodies, most specifically the Moon, the problem is not so pronounced because the eye can take what is in effect a mean measure of visible features to give what appears to be a stable image. It makes sense that scintillation is a bigger problem with objects low in the sky than those directly overhead, as objects viewed close to the horizon are being viewed through a far larger thickness of atmosphere. As soon as it was observed that the thickness of the atmosphere was significant in the level of apparent scintillation, it made sense to site telescopes at high altitude where they had less atmosphere to deal with. This did not mean simply moving to a hill; it required very large differences in altitude—the higher the better.

The question then remained as to which specific component of the atmosphere was causing the most problems. It was not a simple answer but one that should nevertheless be addressed. Atmospheric scintillation is broadly dependent on changing density, so having a telescope where it was subject to small thermal fluctuations and low humidity was important. The answer was to put telescopes in very high deserts. These sites were out of the way of pollution affects that would be a major problem later, not just from solid fuel burning and from smog generated by vehicles using internal combustion engines, but also from light pollution, as they tended to be in inhospitable areas.

The first permanent high altitude observatory was the Lick Observatory on the top of Mount Hamilton in California. This was relatively modest in height but caused considerable engineering problems during its construction, which took place from 1876 to 1887. This was all due to difficulties accessing the site. Lick Observatory gained its name from a bequest from James Lick, who paid for the construction of the observatory. The local authorities needed to provide a road to the top of Mount Hamilton at 1283 m. The road was built winding circuitously around the mountain to keep the overall incline down to a level along which laden horse-drawn carts could manage. This was not only the first high altitude optical observatory but it was also one of the first to recognise the potential difficulties due to ambient light pollution. After nearly a century of operation, in the 1970s, it was found that light from the nearby town of San Jose and the later development of Silicon Valley was becoming sufficiently bright to impede the activities of the observatory. San Jose tackled this problem by installing low pressure sodium lamps. The lick observatory has been instrumental in many steps forward in optical astronomy, discovering the first double planet system and several moons of Jupiter, as well as 55 Cancri, a quintuple planet system. It was also the first observatory to detect emission lines in the spectrum of an active galaxy. The discoveries and clarity of observation possible at Lick demonstrated unequivocally that it was worth making the enormous investment to build such telescopes at altitude.

There have been many other high altitude observatories constructed since the Lick observatory, such as the observatory built in 1878 in the French Pyrenees at 2877 m altitude and much later Mauna Kea on top of a Hawaiian volcano at 4205 m. In studying the meteorology of an area and the general weather patterns associated with high altitude, a number of factors became apparent. Within 80 km of a coastal area, high altitudes benefit from a stable inversion layer, and the site is above most of the atmospheric water vapour. All these points are extremely advantageous for optical astronomy, but of course, not every country has high altitude areas and therefore equal access to such benefits. For example, in the United Kingdom the highest peak, Ben Nevis, is only 1344 m above sea level.

It would not be correct to think that merely siting an observatory at high altitude out of the direct influence of ambient city lights guarantees clear and accurate observation. The observer is still very important. It should always be remembered that there is not only considerable skill in making accurate and useful observations, but also considerable skill in interpreting the results of those observations. One case of note in this respect is the short period in which canals on Mars became a central part of the observations of our near neighbour.

Giovanni Virginio Schiaparelli was born in 1835 and by 1862 had been appointed director of the Brera Observatory in Milan. This was a low altitude observatory located in the centre of the city. In 1877, using an 8¾-inch (22.2-cm) refractor, Schiaparelli started his work on Mars. The date was significant, as by September 5, Mars was at opposition and practically at perihelion. Schiaparelli produced a chart of Mars that was better than any previous ones available and certainly better than could be produced now using the same equipment in the centre of Milan. What was a significant deviation from previous maps was the inclusion of fine lines across the otherwise desert areas. He recorded that they varied in width depending on their position, from 180 mi wide to 20 mi wide, and he was also was the first to use the term *canali* to refer to them. This word better translates from Italian as *channels*, so it would be inaccurate to say that Schiaparelli referred to them as canals. One or two previous observers had included fine lines on their maps, although nothing as complete as Schiaparelli observed. At the next opposition in 1879, conditions were also good for observation. Schiaparelli added new canals to his network, some now seen as double and others capable of moving from single to double overnight.

Upon the publication of these results, there was some scepticism from the scientific community, as no one else had reported canals on Mars. C.E. Burton in Ireland had produced some drawings from the 1879 opposition that contained markings that could have been described as canals, but generally the observations as described by Schiaparelli were not reproduced. Schiaparelli was convinced that the canals were genuine structures for draining melt water from the poles to the arid equatorial regions (Fig. 6.2).

It was in 1886 that the tide of scepticism associated with Schiaparelli's observations moved in his favour, when Perrotin and Thollon working at the Nice observatory with a 76-cm refractor declared that they had seen canals on the surface of Mars. This changed the overall attitude, and there were many observers who also claimed to have seen these features. At the turn of the century, the central character in the Martian canal story becomes Percival Lowell in the United States.

In 1894, Lowell had built an observatory at the elevation of 2100 m at Flagstaff, Arizona. This site had no city lights to contend with, and because of the geography, very few cloudy nights. This was the first time that the primary motivation for choosing a site was the possibility for clear and unobstructed observation. When the site was chosen, it was only a potential; the reality of the situation would only be known once the telescopes were installed. Once it had been constructed, the value of the choice was vindicated, and it became normal practice to consider the position and elevation of observatories with respect to clear skies before making a final decision. Lowell installed a 61-cm (24-in.) refractor specifically to study Mars. He produced maps of the canal system and was convinced that Mars was inhabited by beings of an advanced civilisation that were capable of engineering the canal system. While Lowell maintained that the canals were artificial, others suggested they

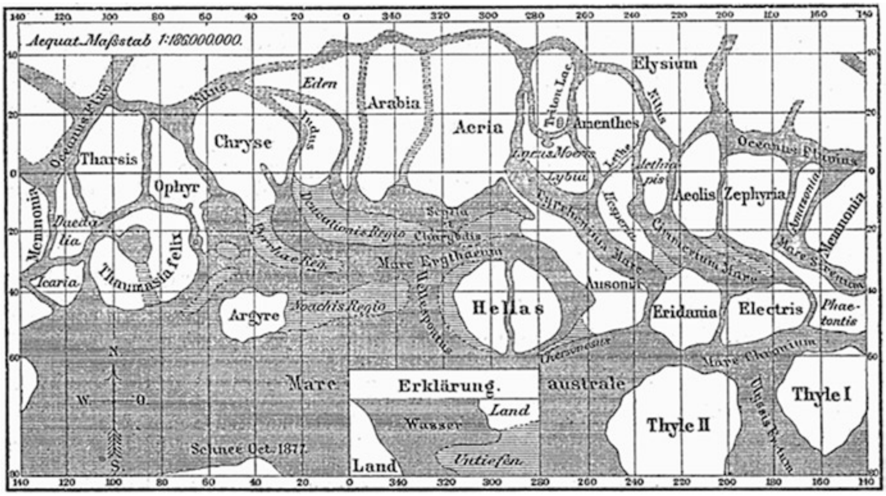


Fig. 6.2 Map of the *canali* produced by Schiaparelli in 1888 (Meyers Konversations-Lexikon (German encyclopaedia))

were geological artefacts. There were also detractors such as Alfred Russell Wallace, who did not attack the idea of canals but by clear argument stated that Mars was too cold and dry for canals to be present.

One of the major problems with the canal maps was that they did not correspond with each other at all; each map was astronomer specific. There were also many astronomers who did not see the canal network at all. After the death of Lowell in 1916, the number of proponents decreased, and the idea of canals on Mars became of less importance. It was as though there was a collective embarrassment amongst astronomers, who thought it best to ignore the questionable existence of the canals in the belief that they would be dropped from the popular imagination. So it was that they gradually died away as a real idea, finally being put to rest with the images from the Mariner space probes. The question remains, however, as to exactly how the 50-year saga of Martian canals managed to sustain itself.

The observation of canals is difficult to explain, but there are two possibilities, neither of which is exclusive. The first is that Schiaparelli was using a poorly adjusted telescope while viewing a low luminosity object. Under these circumstances, it is possible to project onto the retina a shadow of the blood vessels in the eye that could be easily overlaid on the Martian image. Such lines could then have been incorporated into the images being drawn as real features. The time between observations due to the differential planetary orbits could consolidate in the mind the images as drawn. Whether or not this is the case we cannot be sure. The second possibility is one of illusion, in that there is a tendency for point objects to be associated together in low resolution images and at low light by lines of attachment. Schiaparelli became blind some years before his death in 1910, the cause of which we also do not know.

What is of more interest is how the original observations, or more precisely the maps constructed from the observations, could have gained such credibility in the astronomical community. There was certainly an element of momentum in the short-lived idea of canals on Mars, mainly brought about by the idea of Martians and the debate as to what they were like and how we could communicate with them. This in turn seems to have been aroused by the scientific and popular press latching onto the well-presented maps of Mars that became available as printable items of news. It was the unique introduction of cartography to our nearest neighbour that seems to have started the ball rolling; until 1840, no traditional cartography had been applied to a planet other than our own.

In 1840, Beer and Madler applied a conventional latitude and longitude to Mars, implying that the planet was very similar to Earth. It was in fact done to help create a unified basis for a comprehensive map of the planet, as it was becoming apparent that while there were features that kept appearing in different maps, there was otherwise only the broadest correspondence between maps. The method they used was broadly a Mercator projection, giving parallel lines of longitude and latitude. This of course gave a distorted image of the poles. The first new map, as previously described, came from Schiaparelli, who used only his own observations and Nathaniel Green in Britain, who helped create composite picture (Fig. 6.3).

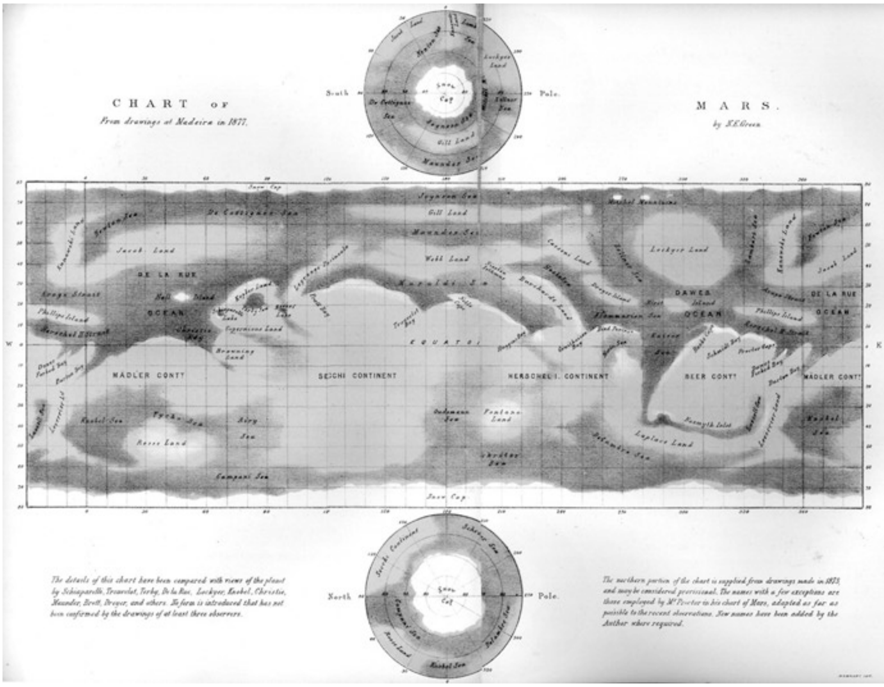


Fig. 6.3 Composite map of Mars painted by Nathaniel Green in 1877 (http://www.uapress.arizona.edu/onlinebks/mars/chap05.htm Wikimedia Commons)

The two images looked quite different: as an artist, Green had painted a subtly graded image of different colours, while Schiaparelli had used a hard line to delineate features. Although the contents of the images could not be compared, the techniques could, as they both used a Mercator projection and an azimuthal projection for north and south poles. The debate regarding the reality of the canals was carried forward in print, with Sir Robert Ball in his *Popular Guide to the Heavens* (3rd Ed 1910) stating that some saw the canals and some not, but that "in the unsteady air of England it is almost hopeless to expect to see many of the finer details".

At the time of publication, the maps produced by Schiaparelli were seen as the most useful and fired up the imagination of other astronomers, who started looking for canals. The nature of the Mars orbit resulted in Schiaparelli adding new canals to his map every 2 years. This had an interesting effect on popular perception. Green's maps were seen as slightly inferior because of the lack of certainty in the execution of the features, whereas Schiaparelli always produced a prominent and dramatic feature when he put anything on the Mars map. It was after 1884 that the maps of Mars and the canals started to become mainstream with more and more astronomers claiming to have seen them, even though there were always some dissenters. Speculation grew regarding life on Mars, culminating in the publication of *War of the Worlds* by H.G. Wells in 1898.

In 1894, Percival Lowell started investigating Mars and without doubt had the best maps. They had a verisimilitude to street maps and plans, which increased the speculation that Mars was populated. It is interesting to note that original sketches of Mars by any astronomer only ever showed a few lines, and no astronomer of the day claimed to have actually seen Martian canals while viewing the planet through a telescope. It is for this reason that we can be sure the maps were different from observation. It is also important to remember the complexity of the mapping process. Lowell is reported to have started the process by mapping the details of sketches onto a wooden globe, which was then tilted and photographed. The negative was then projected onto a Mercator projection and traced out. Once this composite map was produced, it gained an authority that it did not deserve. The story of the canals went into decline when Lowell travelled to South America to take photographs of Mars. These turned out to be very poor, and when articles and books started using photographs rather than drawn maps of Mars, it could no longer be claimed that the canals were visible. An added impetus to the decline of Martian canals came when the astronomer Eugene Antoniadi reported in 1909 that no canals could be seen through his telescope, which was outside Paris. He went one step further when he produced a map very similar to the current maps of the day. The idea of canals lingered among some groups for many years but would have disappeared sooner had *The Planet Mars* by Antoniadi, published in French in 1930, been translated sooner than 1975, that translation being done by another famous astronomer, Sir Patrick Moore (Fig. 6.4).

We can see that regardless of how it started, the influence and plausibility of an idea, in this case canals on Mars, can carry on against all reason. It was fed by the popular imagination embracing alien intelligence and astronomers feeding on the popularity. Regardless of the performance of the instruments being used and the

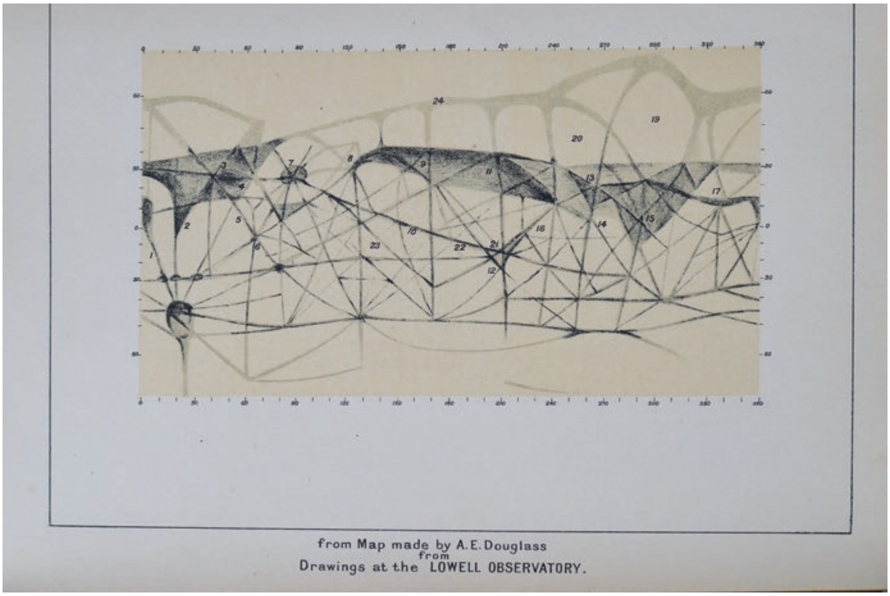


Fig. 6.4 A map of Mars 1896–1897 by A.E. Douglass at the Lowell Observatory (Ball 1910) (Authors photograph from A Popular Guide to the Heavens by Sir Robert Ball, 1910)

increasing resolution, it was the interpretation of the observations that caused such confusion.

As optical telescopes increased in performance, another piece of technology was also improving that was destined to replace the drawn image. The introduction of photography made a huge difference in the reliability of results. No longer would the hand-draw image hold sway over an idea. Photography had a shaky start, with various techniques being tried, most of which were unsuitable for astronomy, not because of the chemistry involved but because of the technology associated with it. Photoactive chemicals had been known for a very long time; making practical use of them was very much more difficult. The earliest attempts at photography required exposures of immense length, measured in hours. In the case of the Daguerreotype, invented by Daguerre in France, the exposure was long and produced a single picture; the final image could not be reproduced. If another image was needed, the photograph had to be taken again. At about the same time, Henry Fox Talbot invented a technique still requiring a long exposure but which produced a negative that could be printed repeatedly. The earliest negative produced by Fox Talbot was of the Oriel window in Lacock Abbey, dated 1835. At about this time, a scientist and polymath started to work on photography—John Herschel, son of William Herschel. He invented a process called the cyanotype, which was the precursor of the blue print. Beside this, in 1839 he took a photograph of the 40-ft telescope his father had constructed. It was in this same year that John Herschel coined the word "photography" and used the terms "negative" and "positive" with respect to photographic images. It was also his discovery that allowed for the permanent fixation of a photographic image.

Introducing photography into astronomy required a rather higher standard of engineering than is necessary when an observer is carrying out work by eye, with notes as the only record. One of the first attempts to capture an image of a celestial object was in 1839, when Daguerre tried to capture an image of the Moon using his Daguerreotype system, which was chemically treated copper plated with silver. He had recognised that with the system he had available at the time, only bright objects such as the Moon could register an image. The length of exposure required was beyond the capacity of the telescope to track, resulting in a smeared image. But the point had been made that one could capture an image if the technical infrastructure was good enough to back up the chemistry. A photograph of the Moon was finally taken in March 1840 by Professor William Draper, a chemist at New York University. It was a Daguerreotype using a 13-cm reflector telescope, but more importantly, it was accurately tracked for the 20-min exposure time.

With time and the realisation that a photograph was perfect for exchanging information, ambitions grew regarding the possibilities of fixing a permanent image. Broadly speaking, the only available technique at this time was the Daguerreotype, even though copies could not be made of the image. In 1842, an attempt was made to photograph the solar eclipse, which sadly failed. But by 1845, the Sun was photographed for the first time. On July 28, 1851, the first successful photograph of the corona of the Sun was taken by Johan Berkowski, a photographer, under the guidance of August Busch, who was the Director of the Konigsberg Observatory. The photograph, like most taken at this time, was a Daguerreotype and reflects the very complex nature of photography in the middle of the 19th century. A recognised photographer was needed as well as an astronomer to create the required image. The instrument used was a 17-cm heliometer with an aperture of 6.1 cm and a focal length of 81 cm. The target had to be tracked, as the exposure was 84 seconds. The length of exposure meant there was little time to put right any errors, hence the second image that Berkowski tried to capture with a 45-sec exposure was actually burnt out as the Moon moved out of alignment and flooded the plate with light (Fig. 6.5).

By the 1850s, an alternative to the Daguerreotype was starting to be used, but this had distinct disadvantages of its own. The process was wet-plate collodion. As the name implies, this used a wet plate so that on long exposures it was inclined to dry out. By 1856, a patent was issued for a dry-plate system using the same chemistry, and by the mid-1860s, this had replaced the wet-pate system. The main advantage was that unlike the Daguerreotype, a collodion image could be repeatedly printed, allowing people to see the image without handling the precious and only picture. Nonetheless, Daguerreotypes were still extensively used, a reflection of them having been in use for many years and although clumsy and delicate, being well understood by the professional photographers of the day.

It was a Daguerreotype that captured the first image of a star—Vega. The image was taken at Harvard College Observatory using a 15-in. refractor in July 1850 by

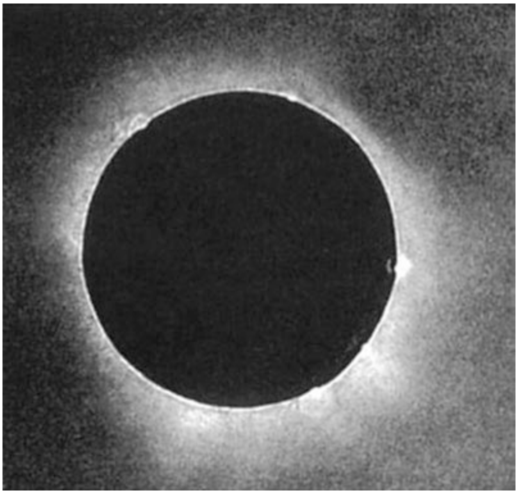


Fig. 6.5 In July 1851, Johan Berkowski took a Daguerrotype, thought to be the first photograph of the corona of the Sun (http://xjubier.free.fr/site_stickers/solar_corona_shape/1851_07_28_Berkowski.jpg)

John Whipple and William Bond. Vega also featured in the 1863 landmark spectrogram showing the absorption lines of the star. William Miller and William Huggins took the picture and captured it on a wet collodion plate.

Such achievements were rare events, and it was only with dry plate negatives introduced widely in the 1870s and onwards that images became reliable. Dry plate image categorically demonstrated that astrophotography was not just a method of recording an event, as in the case of photographs of an eclipse. In 1883, Andrew Common used a dry plate to record the Orion Nebula using a 91-cm reflector at Ealing, London, a private telescope constructed in his garden in West London. Using an exposure of 60 minutes and carefully tracking the nebula, he showed for the first time that one could photograph more than could be seen through the telescope. These images propelled telescopes towards the 20th century with the expressed idea that they should be constructed specifically for photography. Inevitably, it became essential that if one was going to take photographs of celestial objects, long exposures were needed, and with that, reliably clear skies. With the manufacture of telescopes for photography as their aim, new and sophisticated camera systems were developed.

Something else happened as well: the public could now see photographs of astronomical events, which increased the already developing interest in astronomy among the masses. It was still a very expensive hobby and would remain so for the first half of the 20th century. Nevertheless, public access to telescopes increased. In 1906, the Zeiss company recognised that in its reflector telescopes, having the axis of declination as close to the eyepiece as possible increased the viewing comfort not only of professional astronomers but also of the viewing public. This was part of the great commercial power of Zeiss: they could introduce technical and engineering innovations that made their instruments first choice for public and private use. Matched by their optics originating from the associated Schott glass works, Zeiss instruments from telescopes to microscopes became preeminent devices.

References

Antoniadi, Eugene. 1930. *The Planet Mars*. Paris: Hermann & Cie Translated by Moore. K. Reid, London 1975.

Ball, Robert Stawell. 1910. *Popular Guide to The Heavens*. 3rd ed. London: George Philip and Sons.

Close Rolls, Edward, II. 1892. In *Calendar of Close Rolls, Edward II: Volume 1, 1307-1313*, ed. H.C. Maxwell Lyte. London: Her Majesty's Stationery Office. *British History Online* http://www.british-history.ac.uk/cal-close-rolls/edw2/vol1/.

Defoe, D. 1724–1727. *A Tour Through the Whole Island of Great Britain*. London: JM Dent and Co. S. Birt and T. Osborne.

Evelyn, J. 1661. *Fumifugium, or, The Inconveniencie of the aer and smoak of London dissipated together with some remedies humbly proposed*. London: W. Godbid for Gabriel Bedel and Thomas Collins.

Galilei, Galileo. 1610a. *Siderius Nuncius*. Venice: Thomas Baglioni.

———. 1610b. *Siderius Nuncius*. Translated in to English by Albert Van Helden. University of Chicago Press, 1989. Venice: Thomas Baglioni.

Moore, P. 1998. *Patrick Moore on Mars*. London: Cassell.

1674. Proceedings at the Sessions of the Peace for the City of London, Old Bailey, London.

Wells, H.G. 1898. *The War of The Worlds*. London: William Heinemann.

Chapter 7
Moving Observations off the Planet

As the engineering necessary for a stable telescope platform was being taken out of the hands of amateur astronomers and becoming a commercial reality, changes to the optical systems were also moving forward. There were many very good reasons why astrophotography was important in shifting telescopes to higher altitudes and clearer skies. By taking a photograph, it became possible to exchange data and information without the subjective component of a descriptive observation and drawing—a lesson learned from the composite illustrations by astronomers that had created the situation with the canals of Mars. These developments also took away the astronomer's dependency on good eyesight, and the need for objects to be visible to the human eye during observation; low light was not such a hindrance in photography. For long exposures, clear skies were essential so that the imaging process was not interfered with.

Good quality telescopes capable of taking astrophotographs that would be more than just novelties needed either the highest quality lenses for refractors, or mirrors for reflectors. The potential of reflectors to outperform refractors had been known for a long time, but the metal mirrors that were originally available were far too unstable in atmospheric conditions to be reliable. As mentioned previously, this was a problem of tarnishing and gradual oxidation of the surface. It was realised that putting a highly reflective material onto glass would give a well-protected surface that retained the original reflectivity.

In 1835, Justus Von Liebig developed a process for chemically depositing silver onto glass, creating a second surface mirror. A second surface mirror refers to rear surface mirrors, of the looking glass variety, rather than first surface mirrors where the front face is silvered. Using the technique developed by Von Liebig, it was possible to create concave mirrors for astronomy by silvering a convex shape, yet the problems of refraction from the glass and ghosting images reflected from the primary surface made it impractical for astronomy. The process was improved in 1856 and became the technique of choice for creating second surface mirrors. Interestingly, the technique used a modified version of Toller's reagent, which was developed for what became known as the silver mirror test, used in biochemistry to distinguish

W. Wall, *A History of Optical Telescopes in Astronomy*, Historical & Cultural Astronomy, https://doi.org/10.1007/978-3-319-99088-0_7

between aldose and ketose sugars. It detects the presence of aldehyde groups on aldose sugars by causing the deposition of metallic silver, either in solution or onto the inside of the test tube. Ketose sugars, having no aldehyde group, do not cause the precipitation reaction. This method of silvering was fine for looking glasses but remained unusable for astronomy because of the intervening glass.

The situation changed in 1857, when Karl August von Steinheil and Leon Foucault developed a method for front surface silvering that pitched the first surface mirror very definitely back into prime position for astronomical telescopes. They quickly replaced metal mirrors, as glass was a better carrier of shape and through the knowledge of grinding and polishing could be made with a great deal of accuracy. More than this was the ability of first surface mirrors with silvered surfaces to have a high reflectivity. This was appreciated by astronomers, who realised that while glass could be finely polished, a silvering could easily be replaced if tarnished without the need for re-polishing associated with metal mirrors. There were even practical guides available to help the amateur create a telescope (Draper and Ritchey 1904).

The situation remained stable for many years until 1930, when a physicist and astronomer working at Caltech devised a technique for aluminium vacuum deposition. This was carried out in a vacuum chamber by heating aluminium with a hot element. The aluminium streams off and is deposited upon the glass surface, forming a permanent bond. This technique also had the ability to accurately control the thickness of the aluminium deposit. So successful was this method that very quickly, aluminium coated optics for reflectors became the norm. An advantage of this process was that the surface retained its reflectivity for long periods of time without intervention. It was not quite so reflective as a silver surface, and this was one of the reasons that the Kepler Space Observatory uses mirrors silvered by an ion assisted evaporation technique, rather than aluminium. When first deposited, silver has a much higher reflectivity, but if it oxidises the resulting surface is a low reflectivity one. Aluminium on the other hand oxidises to form a thin, hard transparent oxide layer that barely affects the optical performance of the mirror.

In synchrony with the development of silvered mirrors using silver or aluminium came the development of telescopes not designed to be used for direct observation by an astronomer, but rather to take photographs for analysis. The next logical advance was to have specialised devices to take photographs. This not only took away the dependency on accurate recording by the observing astronomer, but it also allowed for the first time the correction of optical aberrations by the receiving film. Photography was going to be a significant force in the development of telescopes, not just specialised astrophotography devices.

When looking for the best sites for locating telescopes, the initial search was confined to high altitudes alone. It was not seen as significant to check for other atmospheric components such as humidity. Very often, these things do go together, although it is not always the case. As mentioned, the first permanent observatory at altitude was the mountaintop Lick Observatory, built between 1876 and 1887 and sited 1283 m above sea level on Mount Hamilton in California. The first high altitude observatory was 2877 m altitude at Pic du Midi de Bigorre in the French Pyrenees. This site was started in 1878, with the first telescope dome not completed until 1904. After these two, the number of observatories at altitude increased considerably over the first half of the 20th century.

One of the major advances came with the decision to create the European Southern Observatory. This originated in 1962, when it was decided to create a pan-European society of pooled resources along with many other countries from South America. The aim was to create a high altitude observatory with an atmospheric humidity as low as possible. The site that was negotiated was in Chile, at Paranal in the Atacama Desert, an area of astonishingly low rainfall, generally less than 10 mm per year and with about 350 cloudless days a year. This also had the advantage of remoteness from all other forms of pollution, lying about 38 km in a straight line from the nearest settlement of Paposa, which itself only has an approximate population of 250. At this site, it was decided to create the Very Large Telescope (VLT), an array of four telescopes that could function in concert to work as if a single 169-m mirror was being used. Although the first light for the first of the four telescopes was in 1998, it was not in full scientific commission until a year later. The manufacturing process of these enormous mirrors was a considerable accomplishment in itself.

The mirrors were mad, one at a time by the Schott Glassworks using their own recipe for a glass/ceramic called ZeroDur. This is a lithium-aluminium silicate glass ceramic that they had been producing since 1968 and which was used for the later Keck telescopes. The process for the VLT mirrors was to produce a molten pour of about 45 Tonnes. The mould for the mirror was then pushed underneath the crucible containing the glass. Pouring through the platinum nozzle at 1400 °C took 4 hours. To prevent uneven cooling, a heated lid was put on the top of the mould while it was being moved to a turntable that could rotate. Once centred, the mould was rotated while the temperature was held at 1200 °C and the mirror blank formed into a meniscus shape. The heated lid was then removed, and the still-molten glass could freely radiate its immense stored thermal energy. A cooling lid was then put over the top to control the cooling so that it was even and no internal stresses were created in the glass. Even though this was not destined to be a lens, internal stresses could make the mirror susceptible to cracking and more difficult to polish.

At this stage, the partially formed mirror blank was moved in its mould to the annealing furnace. This is the same process as any large lens has to be put through and was essentially the same as was carried out on the first large lenses when they were made in the 19th century. If the glass was not cooled evenly and slowly, it formed faults and internal fractures that will made it useless for its designed purpose. If the cooling was significantly uneven, these areas of stress could cause the blank to break very noisily. Once the VLT mirror was in the annealing furnace, it was taken down to room temperature over a period of 3 months. The mirror was then in the final phase of completion, but it still had two major stages and an incredible journey left to make.

The annealed and cooled glass was then rotated through 180°, turned upside down, and ground to what would be the final shape of the mirror. At this point, it was returned to the furnace for prolonged heating so that the mirror was ceramicised to the final structure of ZeroDur. This stage was essential to formalise the internal structure of the ceramic glass with a thermal expansion very close to zero, certainly within the range of normal usage the mirror would not change shape or volume and therefore focus. The mirror at this stage also needed to have an unusually uniform homogeneity without structural flaws that could otherwise cause problems.

The next stage was for a hole to be cut in the centre of the mirror. The hole was cut so that it followed the circumference of the mirror to within 10 μm. At this stage, the mirror, which was still an unsilvered blank, had taken 18 months from pouring the glass to being finished at the Schott glass works and was mounted ready for delivery in the next stage of the operation to make this large piece of glass into a reflector.

As befits an international collaboration such as this, the next stage of figuring was carried out at a polishing facility in France. The blank was wrapped so that it could be transported to REOSC in France for its final polish, but trying to take such a large and delicate object by road was deemed too difficult. Instead, the roads from the glass works to the dock in Mainz on the Rhine were closed. The mirror was moved at 5 km/h by lorry and then loaded onto the Eldor. This ship took it down the Rhine to the sea, along the coast and up the Seine to just south of Paris at Pierre du Perray, where it was again transported by truck to the REOSC plant. Once at the polishing facility, it took 2 years to be polished to its final state, which was so accurate that if scaled up to a diameter of over 165 km, the largest defect would only be 1 mm in height.

This whole process was carried out four times, as there were four identical mirrors in the VLT. They were originally labelled UT1, UT2, UT3 and UT4, but a competition was held to give the landmark telescopes names in the local Mapuche language. So from one to four, they are now called *Antu* (Sun), *Kueyen* (Moon), *Melipel* (Southern Cross) and *Yepun* (Evening Star).

Even though the VLT is in an area of exceptionally low pollution with very little particulate matter in the air, the mirrors do become less reflective over time and need to be re-polished at intervals. Re-polishing for these mirrors involves removal of the surface and recoating the base glass. There is a very particular way of removing the mirrors, as it was part of the original engineering proposal that it should be possible to remove and refit the mirrors.

Removal is carried out by sliding the mirror sideways while the mirror is pointing vertically upwards, effectively lying flat. Once clear of the mounting but still supported by a frame, it is lowered by a purpose-built gantry onto a cradle on the back of a lorry. It then starts its 8-day cycle to the recoating plant. First the underside is cleaned, as it tends to accumulate a fine coating of oil and debris from general use. Next, it has to be moved to the clean room, where all large particulate material can be carefully removed. When the mirror is as clean as it can be, a rotary gantry is used to remove the aluminium coating with a gentle acid wash. Interestingly, it is only at this stage that the underlying colour of the mirror can be seen, which is a soft amber. After thorough rinsing and drying, it can be moved to a vacuum chamber, where an electric plasma is used to vaporise and deposit a layer of aluminium back onto the surface. Although the mirror is 8.2 m in diameter, it only takes 12 grams of aluminium to completely cover the surface. Once the reflectivity has been checked, the process of reinstallation can be carried out.

While the primary mirror of the VLT was a technical and engineering feat, one of the aspects of the telescope that is sometimes overlooked is to be found on UT4, *Yepun*—the innovation of adaptive optics. This was not the first telescope to be fitted with adaptive optics, but it did aid in calming the image from a ground-based telescope, which was already in an area of the world where although visual clarity was very high, any atmosphere could cause some distortion.

Adaptive optics had been fitted to other telescopes before and had a long theoretical history. In 1953, Horace Babcock described a system where the optical distortion of the atmosphere could be measured and then compensated for. At the time, the electronics would have been impossible to create on any scale that could have been used in the modern manner. However, it was possible to have a simplified system, and so in 1957 Robert Leighton partially corrected the 60-in. (152.4-cm) Mount Wilson telescope using a system where the secondary mirror was tilted rapidly several times a second, allowing the secondary image to become a bit sharper. The main idea of adaptive optics is to remove one of the most problematic errors in any optical system, statistical errors. These are unpredictable but broadly have a random distribution about a mean. Knowing this allows the error to be compensated for.

In the case of the most sophisticated adaptive optics, as in the VLT, this can be done in a much more complicated way, yielding a much clearer image. The primary mirror of *Yepun* is 17.8 cm thick and therefore a rigid piece of glass. The secondary mirror is quite different: at 1.1 m diameter and only 2 mm thick, it can be bent and deformed by a considerable amount without risk of cracking. By having it mounted with rear electromechanical actuators, it is possible to deform the mirror to mimic the shape of the deformed waveform of light reflected from the primary mirror. These deformations are relatively slow, as the atmosphere moves and the refractive nature of density and humidity changes over time. Of course, it is not possible to use the light from the star under observation to calculate the optical distortion, because one does not know what it should look like without any distortion. The answer is to create what is in effect an artificial star and measure the distortion of the light from that. This is done by shining four converging lasers to a point approximately 90 km above the Earth into the mesosphere.

The part of the atmosphere known as the mesosphere is not well understood but runs from about 50–100 km above sea level, although the depth varies according to geography and climate. Lying directly above the stratosphere, the mesosphere contains very little water, and the temperature is low. When the temperature goes below −120 °C, noctilucent clouds can form. These are ice clouds that are only visible at twilight when they are illuminated from below. Also in the mesosphere is a sodium layer, the area that is utilised by astronomers for their artificial stars. The sodium layer varies in height from about 80–100 km and is about 5 km thick. The sodium layer of the mesosphere is made up of neutral sodium atoms that can be stimulated to emit light. Below this depth, the sodium is normally bound into molecules of various sorts, and above this the sodium is ionized. The lasers excite the neutral sodium to radiate light at 589 nm, the sodium D line. The variation in the excitation due to the intervening atmosphere is used to control the mirror actuators and correct for the twinkling of the stars as observed at ground level.

Adaptive optics have helped in many ways to increase the visual acuity of ground based telescopes, and for many years they were held as the only way to gain a clear image of the skies. There was going to be a conceptual leap when it became apparent that what had always been considered impossible was a potential reality: a space telescope.

In 1837, two astronomers, Wilhelm Beer and Johann Madler, speculated about the advantages of an observatory on the Moon. They were quite familiar with planetary observations, having produced in 1834 a four-part *Mappa Selenographica*, the first good quality map of the surface of the Moon. The four-quadrant map was dedicated in Latin to His Majesty Frederik VI, King of Denmark, with great reverence. Frederik VI was a patron of astronomy and in 1832 offered gold medals to the discoverers of new comets using a telescope (Fig. 7.1).

Fig. 7.1 Part of *Mappa Selenographica*, including the dedication to Fredrik VI (SLUB Dresden, Wikimedia Commons)

In 1840, Beer and Madler mapped Mars as well and managed to calculate the rotation as 24 hours 37 minutes 22.7 seconds, within 0.1 second of the current value. Their speculations about the possibility and value of a lunar observatory was based on the direct observation of what they saw as an unchanging Moon, correctly realising that this implied that there was neither wind nor water, so obviously no atmosphere to interfere with observations. This speculation had no practical aspect to it; it was much later that practical calculations were made to keep the idea of extra-atmospheric observatories alive.

In 1946, Lyman Spitzer theorised that a telescope outside the atmosphere could be a practical idea of immense value to optical observations, although it would not be until 1968 that the USA launched the very first orbital telescope, the Orbital Astronomical Observatory. This particular telescope was in a near circular orbit of about 75-km altitude. It operated mainly in the ultraviolet, not in the optical range. A precursor to this satellite was launched in 1966, but this carried detector instruments rather than imaging devices. Spitzer maintained his interest in the idea of telescopes clear of the atmosphere and lobbied for the Hubble telescope to be built. When it was finally agreed, Spitzer became a significant figure in the design of the instrument (Fig. 7.2).

Part of the slow developmental pace of space telescopes was the question of observation and more specifically the observer. If you have a telescope, then you need an observer, and if the only observer you have is a camera with film, then the results will tend to be disappointing. This is a consequence of the time lag between taking a picture and having the image returned to Earth. If it is done via the electronic systems available in the middle of the 20th century, raster-scanned images of low resolution using television technology, all of the advantages of a space telescope would be lost in the final image.

Persistence was crucial in pushing forward the idea of having a telescope that could only be operated remotely. If high resolution images were going to be of use, then they would have to be on film that could be returned to Earth. The use of reconnaissance aircraft during World War II had advanced the plate cameras, which were thought to be essential for this sort of instrument. It is interesting that the first images taken at high altitude were not destined for astronomical use; indeed, the camera was pointing in the wrong direction, aimed at the ground. This was a 35-mm black and white cine film taken on October 24, 1946 aboard a largely unaltered V2 rocket fired from White Sands in New Mexico, achieving an altitude of 105 km. The V2 rocket (the V stood for vergeltungswaffe—literally "retribution weapon") was developed as a weapon during World War II by the Third Reich. The V rockets were largely designed by and under the leadership of Wernher Von Braun in Germany. He went to the USA after cessation of hostilities and continued working on the design and development of rockets for the United States government. When the test rocket was fired from White Sands, it had already travelled the considerable distance from Europe by sea. The lead scientist for photography was Clyde Holliday from John Hopkins University Applied Physics Laboratory. The addition of the cine camera to the rocket was not intended to take images of space but to determine the pitch, yaw and rotation of the rocket in flight. Even so, the curvature of the Earth was still clearly visible on the returned film (Fig. 7.3).

Fig. 7.2 Lyman Spitzer, considered as the father of the Hubble Space Telescope, photographed in a reflective pose (http://www.nasa.gov/audience/foreducators/postsecondary/features/F_Lyman_Spitzer.html)

Fig. 7.3 An original V2 rocket at launch (c1944) (German Federal Archive)

The poor image quality and transient nature of high altitude rockets left astrophotography as a terrestrial activity for many years. Even when Earth orbital satellites were available, the problem of returning a delicate film back to the ground after exposure remained. This situation began to change when it became important to return satellites to Earth without significant damage, a situation that had to be addressed when manned space flight started. Although not the first man in space, when John Glen became the first American to orbit the Earth in February 1962 he took a camera with him. This was a Minolta 35-mm rangefinder camera with automatic exposure, bought locally and very much as an afterthought. Little was expected of the photographs, and there was concern that taking pictures of countries as seen from space could be misconstrued as spying and an act of aggression by sensitive regimes. The results were still significant in showing the potential of photographs from space, in this case mainly of Earth, and it started to be seen as a method of bringing the public onto the side of space exploration.

Attitudes definitely seem to have changed with the later space flights and certainly the last two Mercury one-man missions of 1962 and 1963, which were equipped with standard 550c Hasselblad cameras. These were not only medium format cameras with pre-loaded camera backs, but they also had some of the best lenses available at the time, made by Zeiss. This association with space turned the fortunes of both astrophotography and Hasselblad. The camera company had been in existence since the end of the 19th century, making high quality cameras, but these had never made a profit. Hasselblad cameras was a company kept going from profits made as a distributor for other photographic appurtenances, which included being the sole distributor of Kodak-Eastman in Scandinavia.

Changes in public attitudes to extra-planetary observations quickened the proliferation of high quality images of the Earth. These came from the Apollo 8 mission, the first to leave Earth orbit to go around the Moon and back, and then Apollo 10, which also orbited the Moon. The optical quality of the cameras and the distance from the Earth resulted in spectacular images of our planet, the Moon and probably most evocative of all, an image of the Earth rise over the Moon. These images, giving as they did a clear demonstration of the finite nature of our planet, are regarded as being partially responsible for the development of our ecological concerns. They emphasized that there was nowhere in our immediate surroundings for us to go if we did not take care of our own world.

The cameras used on these missions were Hasselblad 500Els, which had an automatic wind-on facility. Interestingly, these cameras are generally described as automatic with the astronaut only needing to set the distance, aperture and speed, the winding and shutter tension being carried out automatically. This underestimates the need for attention when making exposure adjustments, whereas the winding on is something that can be done without looking. By the time of Apollo 11 in 1969, there were several different cameras being carried on the mission, including three Hasselblad 500EL cameras. Something that had to be addressed was that since these cameras were being used in the vacuum of space, modifications were needed to make sure the cameras functioned correctly when operated with astronaut gloves on. By the time Apollo 11 landed on the Moon, it was a clearly recognized function of the astronauts to provide clear photographic images that could be used for publicity.

Changes to the details of the operation of the cameras included changing the lubricants used so that they did not boil in the vacuum and leave a solid residue, which would not lubricate and acted like glue. Also, having no easy route to dissipate static electricity build-up when the film was wound on, sparks could discharge inside the camera. Modifications were therefore made to introduce an Earthing system to discharge the static electricity before it became disruptive to the camera. A reseau plate comprised of fiducial marks in a lattice form was introduced into the focal plane in front of the film so that by checking the position of the marks on the negative, it was possible to check whether the large negative had been distorted during processing. The same marks were also used to check for distortion when the film was subsequently printed. To try and even out the potential for differences in temperature, the cameras were all silvered to reflect heating from infrared radiation.

Hasselblad's association with NASA was very profitable, allowing the company to become a profitable camera manufacturer without the need for any additional dealerships. In fact, the association featured widely in the advertisements for the cameras, including the now well-known Earth rise over the Moon taken in 1968 when Apollo 8 was in lunar orbit. The cameras were taken to the lunar surface, but only the camera backs containing the exposed film were returned; the camera body and lens were left in the Sea of Tranquillity at the landing site.

There is no doubt that it was the high quality images taken from outside the Earth's atmosphere that brought home to politicians the value of space telescopes. It should be remembered that the Apollo and Space Shuttle missions had demonstrated the engineering potential of NASA and its technical suppliers. Space telescopes were technically achievable, what was required was the political will to fund them. There was a particular anomaly in that while the movement to create a space telescope gained momentum, helped along by the spectacular images taken on the Moon, no stars were visible in the images. This was a simple case of exposures being gauged for taking photographs of strongly illuminated subjects close to the camera; the stars in the background were so under exposed that they did not register.

There was no doubt that after the start of the space age in the 1960s, an enormous amount of interest was generated in amateur astronomy. This was helped by the commercial development of high quality small reflector telescopes. The huge interest in astronomy among the general population helped to keep these instruments down in price and up in performance. The commercial development for the amateur market was led by Celestron in the USA. Founded in 1960 as an offshoot of Valor Electronics, the company started feeding the market in 1969 at the height of the Apollo missions with the introduction of a set of six Schmidt-Cassegrain telescopes for serious amateur astronomers. Unlike previous manufacturers, there was a deliberate building of identity around Celestron's telescopes: originally, all the telescopes were in blue and white, and later they became distinguishable at a distance by having orange bodies.

Ground-based telescopes continued as the linchpin of astronomical observation, but space telescopes were going to take a massive leap forward in the 21st century with the launch of the Hubble Space Telescope.

References

Draper, H. 1864. *On the Construction of a Silvered Glass Telescope*. Whitefish: Kessinger Publishing. Reprinted 1904 Smithsonian Institution.

Foucault, L. 1857. Note sur un télescope en verre argenté. *Comptes Rendus* 44: 339.

Ritchey, G. 1904. *On the Modern Reflecting Telescope*. Washington: Smithsonian Institution.

Chapter 8
The Hubble Space Telescope

There are two things about the Hubble Space Telescope that make it stand out and justify giving it a chapter to itself. The first is that when it was launched, it became the most scientifically productive single instrument ever made, with well over 15,000 scientific papers being produced in 20 years. The second is that this is as near as we can ever get to a time machine. By looking at the faint galaxies at immense distances, we are looking further back in time than we have ever been able to before, towards the beginning of the universe.

To appreciate the immense achievement and success of the Hubble Telescope, it is worth considering why it was so important to pursue the creation of a space telescope no matter how improbable it was thought to be in purely practical terms. Herman Oberth had suggested that a space telescope should be considered for the future in 1923. Oberth is regarded as one of the fundamental engineers of 20th century rocketry, one of his students being Wernher von Braun.

It was understood from early on in the speculations about a space telescope that since ground-based observations were limited by the part of the optical system that is the atmosphere, without this the only limiting factor would be the optics of the telescope itself. This is essentially correct, but with the limitation associated with the sensors attached to the telescope. As there would be no direct observation by human eye using this device, the images would be sent to Earth from digital arrays. It was remarkable that once the telescope was fully functional, it was directable to an accuracy of 0.007 arcsec, but more than that, the telescope had the ability to distinguish objects of 0.05-arcsec diameter, which is the theoretical diffraction limit for a mirror of 2.5-m diameter.

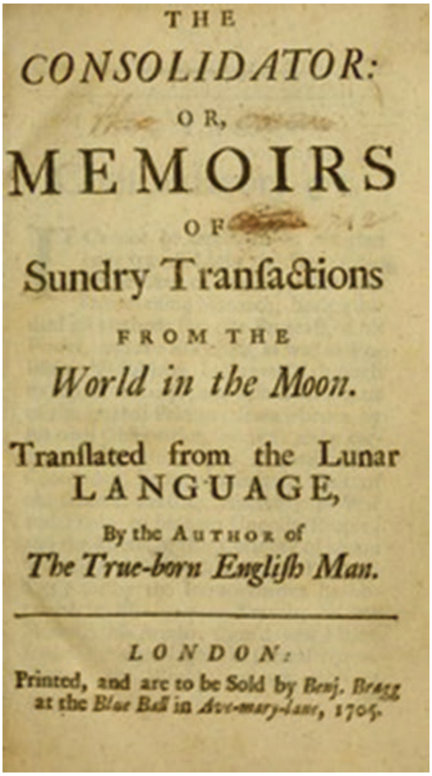
Before this could be achieved, there was a long way to go. Large engineering projects of this size, not just in astronomy but in any area of the public domain, are dependent on goodwill and active political participation by many people, most of whom have no scientific training. The era of wealthy individuals being able to spend their fortunes on projects with no discernible benefit had more or less disappeared by the time of the First World War. There seems to be a resurgence of massive wealth focussed in a few hands with the initial commercial development of the

W. Wall, *A History of Optical Telescopes in Astronomy*, Historical & Cultural Astronomy, https://doi.org/10.1007/978-3-319-99088-0_8

Internet, which is now feeding through into private space projects. Such ventures always have a commercial aspect; rarely if ever can one succeed when fuelled exclusively by simple curiosity.

Thoughts, writings and private discussions predated the plans for a space telescope. Speculations over the scientific and technical possibility of making such an instrument could be found in both serious scientific literature and in science fiction. Very early in the canon of fiction, in 1705 Daniel Defoe produced *The Consolidator: Or Memoirs of Sundry Transactions From The World of The Moon*. This was a mixture of political satire—the name derives from a political crisis of 1704 that threatened the survival of the moderate government—and fantasy, describing viewing life on Earth through a lens on the Moon. The book is still worth reading (Fig. 8.1).

Although a long way from what would become the Hubble Space Telescope, in 1962, NASA, (which had only recently been formed in 1958) sent into space the Orbiting Space Observatory. This was not an imaging device in the strict sense, as it was designed to measure the spectra for Gamma rays, X-rays and ultraviolet radiation. Also in 1962, an orbiting solar telescope was launched by the UK. This was Ariel 1, named after the sprite in *The Tempest*. This achievement made the UK the third nation to send a satellite into orbit after the USSR and the USA (Fig. 8.2).


THE
CONSOLIDATOR:
OR,
MEMOIRS
OF
Sundry Tranſactions
FROM THE
World in the Moon.
Tranſlated from the Lunar
LANGUAGE,
By the AUTHOR of
The True-born Engliſh Man.

LONDON:
Printed, and are to be Sold by Benj. Bragg
at the Blue Ball in Ave-mary-Lane, 1705.

Fig. 8.1 The cover of *The Consolidator: Or Memoirs of Sundry Transactions From The World of The Moon*. Since all illustrations had to be engraved from originals, cover illustrations were unknown at the time this was published in 1705 (Wikimedia Commons, Boston Public Library)

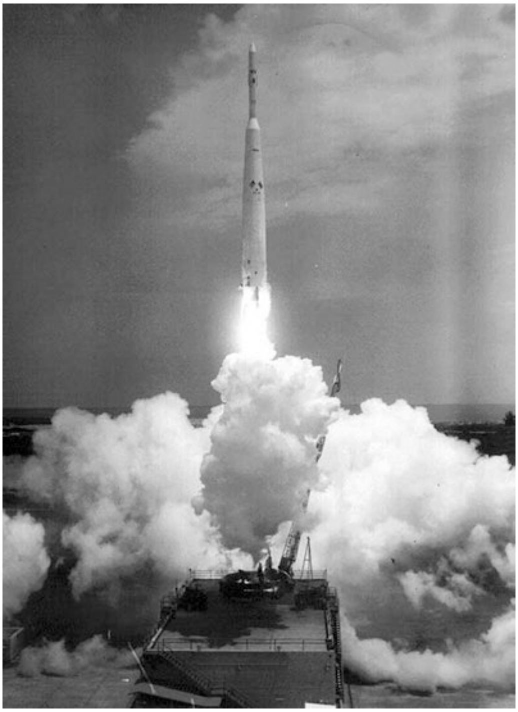


Fig. 8.2 Launch of the Thor Delta Rocket with the first UK satellite Ariel 1, April 26, 1962 (NASA)

In 1966, NASA launched the Orbiting Astronomical Observatory (OAO). Unfortunately, the battery failed after only 3 days. The next attempt, OAO 2, was launched in 1968 and ran until 1972 even though it was only designed to last a year. It measured UV spectra rather than imaging the sky. The same year that OAO2 was launched, 1968, NASA planned a 3-m reflector for space. The original plan was to have the telescope launched by 1979. This turned out to be hopelessly optimistic, but was based on being able to use the shuttle as a service vehicle to maintain the telescope and increase its working life. This original telescope was referred to as either the Large Orbiting Telescope (LOT) or Large Space Telescope (LST), reflecting that it was only a plan and had no official designation at the time. It was the astronomical community rather than the space engineers that pushed for a space-based telescope. This was mainly because of the success of the OAO. This had worked longer and better than had been expected and raised hopes for a much larger instrument that could explore the sky in a more traditional way by creating images without the interference of the atmosphere.

Two committees were set up to investigate the possibilities of the next generation space telescope. The first was charged with investigating and reporting on the engineering that would be involved in creating an instrument, and the second was a committee to define the scientific goals such a telescope would be expected to achieve. It was the scientific committee that arguably had the most difficult task, as it had to create achievable goals which would inspire and motivate the funding bodies to give a very large sum of money to a project that had no real precedent. Once there was a clear idea of what was wanted and how much it would cost, NASA approached Congress with the intention of raising the funds for the project. The proposed budget, much reduced in Congress, was stopped in 1974 due to budget cuts. This was a sore disappointment, and public lobbying by professional and amateur astronomers on the scientific benefit of having a space telescope led the Senate to provide a budget for the project—half of what Congress had previously agreed to.

It was this reduction in funding that also changed the original plan for a 3-m mirror to a mirror of 2.4 m, which also made it easier for the finished instrument to fit into the cargo bay of the space shuttle.

There was another area where a major reduction was made: the pilot project. This had originally been calculated and included in the budget proposal, but with reduced funding, the idea of testing out the systems using a 1.5-m mirror as a test device was completely scrapped. This was in itself no bad thing, since the engineering paradox would have been that if it did not fail, money would have been wasted on the project, or the 2.4-m telescope was not needed; and if it did fail, the engineering would not have been thought out properly to start with. With no pilot project to test things out on, the model had to be correct the first time, which like all projects where pretesting of individual components is possible but testing the complete device is not, meant that there had to be the most rigorous attention to detail at all stages of the project.

One of the important spin-offs from the budget cuts to the project was the development of a collaboration with the European Space Agency (ESA). ESA provided funding and some instrumentation, as well as the solar cells that would power the telescope once it was in orbit. ESA also provided a number of scientific and engineering workers. In exchange, ESA was promised at least 15% of the telescopes time when it was up and running. It was not until 1983, the projected year of its launch, that the telescope was formally given the name Hubble Space Telescope in honour of Edwin Hubble. Like most projects, the timetable slipped and the launch was delayed, as would happen repeatedly over the next few years.

Designing and building of the telescope was controlled by a team at the Marshall Space Flight Center, although this was mainly a major coordination role for the various contractors who made the equipment. The George C. Marshall Flight Centre is the largest facility that NASA has for research and development of civilian rocketry. It is named after General George C Marshall, Chief of Staff during World War II, although he is better remembered for introducing the Marshall Plan. This was an economic development system designed to rebuild the devastated regions of Europe after World War II.

The other major coordination group was based at NASA's Goddard Space Flight Center, which coordinated both instrumentation and ground control. The site was named after Robert H. Goddard a rocket engineer in the USA who pioneered liquid-fuelled subsonic and high altitude rockets, rather than orbital.

There were a large number of different contractors, but the two main ones were Lockheed, who produced the spacecraft, and Perkin Elmer, who produced the telescope. It was the telescope which gave the greatest risk to the entire project.

The Hubble telescope is a Cassegrain reflector based on a Ricthey-Chretien pattern. This design has a hyperbolic primary mirror and a hyperbolic secondary mirror, which helps eliminate off-axis errors of coma. The main reason for choosing this design is that it results in a much wider field of view free of optical errors, which means a much larger proportion of a very expensive mirror can be used effectively. Most large telescope mirrors are of this Ritchey-Chretien type. Examples of this can be found at the Kek observatory and the European Space Organisation Very Large Telescope in Chile.

The drawback of these mirrors is that it is technically very difficult to polish them to the hyperbolic shape. This was compounded for the Hubble telescope because it was intended to be used from visible wavelengths right through to UV wavelengths. This required a much greater level of polishing accuracy than had previously been necessary for a mirror that was only intended for optical wavelengths. To make the mirror useable over this range, it had to be accurate to within about 10 nm, or 1/65 of the wavelength of red light. Although it would have been a useful tool if it was able to operate in the infrared, the mirror is held at a constant 15 °C, giving it a limited performance past the long wavelength end of the optical spectrum. This wide potential range of use is an intrinsic part of a Ritchey-Chretien design, as there are no refractive elements used in the telescope.

Perkin Elmer gained the contract for the work, a company with a considerable track record in specialist optical devices. Perkin-Elmer had an interesting history. It was founded in 1937 by Richard Perkin and Charles Elmer as an optical design company, producing sophisticated scientific instruments. Then, for a short while, the company was involved in computer production. It was this ability to manufacture integrated scientific instruments and measuring devices that led it to propose a complicated electromechanical computer-controlled system for polishing and figuring the Hubble mirrors. The potential to control the accuracy of the process was unprecedented, but it was also of untested sophistication and complexity. This untried method caused some disquiet in NASA, which asked Perkin-Elmer to subcontract to Kodak, in a belt-and-braces action to make a backup primary mirror using more traditional methods. Kodak was not chosen at random, as in conjunction with Itek, it had originally put in a bid for the contract, so it already had a plan in place for constructing a mirror. The skills that Itek brought to the contract were based around its long history of making the optical components for spy satellites. When the entire space telescope was finished and launched, it was the Perkin-Elmer mirror that made it into space. The Kodak backup mirror is now on show at the National Air and Space Museum in Washington, DC.

Perkin-Elmer started work on the mirror in 1979. It polished and figured a glass blank provided by Corning, made out of a low thermal expansion glass. The mirror was to be made of two 25-mm-thick plates separated and supported by a honey comb. This would reduce the weight while maintaining the rigidity of the finished mirror. Polishing of the mirror went on until 1981, when questions started to be asked regarding the management style of Perkin-Elmer. These queries were precipitated by increasing costs, far beyond the original estimate, and slippage in the schedule that pushed the date for completion back. The decision was taken to move the date of completion to 1984 and to simultaneously stop further work on the backup mirror to ease the cost overrun.

By the end of 1981, the mirror was polished but of course not finished. Even with the finest of polishing materials, any remnants could constitute a greater deviation from the mean surface than any imperfection in the material. For this reason, the next stage required a thorough washing with 9100 litres of hot water. It was as close to pure H_2O as was possible to get so that there was little or no risk of evaporative deposition of mineral crystals. It was then coated with 65 nm of aluminium, the reflective surface, and above that 25 nm of Magnesium fluoride (MgF_2), the protective surface. MgF_2 is a tough material that protects the rather more delicate aluminium underneath. It was chosen as a suitable material because it has a wide range of transparency, from 0.12 to 8.0 μm, which extends from the ultraviolet into the infrared, although the transmission is at its best after 0.2 μm and quickly drops off after 6.0 μm. This still covers a wide range of wavelengths with little absorption of energy.

By this time, the rest of the Perkin-Elmer contract for the assembly had also slipped, and NASA again moved the projected launch date, this time to April 1985. Further slippage caused a launch postponement to March 1, 1986 and then September 1986. Eventually, it would be launched in April 1990. Besides the problems of time slippage, the whole project came in far over budget, costing $1.175 billion.

It would be true to say that although the mirror assembly was the central part of the equation when constructing the telescope, the construction of the surrounding structure was just as crucial, so that the telescope and associated sensors were supported and protected during the flight and final deployment in orbit. This part of the operation was being constructed by Lockheed, but deadlines slipped by 3 months, and budgetary requirements went up by 30%.

The supporting frame was made of epoxy-graphite composite covered in an aluminium case, for strength and lightness, the whole thing being wrapped in a reflective insulator. Although this was designed to hold the temperature relatively stable, the graphite composite was difficult to work with. This material is hygroscopic, so while under normal conditions it is not a problem, being made in one environment and deployed in another could result in problems. It was necessary to control the humidity at all stages, otherwise when deployed in space the moisture could come out and adiabatically freeze on other parts of the telescope.

By 1986, it seemed likely that an October launch would be possible, but early that year, the Space Shuttle Challenger exploded just over a minute after launch. This had the immediate effect of halting the entire United States launch programme, including that of the Hubble telescope. This was quite understandable, as it was to be deployed by a manned crew on a space shuttle, and until the cause and solution of the Challenger disaster was found, it would be inappropriate to send another shuttle into space. This resulted in the completed telescope and instruments being packed away into an atmosphere-controlled storage facility for over 4 years. Eventually, when problems with low temperature launches of the shuttle had been adequately addressed, the launch was scheduled for April 24, 1990. This was to be a shuttle flight designated STS (Space Transport System) 31. Although it was numbered 31, it was in fact launch 35, but this reflects an anomaly between designated launches and actual launches.

In April 1990, five astronauts aboard space shuttle Discovery took Hubble into orbit. Deployed about 600 km above the Earth and orbiting the planet once every 97 minutes, the Hubble was launched relatively smoothly, with the exception of a solar panel that did not deploy itself correctly on the first attempt. While the astronauts were preparing to go outside and manually help it to unfurl, ground control managed to get the right signal to the solar panel that allowed it to deploy properly. With the telescope in orbit, expectations were running high for the brightest and best scientific instrument ever put into orbit. When the first images came through, the disappointment was described as palpable. The images were well below expectations—it was quickly realised that they were no better than a ground-based telescope of the same size. This was clearly due to some sort of instrument error, but where exactly the problem lay was not immediately obvious.

Measurement and calculation made it possible to state the level of imperfection in the images as having a point spread function of greater than 1 arcsec. This was in stark contrast to the expected point spread function, which should have been 0.1 arcsec. It was realised that this massive difference must have a very specific cause. Any error if originating from one place could be far more simply corrected than if it was a cumulative error throughout the instrument. The suspicion immediately fell on the optical system and specifically the primary mirror. To account for the error, the edge of the mirror would have to be too flat, and indeed this turned out to be the cause of the problem. While the surface of the mirror was smooth to within 10 nm, the edge was flattened by 2200 nm, giving significant spherical errors with exactly the predicted result.

While this was very poor, if not almost unusable for observation, bright objects could still be viewed at high resolution. Similarly, spectroscopy could still be carried out on bright objects as long as they were point sources. Even so, spectroscopy was with a reduced sensitivity, as the light being measure was spread over a larger than desired area. It was for this reason that faint objects were knocked off the agenda for measurement; a faint object with a large spread went beyond the current sensitivity of the instrument.

When the knowledge of the problem made it into the public arena, the Hubble Space Telescope became a joke. It had been sold to the administration and the general public as a most remarkable instrument, but what it was seen as was a rather poor instrument that had simply wasted money. Nonetheless, by calculating that the spherical error was uniform, it was possible through mathematical deconvolution to improve the resolution of the images. Something else quickly became apparent from the uniform nature of the error; that it was a problem of manufacture. If it had been a non-uniform error, it may have been due to damage or marks on the mirror, possibly caused in transport or deployment. There were only two things to be done, if they were possible: either quantify or correct the problem. These small questions with significant answers, both scientifically and politically.

As was normal in modern high-value projects funded by public money, the failure of the technology required a robust and detailed investigation. Although this was primarily to ascertain what systems failed and what could be done to stop the same problem reoccurring, in the public mind it was to assign blame; a pointless exercise in itself since apportioning blame would not make the space telescope work.

NASA quickly created a committee to look in detail at the problem headed by Lew Allen, the Director of the Jet Propulsion Laboratory. The Committee was made up of a total of six members, as described by Parkinson (1957), small enough to make sure decisions could be made and conclusions reached. This was apparent, as all six members signed the report with no dissenting voices. The committee was wide ranging in its investigation but inevitably became concentrated upon the mirror, and more particularly, the way the mirror was made. Although there had been original doubts as to the new methods of polishing and figuring the 2.4-m mirror, this was not the problem. It was soon realised that it was the way the curvature of the mirror was measured that had given rise to the problem, which was clearly defined in The Hubble Space Telescope Optical Systems Failure Report (NASA 1990).

The method used to measure the curvature of the mirror and polish it to the right shape involved a null corrector. This is a test device that measures the deviation from a reference shape by generating a contour map. The reference in the usual form of a null corrector is a sphere, and in their simplest form these devices are normally used to measure the deviation from a spherical shape. When the polished surface matches the reference, there are no contours visible, hence the "null" in the name. When these checking devices are used to check a hyperboloid mirror surface, a mirror is normally used to make the hyperboloid surface appear spherical so the deviation from the desired shape can be measured. It was this specialised null corrector that had failed in practice by having the additional lenses incorrectly spaced. Unfortunately, nobody had checked the null corrector after it had been put together—it was assumed that it had been constructed properly and thereafter was implicitly relied upon. A special inverse null corrector had also been designed and built as a one-off instrument specifically to mimic the reflection from the Hubble mirror if it was perfect. When this was used, from the original data, it clearly showed the error in the results from the standard null corrector. Since there were two instruments contradicting each other, some sort of decision had to be made, but it was not that simple. There was a second null corrector made only with lenses that was to measure the vortex radius of the finished primary mirror, and this also showed an error. Both of the two instruments that conflicted with the first null corrector, both of which showed the error, were discounted as flawed.

Errors of this sort, that is, flawed figuring of a hyperboloid mirror, had been seen before in other telescopes. It was most definitely a problem of time and cost restrictions for Perkin Elmer, and this in itself was a result of poor supervision of the project. In this respect, NASA did not come out of the report uncriticised, as it was said not to have overseen the project, most specifically the figuring of the mirror, and almost as a direct consequence was not aware of the conflicting results from the three measuring devices. Strangely for a project of this magnitude, it was said that

Perkin Elmer had not put its best optical team on the task once it had gained the contract. The report, dated November 1990, made no suggestion of a solution, as that was not its purpose, but a solution had to be found to regain full use of the optical system orbiting the planet and to reengage the public in support of this massive project.

Even while the report was being written, scientists and engineers were looking at ways to correct the problem. It was obvious that replacing the mirror was not an option, as any correction had to be carried out while the telescope was in orbit. The idea of bringing the entire satellite down from orbit, replacing the mirror and then re-launching it was dismissed as far too expensive. The first thing that had to be done was an exact quantification of the optical problem in terms that could be used to create an optical solution.

Analysis to quantify the problem started by looking at images from point sources, from which it should be possible to gain a measure of the conic constant, sometimes called the Schwarzschild constant. This is a single figure, where for a circle it is 0, parabolas -1 and hyperbolic shapes >-1 (in a negative direction). Detailed analysis showed that the mirror as built had a conic constant of -1.01390 (+/− small deviation error), while what was actually wanted was a value of -1.00230. It can be seen from this that, as suspected, the mirror was slightly flatter than designed. It was however a constant across the entire mirror. Interestingly and disappointingly, these two very important figures were available by looking in detail at the measurements that had been made by Perkin Elmer when the mirror was being made. Although it seems that poor teamwork and lack of coordination was the cause of the problems on the telescope, it would be good teamwork and coordination that would put it right.

Knowing exactly what the problem was and where it was located it made it possible to start thinking about corrective optics. These would be of two different types, as the images were being used in two different ways.

Some of the equipment had internal optics that could be modified, whereas others had neither relay mirrors nor separate optics. The first way to correct the optics was to replace the entire instrument, and the second was to introduce an external package of optical correction. The instrument that had its intrinsic optics and therefore could be replaced in its entirety was the Widefield Planetary Camera (WPC). Built by JPL, it was a fairly large piece of equipment that was separate and therefore easy to replace with the WPC2 that would have corrected internal optics. The replacement had its own corrective optics and a new collection of CCDs, as these degrade over time and were planned to be replaced anyway. The first routine service mission in 1993 saw space shuttle Endeavour take up the replacement WPC2. This had an exact opposite distortion to the primary mirror of Hubble built into relay mirrors, thereby correcting the distortion. The solution worked very well indeed.

At the same time that WPC2 was installed, the other instruments gained their own corrective device, called COSTAR. This clumsy acronym stands for Corrective Optics Space Telescope Axial Replacement and was designed as a standalone device for the instruments that did not have their own relay mirrors or separate optics. It was in effect much the same as a corrective pair of spectacles. It was primarily designed to correct for spherical aberration focused at three instruments: the Goddard High Resolution Spectrograph (GHRS), the Faint Object Camera (FOC), and the Faint Object Spectrograph (FOS). It was made up of two mirrors, one of which was figured to exactly counteract the aberration of the primary mirror (Crocker, 1993).

The size and complexity of COSTAR required space which was not initially available. The team needed to find room for it within the structure of the telescope, and the only way of doing this was to take out one of the other instruments. It was decided that the High Speed Photometer should be removed. COSTAR was built by Ball Aerospace Corporation, and although not a household name, they had been making equipment for rocketry since 1956. The immediate result of COSTAR was unrivalled clarity, far beyond anything that Earth-bound telescopes were capable of, even though it was only ever to be a stop-gap until all the different pieces of equipment could be corrected or replaced individually. By 2002, all the individual instruments had their own corrective optics, and by 2009, COSTAR could be decommissioned and brought back to Earth by the fifth service mission to the Hubble Space Telescope.

With the level of engineering carried out in the design and execution of COSTAR, it should not have been such a surprise that the results were better than expected. The myopic telescope was now in full working order. The other engineering feats of Hubble should not be overshadowed by the success of COSTAR.

The two groups of instrument on board are divided between imaging and spectral analysis. This works especially well for radiations such as IR and UV, which are absorbed or distorted by the atmosphere. The entire device is kept steady by gyroscopes and star trackers and data sent via a communications satellite to White Sands in New Mexico, from where it can be distributed to laboratories around the world. Usually more than 15% of observing time goes to ESA, where the Hubble archive at Munich collates the data.

The discoveries made using the refurbished and optically corrected Hubble are stunning not just visually but also scientifically. Although the images are striking, it is the data which is of greater significance for our understanding of the universe. Nevertheless, the high resolution images that have come out of the Hubble project are of great value. The general public, who could not understand the research data, became keenly aware of and captured by the immense capability of the telescope they had paid for. With an increasingly educated population, it became increasingly important for politicians to justify their expenditure on large projects by clearly explaining their value. The images coming from Hubble made this task much easier, as they capture the imagination of the public and engendered an enthusiasm that few other large-scale scientific projects can match.

The ability to image in the infrared has proven to be of great value to astronomers, as it allows for data to be collected from behind dust clouds that are not easily penetrated by visible light. This is well documented in the photographs taken in 1995 of the Eagle Nebula, popularly called the “Pillars of Creation”, which are spectacular in visible light but reveal so much more with the infrared image. The number of objects discovered by the Hubble Space Telescope and the knowledge gained from it is immense—indeed, this is well demonstrated by the 10,000th paper using Hubble data that was published in 2008. There were images of Shoemaker-Levy 9 plunging into Jupiter, and primitive galaxies 13 billion years old.

In 2008 came the first image of an exoplanet, Formalhaut b. This only a few pixels on the image of the system, but it could be determined to have an orbit of 872 years and a mass of approximately three times that of Jupiter. The complexity of analysis is clear, since the images were taken in 2004 and 2006 but the report in *Science* did not appear until the end of 2008. This was also the year of Hubble's 100,000 orbit. In the search for extrasolar planets, Hubble has been invaluable. It is often forgotten that until the last quarter of the 20th century, it was pure conjecture as to whether or not there were any planets outside our Solar System. It was only when technical developments allowed the measurements of tiny fluctuations of luminosity in a star that circumstantial evidence started to build up for the existence of plants around other stars. Before that, it was only a logical assumption that such planets existed. In the popular imagination, it has always been known that there were planets around other stars, even with no evidence available. In a similar way, it has always been assumed that life abounds in space. The reality will almost certainly be quite different to casual assumptions. In all probability, alien biochemistry will be so different from life on Earth as to have no common point of contact, other than carbon and water (Fig. 8.3).

We may only ever be able to determine the existence of life on other planets outside our Solar System by the use of space telescopes like Hubble. Such insights as we are able to gain from detailed spectrographic analysis of extrasolar atmospheres may be as close as we can expect to get to extrasolar life. The recognition

Fig. 8.3 Hubble over planet Earth in 2009. The majesty of the technical achievement is encapsulated by this image. Image courtesy of NASA and STSci (NASA)

of our limitations in the face of physics and space travel may well result in a reduced appetite to fund space telescopes, although for now, their value will continue for as long as we can extract new information from them.

The telescope was originally designed to have a 15-year life but exceeded this, with the end of the satellite being properly organised today. An unmanned probe will link to it and after docking will leave a rocket pack behind. The final descent will be controlled for safety, since this is a very heavy instrument (just over 11,000 kg) of immense complexity, containing over 3000 sensors continuously monitoring the hardware.

References

Crocker, J.H. 1993. Engineering the COSTAR Optics. *Photonics News* 4: 11.

Defoe, D. 1705. *The Consolidator: Or Memoirs of Sundry Transactions from the World of the Moon*. Translated from the Lunar Language By the Author of The True-born English Man. London.

Hubble 25. 2015. *A Quarter Century of Discovery with the Hubble Space Telescope*. Washington, DC: National Aeronautics Space Administration. Nasa and ESA, produced by Space Telescope Science Institute.

NASA. 1990. *The Hubble Space Telescope Optical Systems Failure Report*. Washington, DC: National Aeronautics Space Administration.

Parkinson, C.N. 1958. *Parkinson's Law: The Pursuit of Progress*. London: John Murray.

Chapter 9
The Future: James Webb and Beyond

With the advent of the 21st century and the realization of humankind's limitations for travel, we are ever more reliant upon remote sensing to determine some of the most fundamental questions we can imagine. These are questions that are unlikely to be answered by manned space flight between planets, but they may be answered by highly advanced equipment like Hubble. Even so, it will be necessary to maintain a manned space programme, as space telescopes will require human intervention from time to time for servicing. As we are unlikely to ever be able to travel to these far-distant stars for ourselves, it is the light which we can garner through our instruments from these distant objects that will tell us about the universe.

The limitations that astronomers work under are not always accepted as final by the general population, even though the limits represent physics at its highest level. Consequently, it is still possible to read, especially on the Internet, that faster-than-light travel is possible, or that near-light-speed travel is an achievable goal. This fuels the belief that humanity can visit far-off planets and colonise the universe.

There is an interesting line of thought, primarily considered the work of mathematician John von Neuman, that suggests that a general purpose universal constructor able to replicate itself would be an ideal explorer of space on our behalf. This possibly sidesteps the idea von Neuman originally had, that a machine could indefinitely reproduce itself with the potential for evolved complexity. His ideas were broadened in his posthumously published work, *The Theory of Self-reproducing Automata*, which was based on his lectures given in the late 1940s before the age of computing. The ideas were more about proving whether a biological unit, cell or organism, could be regarded as a self-replicating machine in the way that we think of machines, and less about actually suggesting a practical approach to interplanetary colonialism.

This work was carried out about 10 years before the discovery of the double helix structure of DNA with its concomitant ability to self-replicate as well as create the cellular environment for its continued existence. The idea that a self-replicating machine could explore the universe on our behalf traveling the vast distances between stars is fraught with philosophical criticisms. The first of course is why a

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machine rather than a human? Trickier still is how we could possibly gain any useful or even meaningful information from an exploratory probe travelling over a period of time that would be longer than humankind has existed as a city builder.

Electromagnetic radiation in all its forms can tell us a great deal about distant stars and planets. It may not be ideal, as it does most definitely have limits and sometimes the information gathered can be open to a wide variety of interpretations, but it is available with modern technology. The Hubble Space Telescope was primarily designed to operate and image in the visible part of the spectrum, but the next large orbiting telescope will be working primarily at the longer wavelength end of the visible and beyond into the infrared, parts of the spectrum which are particularly disrupted by the atmosphere.

The newest orbiting telescope is the James Webb telescope, originally called the Next Generation Space Telescope (NGST). James Webb was the second administrator of NASA and held the post from 1961 to 1968. There are many things we can learn about the telescope from its name. The naming of telescopes, even very large ones, has always been a rare event. The only reason for giving them a name is to engender a feeling of humanity to what is a large and impersonal piece of equipment of such complexity that no individual can grasp all the parameters with which it works. Thus, bestowing it with a name humanises it and makes the public feel as though it can be related to. Naming it after a virtually unknown administrator is an interesting choice and in some respects undoes the support that naming it to honour an already famous person can create, which is important to keep the public onside to fund these very expensive projects.

The James Webb telescope is a joint project between NASA, ESA and the Canadian Space Agency. It was scheduled for launch in 2019, but delays and questions about cost make it more likely that its launch from the European facility in French Guiana will not take place until the middle of 2020. One of the many things that will make James Webb unusual will be its position at Lagrange point 2, usually just described as L2. The Lagrange points, of which there are five, are named after Joseph Louis Lagrange, a mathematician who described them in 1772. While it was Lagrange who described L4 and L5, Leonard Euler had predicted the existence of Lagrange points L1, L2 and L3 before the paper written by Lagrange (Fig. 9.1).

The Lagrange points are the points where the combined centripetal force of solar orbit and opposing gravity from the two bodies, in this case the Sun and the Earth, gives a point at which the angular velocity around the Sun matches the angular velocity of the Earth. From this we can easily see that L1 lies between the Sun and the Earth, about 1.5 million km from the Earth. L2 is less obvious, but lies about 1.5 million km beyond the Earth. L3 lies on the opposite side of the Sun and has never been used, since it is permanently obscured by the Sun. These three points are regarded as unstable, since the point of balance is quite delicate. To keep the James Webb telescope in position at L2 will require regular small adjustments. L3, being completely obscured by the Sun, has a particular place in science fiction writing, being held as the home of counter Earth in many stories.

The two other Lagrange points, L4 and L5, are stable, and once an object is in position it requires energy to move it from that place. They are positioned 60° in

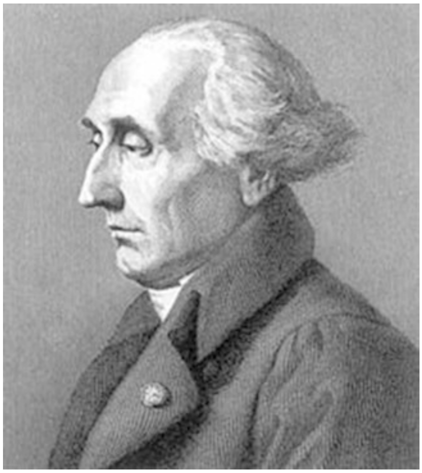

Fig. 9.1 Joseph-Louis Lagrange, originator of the eponymous 5 "L" points in space (St Andrews University/public domain)

front or behind the Earth, forming an equilateral triangle between the Lagrange point, the Sun and the Earth. Generally, L4 is in front of Earth and L5 trailing Earth by the same distance. These points are consistent with any three-body system where the smaller of the two orbiting bodies is no more than 4% of the mass of the larger body.

L1 and L2 have already been used for specific satellites. The Deep Space Climate Observatory is positioned at L1, so with the Sun behind it, the view of daylight Earth is continuous and uninterrupted. At the same time and facing in the other direction is the Solar and Heliocentric Observatory. L2 has been used for satellites before, but the most significant use will be for the James Webb Telescope, where it will sit in the shadow of the Earth, shielded against the extremes of the Sun. Prior to the James Webb launch there will be another satellite paving the way—the Transiting Exoplanet Survey Satellite, which will be searching for exoplanets as they transit stars and temporarily dim the light. Data from this satellite observatory will be used by the James Webb to make more detailed investigations of the exoplanets themselves where possible, but also to look further back in time than even Hubble has managed. It does not replace Hubble—it is the successor to it. The Lagrange points are so far out of our general ideas of orbit that it has been accepted that the James Webb has to be right first time, as there will be no potential to visit with corrective optics.

The James Webb space telescope is made of 18 hexagonal segments, giving a total diameter of 6.5 m, although because of the method of construction and the material used the mass will be only half of the Hubble mirror. This is achieved by making the mirrors with what is in effect the ultimate speculum metal, beryllium, and then coating it in gold. The density of beryllium is one of the factors that makes it suitable for this job, being only about 1.85 g/cm^3. At the same time, it is both rigid and thermally stable while having a high thermal conductivity. The thermal stability helps to hold the focus, as does it being at Lagrange 2, which puts it in permanent Earth shade, so there should be little temperature change throughout its life.

In the first two centuries after the invention of the telescope, it was quite likely that an astronomer would make his—for they generally were male—own telescope. Some of them would make their own lenses or mirrors as well to great effect. Even when they were employing others to make their lenses, they would often be self-financed and to their own design or specification. It was because individuals were making their own equipment, from optical parts to mechanical components, and then becoming the exclusive users that very often high quality observations and discoveries were made. Being the makers of such instruments supplied these early astronomers with a detailed knowledge of their workings, which meant that they could be used to the very limits of their performance. The personal nature of these telescopes also resulted in them tending to fall into disuse when the original owner died. This is exemplified by a photograph taken in 1924 by W.H. Steavenson of the remains of the 40-ft telescope that Herschel had erected at Observatory House in Slough.

It would take a great deal of understanding of the instruments to get the most out of them, the limits of their performance being intimately associated with the skill of the observer, which is one of the reasons that they were often personal instruments of exploration. As Nigel Calder put it in his book *Violent Universe* (1969) when referring to the Orbital Astronomical Observatory (OAO) launched in 1968: “With the OAO, the lonely astronomer on the mountain-top is replaced by the machinery, computing and teamwork of an elaborate space flight.”

The importance of collaboration and teamwork has become prominent and near-indispensable in the production of the new age of astronomy. This did not start abruptly in the second half of the 20th century; rather, it evolved. As the scale of equipment became larger, so too did the complexity, becoming too big for a single individual to grasp. Similarly, as the time scale became too long for an individual to make all the various parts, the incorporation of teams became essential.

We are lucky to have available some details of at least one early team undertaking in astronomy. In earlier centuries, the names of the skilled workmen who carried out the practical tasks of a project were regarded as of less importance than the originator of the idea. In the case of the Link Observatory, this is not the case. This observatory, which was started in 1937 and completed in 1939, is situated a few miles south of Mooresville, Indianapolis and takes its name from its originator, Dr. Goethe Link, a renowned surgeon at Indianapolis. It is said that Link received a sketch of an observatory building from Russell Porter, himself an accomplished artist and astronomer. The design was interpreted and built by an Indianapolis carpenter, C. Bowers, and the optics were created by two amateurs, Maier and Herman. The grinding machine was constructed specifically for the task by C. Turner. This group constituted the core of the team that produced what was at the time the largest amateur telescope in the USA, a 36-in. reflector. Both the site and telescope were given to Indiana University School of Astronomy in 1948. Most of the details we know about the construction come from the observatory archive, which went to the University when the observatory was handed over. This is quite unusual, and until the 20th century, archival material regarding the construction and maintenance of the personal observatories of amateur individuals, rather than groups, tended to be lost. This is a common enough problem, as descendants may well have no particular interest in the subject, and other than giving the equipment to an interested group or individual, they may well dispose of the historical documents that have no perceived value.

Until well into the 20th century, observation was still a process of an individual being the observer, and a camera, if there was one, being the record of the observation. Failing, meticulous notes were made, and measurements were noted by hand to be transcribed later. With 21st century telescopes and the huge computing power available, the instrument became the observer and recorder, and the human becomes the interpreter, now one step removed from the data and reliant on the instrument and programmer for accuracy. The amount of data that has become available on a routine basis is truly vast—a terabyte a day is not out of proportion. This cannot simply be handled as raw data; it has to be processed and cut down to size before it can be comfortably utilised. Storage of this vast amount of data is not an issue, as small computers routinely come with terabyte storage. What is an issue is extracting information from this amount of data without losing sight of the fine nuances that may be essential to a complete picture.

There has been an interesting and profound change in scientific investigations brought about primarily by large-scale data handling. This is the change from a traditional scientific investigation that would run along the lines of *observe, create a hypothesis, test*, to *collect data, report observations*. So often these articles have a section described as *conclusions* but which just reiterate the points observed, no conclusion forthcoming. This is most often found in the biomedical field, where very often scientific papers are needed for career enhancement but are little more than natural history observations, where conclusions are neither wanted nor expected. In astronomy, the temptation of being a passive observer and reporter has to some extent been circumvented, although constant increases in observing power have increased the catalogue of celestial objects. Many of the large and complicated instruments are being created to answer questions of a very fundamental nature. For this, the extraction of information and understanding from the enormous datasets is a problem in its own right, but it is recognised that just to report a bigger, brighter object without some insight to go with it is not enough.

It is easy to become enamoured by large data as a proxy for science, which should have testable hypotheses that can be joined together into a composite whole and become a theory (Popper 1959). It is often considered that the more often a hypothesis passes a test and the hypothesis refined to a simpler version—the reductionist ideal finally being achieved—the more reliable it is. This of course trusts the an assumption that reductionism works. As an example, in the case of balancing on a bicycle, this is not so. The oft-quoted idea that science cannot explain how a bicycle stays upright shows a lack of understanding of just how complicated systems can be; if it was a simple physical system, the bike would balance itself.

There are many ways that knowledge can be extracted from the massive data sets generated by the new breed of astronomical instruments. Probably the first attempt to look through huge swathes of information was citizen science, using idle computer capacity to analyse signals for patterns. SETI was an early adopter of this technique, although it has been largely superseded by faster computers. Citizen science is still a very useful tool and is still used as a method of classifying galaxies by type from vast star field data. These citizen science projects are essentially straightforward techniques, searching for patterns or variation when compared with a standard data set. The real complexities arise from trying to learn something new, rather than more of the same, by data mining. It is very easy to lose sight of the important part of a project as one is swamped by numbers. A good example is event frequency data, where endlessly collecting more numbers is a waste of resources, as once a frequency has been ascertained, adding in more numbers will not improve the accuracy.

Data mining is sometimes described as discovering hidden knowledge contained in a large database and involves some quite sophisticated techniques. It is wise to consider the outcomes of data mining, rather than the mathematical complexity of the analysis. Techniques that have been employed include neural networks and decision trees, as well as Bayesian analysis. These last two methods are interesting in their historical attributes.

Bayesian statistics languished for many years as a simple curiosity created by the Reverend Thomas Bayes, a Presbyterian minister of the 18th century. Although not of direct relevance to astronomy, the constant adjustment and explanations of traditional statistical analysis has been likened to the constant addition of epicycles to epicycles to make theory fit observations and hold up a creaking notion of the universe. Bayesian systems can change the probability of an outcome as more information becomes available, a more fluid approach than the rather more traditional testing of a null hypothesis against itself.

The decision tree is easier to put into context, as it is really a type of analysis based on the dichotomous key used by biologists for many years. For those unfamiliar with the dichotomous key, this is a method of identifying a species existing in four dimensions (three spatial + colour and pattern) using a written description. Jean Baptiste Lamarck is generally credited with constructing the first text-based dichotomous key in 1778 with publication of *Flora Francaise*, although in 1689 Richard Waller had produced a pictorial key for identifying British plants. Jean Baptiste Lamarck is now much better known for Lamarckism, generally regarded as a discredited explanation of evolution, where changes in an animal caused by the environment are passed onto future generations.

An example of the scope of the amount of data that the triumvirate of telescopes, detectors and computers can generate can be found in the Large Synoptic Survey Telescope (LSST). This will be located in Chile at Cerro Pachon in Chile and is due for commissioning in 2019. It will have an 8.4 m mirror, but the important thing here is that it will have the largest CCD camera ever made, with 3.2 gigapixels. This is anticipated to generate something between 10,000 and 100,000 nightly alerts. An alert in this case is a signal which makes a change of brightness, position or is something new in the scanned part of the sky. These alerts are logged and catalogued daily; the understanding of their significance remains with the astronomer. The highly automated process is entirely defined by the voracity of the algorithms employed.

The process and methods used to handle the massive amounts of data have spawned the new technology of astroinformatics. This follows the model of bioinformatics, which came into being with the huge amounts of data generated by the human genome project. Astroinformatics has to manipulate huge datasets on both spatial and temporal scales. This involves developing computer models of natural systems to aid in decision making. The risk is that information overload becomes a distinct possibility, with important observations being lost. All of the data and all of the information is not for its own sake—it is for clarifying our understanding. This is exactly what the ancient astronomers were trying to do. Remember that astronomy is the most ancient of sciences, able to take observations of the sky and make predictions as to where the Sun and Moon will be. As we have seen, it could become corrupted when an incorrect line of reasoning took hold.

Astronomy has always been about stretching human vision and imagination. As the ability to scan a star field daily and to access the concomitant collection of data becomes routine, we should not lose sight of the principles underlying scientific study and should take especial care not to turn big data into a self-justifying system.

References

Calder, Nigel. 1969. *Violent Universe*. London: BBC Publications.

Lagrange, J.L. 1772. Chapitre II: Essai sur le problème des trois corps. In *Œuvres de Lagrange*, vol. 6, 229–334. Paris: Gauthier-Villars.

Lee, P.M. 1989. *Bayesian Statistics*. London: Arnold.

Popper, K. 1959. *The Logic of Scientific Discovery*. London: Hutchinson and Co.

Von Neumann, John. 1966. In *The Theory of Self-reproducing Automata*, ed. A. Burks. Urbana, IL: Univ. of Illinois Press.

Chapter 10
Timeline of the Optical Telescope

A timeline is not a simple list of events. It represents the flow of ideas through time, each one connected in a chain to its predecessor and successor. There seems to be periods in history when an apparent rush of ideas spontaneously appeared to push science forward. This is a reductionist view of history, as it reduces progress to a series of unrelated events, where in reality they have all developed from previous events and tested hypotheses. Isaac Newton is sometimes quoted to have said, "If I have seen further it is by standing on the shoulders of giants" in a letter to Robert Hooke. This is not the origin of the idea, which can be seen as far back as *Nanos gigantium humeris insidentes*, roughly, "dwarfs standing on the shoulders of giants", attributed to Bernard of Chartres in about 1128. You may also see the same idea slightly shortened on the home page of Google Scholar as, "Stand on the shoulders of giants". Wherever they appear, the sentiment is the same: it is a deprecating statement highlighting current scholarship's dependence upon previous work. It is easy to imagine that science moves forwards in unrelated leaps orchestrated by individuals of genius. There is no doubt that there have been such people, but it is also true that as we go back in time, only the major players have been recorded, and minor helpers and thinkers of equal value tend to be side-lined or forgotten. This was a function of recorded information. Aristotle has his name recorded on many works of different types, but if a philosopher did not write their work down, those ideas and that person's name would be lost as history filtered the recorded works.

It was well into the 19th century and the advent of the professional scientist that publication became the *de facto* mark of success. *Lancet* was first published in 1823, *BMJ* (under a different name) in 1840, *Nature* in 1869, *Science* in 1880 and just into the 20th century, *PNAS* started publication in 1915. Until the advent of an education that valued science for itself over theology and medicine, it was only the leisured who could spend a large amount of time and money researching those interesting questions that we now recognise as fundamental to the world, such as the relationship between pressure and temperature, or voltage and current.

There is another reason for finding clusters of primary activity within a subject area; equipment. The telescope is a prime example of this. Until the telescope was a

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useable invention, astronomy depended upon eyesight and had therefore not materially improved through recorded history, so results were limited. Introduction of the telescope suddenly made the invisible both visible and measurable, spurring a time of astronomical discovery.

In the modern era, all contributors to a piece of published work are named as authors so no one gets forgotten. But this is a very new phenomenon. Although specifically looking at astronomy in analysis of papers published is rather difficult, mainly because of the large overlap between fields, we can broadly look at papers on "space science". In 2002, six papers published in the field of space science had more than 100 authors. In 2009, the number was 80, and in 2010, 102. We can see from this that not only does big science need lots of people, but also that contributors are rightly recognised. At the same time, the number of single author papers has been going down across all disciplines of science, reflecting increasing complexity of measurement and analysis. This, of course, makes it more difficult for the original thinker to stand out from the crowd.

As we move further back in time, many dates become estimates. Precision is lost over time, and an early record may not be the first record—it is only the latest date for that event or discovery to have taken place. Following is a comprehensive timeline of astronomical and general events from 3000 BC to 2008 AD that put the entire history of optical telescopes in perspective.

Date	Astronomical	General
c3000 BC	The use of instruments capable of precise sighting celestial bodies is clear from the accurate alignment of the Egyptian pyramids at Giza. About this time, the Babylonians predict an eclipse.	
c2200 BC	Chinese observers make the earliest record of a comet in 2296 BC. The Sumerians have a dual calendar, 360-day solar and 354-day lunar years.	Two concentric circles are erected to form Stonehenge in the south of England.
c1500 BC	The gnomon is being used on sundials by the Egyptians	
c750 BC	In 763 BC, a solar eclipse is recorded in Babylon.	The first Olympics held in Greece in 776 BC.
c720 BC	Records start to be kept of solar eclipses in China under the Zhou dynasty, the longest lasting in Chinese history.	
c580 BC	Thales of Miletus predicts the eclipse of May 28, 585. It is unlikely that the prediction would have been more accurate than to within a year.	This is probably the first date which can be accurately placed in our calendar. The astronomical records of China can also be seen as the first claimant to an accurate date.

Date	Astronomical	General
c515 BC	Anaximander models the Earth as a cylinder.	
c500 BC	The Pythagoreans claim the Earth is a sphere.	
c480 BC	Oenopides calculates the angle of tilt of the planet. At 24°, this is only half a degree out. This is probably the first attempt at this calculation.	During this period, the debate over matter rages widely. Heraclitus claims fire as the primary substance; Anaxagoras suggests a philosophy of matter being made up of large numbers of seeds. Later on Empedocles says that the elements are fire, air, Earth and water. Plato accepted the ideas of Empedocles and coined the term element. While Empedocles believed the elements to combine in different proportions but were themselves immutable, Aristotle suggested that the elements themselves changed when combined.
c440 BC	Meton formulates a 19-year cycle for the Sun and Moon that can be used to predict eclipses. Also to form the basis of a useable calendar.	The philosophical discussion about the structure of matter continues, with Leucippus introducing the idea of an indivisible unit of matter, the atom. Democritus was an exponent of the atomic idea, with atoms having no limit on their size and determining the nature of matter by whether the atoms stick to each other (solids they do; liquids they do not). This was not a generally accepted idea for nearly 2000 years.
c390 BC	Heracleides suggests that Venus and Mercury orbit the Sun.	Plato considers the possibility of another continent opposite Europe, which he calls Antipodes.
c380 BC	Democritus suggests the Milky Way is a composite of stars.	
352 BC	Chinese astronomers make the first record of a Supernova, although details are sketchy.	
c300 BC	Chinese astronomers produce star maps that are used throughout the empire.	
c270 BC	Aristarchus claims the Sun is the centre of the Solar System, contrary to the teachings of Aristotle	
c130 BC	Hipparchus of Nicea calculates both the distance and size of the Moon by parallax measurements during and eclipse. He had earlier described the precession of the equinoxes.	

Date	Astronomical	General
46 BC	A Greek astronomer, Sosigenes, advises Julius Caesar on the introduction of what we now call the Julian calendar. This included years of 365 days, with every fourth year being of 366 days. To start with the seasons matching the date, the longest year on record, 46, had 445 days. This calendar would still slowly drift until the introduction of the Gregorian calendar.	
c100 AD	Ptolemy writes *Megale syntaxis tes astronomias* which describes the Earth as the centre of the universe. When it was translated into Arabic it was called *Al magiste*, The Greatest. This was shortened by usage to *Almagest*.	
635 AD	Chinese documents clearly detail that the tail of a comet will always point away from the Sun. At the same time, though in different documents, π is given to an accuracy of seven decimal places.	This is the slow period of astronomy. Work is translated from previous years and observations made of unusual events, such as comets and eclipses, but little of originality is forthcoming. The Ptolemaic universe causes increasing problems of complexity as more accurate measurements of the fixed and moving stars are made.
827 AD	*Almagest* is translated into Arabic.	
c890 AD	Al-Battani accurately calculates the precession of the equinoxes, correcting the obliquity of the ecliptic. He also works out more accurately the length of the year.	It is about this time that paper money, in a form we would recognise, is printed and used in Szechuan, China.
c1000 AD	India introduces a year of 360 days, requiring regular additions to keep the calendar stable.	
1167 AD		Oxford University is founded, although some teaching was carried out earlier.
1175 AD	Gerard of Cremona translates the *Almagest* by Ptolemy, originally written in Greek, from Arabic into Latin.	
1250 AD	Alfonso X of Castile decrees the production of astronomical tables which become known as the Alfonsine tables.	
1252 AD	The Alfonsine tables are completed.	About this time (usually said to be 1253), the Sorbonne in Paris is established.

Date	Astronomical	General
c1300 AD	Corrective eyeglasses become available.	
1391 AD	Geoffrey Chaucer writes a treatise on the astrolabe, which describes its construction and use.	
c1420 AD	Ulugh Beg builds the great observatory at Samarkand.	
1483 AD	Although completed in 1252, it is only now that the Alfonsine tables are printed.	
1514	Copernicus writes his first version of his heliocentric theory of the Solar System, although this is not published.	Vander Hoecke in Holland uses the + and − signs as we would use them in an algebraic expression for the first time.
1540 AD	Peter Apian describes cometary tales as pointing away from the Sun. This had been known for a time in China but had not previously been noted in Europe.	
1543 AD	*De revolutionibus orbium coelestium* was published by Copernicus, describing a heliocentric solar system. In May, Copernicus dies.	
1572 AD	Tycho Brahe observers a new star. He called it a *nova*; we would call it a *supernova*. It was visible for 15 months and recorded by Chinese astronomers as well.	
1573 AD	Tycho Brahe publishes *De nova stella*, describing the supernova of the previous year.	
1577 AD	Tycho Brahe demonstrates the distance of a comet using parallax, which demonstrates that comets are definitely not an atmospheric phenomenon.	
1582 AD		After consulting Christopher Clavius, astronomer, Pope Gregory XIII reforms the calendar across much of catholic Europe. This takes out 11 days in October, making 1582 the shortest year on record.
1600 AD	Johannes Kepler joins Tycho Brahe as assistant in Prague.	

Date	Astronomical	General
c1600 AD This is the significant date for astronomy, with the introduction of the telescope. As can be seen, before this date there were a lot of translations of old texts and considerable efforts put into refining old measurements and catalogues of visible stars. From time to time, events such as supernova were recorded, but overall astronomy had come to something of a standstill, awaiting a tool that could increase the observational power of astronomer. With the reliance upon the naked eye, explaining the observations of the sky was almost a matter of opinion. It was only as more accurate observations were made using telescopes that basic explanations of the Solar System and beyond had to incorporate new stars and planets moving in orbits, which could not be easily fitted into the older ideas of how the Solar System was laid out and how planets and stars moved. Like many advances in science, the introduction of a new instrument (telescope, microscope, mass spectrometer) or technique (photography, polymerase chain reaction, Southern blotting) enables scientists to guide their activities in specific directions, giving rise to huge leaps in understanding.		
1609	Galileo builds a telescope, eventually achieving a magnification of approximately 30 diameters. Kepler publishes his hypothesis of elliptical orbits sweeping constant areas in constant time. Simple sketches of the Moon are made by Harriot using a telescope.	It is about this date when the compound microscope was first constructed.
1610	Starting early in the year, Galileo makes full use of his new instrument. He records the Moons of Jupiter, the rings of Saturn and individual stars in the Milky Way.	
1611	Sunspots are discovered simultaneously by several astronomers. The Orion Nebula is discovered.	The King James Bible is published, becoming the standard translation used in Anglican Churches. The translation had been started in 1604. Johannes Kepler publishes the first western description of snowflakes as hexagonal structures.
1613	Galileo reports on sunspots and produces his first statement favouring the Copernican system.	
1616	The dogma of the Catholic church feels challenged, and Galileo is warned by Cardinal Bellarmine that he should not defend the Copernican model. *De revolutionibus* appears on the *Index Librorum Prohibitorum* where it stays until 1835.	Literature lost both Shakespeare and Cervantes on the same day, April 23 of this year.
1619	Kepler defends the Copernican system in *Epitome astronomiae*, which is put on the *Index Librorum Prohibitorum*.	
1627	The Rudolphine Tables are produced by Kepler, using much of the data from Tycho Brahe.	The Auroch, the large progenitor of domestic cattle, is seen for the last time. It is now extinct.

Date	Astronomical	General
1631	The first observation of a transit of Mercury across the Sun.	Pierre Vernier describes his eponymous scale.
1633	Galileo is forced to recant his Copernican view of the Solar System by the Inquisition.	
1639	A transit of Venus is predicted and observed by Horrocks in England.	
1642	Galileo dies on January 8.	
1647	*Selenographia*, the first map of the visible face of the Moon is made by Heelius.	
1656	Christian Huygens demonstrates that the "handles" that Galileo had seen on Saturn were rings. He also develops a pendulum clock.	
1659	Christian Huygens makes the first observation of surface features of Mars.	
1660		Robert Boyle demonstrates that removing and creating a vacuum extinguishes a flame and kills small mammals.
1663	James Gregory publishes *Optica Promota*, containing the first description of a reflecting telescope.	
1664	Borelli calculates that the orbit of a comet is parabolic; previously, it was thought to be circular or elliptical. Robert Hooke discovers the rotation of Jupiter and the great red spot.	Christian Huygens suggests that a standard of length should be the length of a pendulum having a period of 1 second.
1665	The rotational velocity of Jupiter is measured by Cassini.	Robert Hooke publishes *Micrographia*, describing cells in plant material using a microscope. The Great Plague of London (Black Death) devastates the population of Great Britain.
1666	Polar ice caps are observed on Mars by Cassini.	The great fire of London destroys much of the city.
1668	A reflecting telescope is made by Newton.	
1670		Boyle discovers "flammable air", now called hydrogen.
1671	Cassini discovers Iapetus and calculates the distance from Mars to the Earth, close to the accepted measurement.	
1672	Cassegrain invents the style of reflecting telescope that bears his name.	

Date	Astronomical	General
1675	Cassini shows that the rings of Saturn are not a single construction but have breaks in them.	
1679	Cassini produces a map of the Moon.	The Writ of Habeas Corpus is introduced in the UK, a method whereby a court can demand that an official produces an imprisoned person and demonstrate reason for their incarceration.
1680		It was about this year that the Dodo became extinct. Endemic to Mauritius, it stood about 1 m tall and achieved posthumous fame in *Alice's Adventures in Wonderland* by Lewis Carroll.
1682	Edmund Halley observes a comet that seems to have appeared in texts in previous years with a period of about 76 years.	
1684	Dione and Thetys, satellites of Saturn are described by Cassini.	
1687	Newton publishes *Philosophiae naturalis principia mathematica*, which outlines his three laws of motion and universal gravitation.	
1700	The meridian telescope is invented by Ole Romer.	
1702	*Astronomie physicae et geometriae elementa* by David Gregory is published.	The first daily newspaper is published in London. Although not intrinsically important, it reflects the growing educated middle classes and an increasing curiosity about the world.
1704	Newton's *Opticks* is published.	
1705	Edmund Halley calculates that the Great Comet will return in 1758, having observed it in 1682. This becomes known as Comet Halley. This is published in *Synopsis astronomiae cometicae*.	
1714		Gabriel Fahrenheit makes a mercury thermometer with his eponymous scale. The Fahrenheit and Celsius scale cross over at −40°, so at this point they represent the same temperature.
1718	The proper motion of fixed stars is described by Halley by using data from the present and positions given by Ptolemy and Hipparchus.	
1720	Halley becomes Astronomer Royal.	
1723	John Hadley builds a high quality reflector telescope.	

Date	Astronomical	General
1725	Flamsteed publishes a catalogue of stars	
1733	Chester Moore Hall invents the achromatic telescope with an objective lens made of two component parts of different refractive indices. Anders Celsius publishes his observations on the Aurora Borealis.	
1737	John Bevis records the transit of Venus in front of Mercury at Greenwich Observatory.	Euler proves that e is an irrational number.
1740	Anders Celsius becomes director of the observatory in Uppsala.	
1741	James Bradley becomes Astronomer Royal, succeeding Edmund Halley who dies the following year.	Stellar's sea cow is discovered. It takes just 27 years to hunt it to extinction. This species could reach 8 m in length and other than whales was one of the largest surviving ancient mammals.
1742		Anders Celsius originates a scale of temperature, not a thermometer. It originally has 0° as the boiling point of water and 100° as the freezing point. It gained credibility when the two figures were reversed.
1743	The polar flattening of the Earth is demonstrated by Clairaut in Paris.	
1744	The Roman Catholic Church allows the publication of Galileo's discussion of the Copernican system, as long as his recantation is included in the work.	
1746	Clairaut publishes a work on the three-body problem of objects interacting in space. This will be important in defining the Lagrange points.	
1750	A catalogue of 200 stars visible in the southern hemisphere is made by Nicolas de Lacaille.	
1752	Marbach publishes tables of the motion of the Moon relative to the stars, enabling accurate determination of longitude.	Great Britain and colonies adopt the Gregorian calendar. This involves having September 3 being followed by September 14, bringing the UK into line with continental Europe.
1754	John Dollond invents the heliometer that can be used to find the diameter of the Sun or the distances between stars.	The first female graduate in medicine gains a degree in medicine from the University of Halle in Germany.

Date	Astronomical	General
1757	Clairaut measures the mass of the Moon and of Venus with considerably greater accuracy than had previously been achieved.	John Campbell changes the quadrant used in navigation by increasing the arc from 90° to 120°, thereby creating the sextant.
1758	John Dollond creates an achromatic telescope, which he presents to the Royal Society. Halley's Comet is seen, exactly as predicted by Halley in 1705.	A commission is created in Great Britain that sets the Imperial Standards for measurement.
1760	Johann Lambert publishes *Photometria*, an investigation of light and its reflection from planets. This introduces the term albedo.	
1761	The atmosphere of Venus is recognised by Mikhail Vasilievich while he is viewing a transit of Venus across the face of the Sun.	
1765	Nevil Maskelyne takes over as director of the Greenwich Observatory.	An account of the precession and nutation of Earth is given by Leonhard Euler.
1768	James Cook starts a voyage to the Pacific Ocean, where he will observe the transit of Venus.	Encyclopaedia Britannica starts publication in weekly parts.
1769	The transit of Venus is viewed from many places around the world.	
1774	Nevil Maskelyne calculates the mass and density of the Earth by how far a mountain causes a plumb line to deviate along the horizontal.	
1776	Herschel builds a 7-ft (2-m) telescope.	Britain's colonies in America declare independence, strange.
1778		James Cook discovers the Hawaiian islands.
1779		Lavoisier proposes the word "oxygen" for the combustible part of air. Abraham Darby builds the first cast iron bridge over the river Severn in Shropshire. Comte de Buffon claims the Earth is 75,000 years old, the first suggestion that the Earth is older than simple biblical analysis would have it.
1781	Herschel discovers Uranus. He originally thinks it is a comet; Anders Lexell ascertains it is really a planet.	By careful measurement, Lavoisier determines that in a chemical reaction, the total mass does not change.
1783	William Herschel produces a catalogue of double stars.	The Montgolfier brothers demonstrate a hot air balloon in August, and in November, the first human ascent is made.

Date	Astronomical	General
1785	William Herschel publishes *On The Construction of The Heavens*, containing a generally correct description for the shape of the Milky Way, although his estimate of the size is three orders of magnitude smaller than reality.	The first fatalities of air travel occur when two aviators trying to cross the English Channel in a hot air balloon crash.
1786	William Herschel publishes *Catalogue of Nebulae*, which will eventually become the *New General Catalogue*, NGC.	
1787	Herschel builds a 20-ft telescope.	
1789	Herschel finishes his 40-ft focal length telescope with a mirror of 48-in. diameter.	Lavoisier publishes a table of the elements, containing 31 elements along with heat and light, which he regards as massless elements.
1791		The Metric system is suggested as method of measurement in France.
1796	*Exposition du Systeme du Monde* by Pierre-Simon Laplace is published in which he suggests that the Solar System evolved from a cloud of gas condensing.	Edward Jenner performs the first vaccination, using cowpox as a protection against smallpox, both being caused by a variety of vaccinia.
1797	Caroline Herschel discovers her eighth comet.	
1798	Brandes and Benzenberg use triangulation techniques to measure the height at which comets burn in the atmosphere.	
1799	Wilhelm von Humboldt observes the Leonid meteor shower.	A preserved frozen mammoth is found in Siberia, and the first scientific account is made of the Duck-Billed Platypus.
1800		William Herschel describes his discovery of infrared radiation.
1802	William Herschel publishes a third list of nebulas and establishes the existence of binary stars. He observes dark lines in a solar spectrum but does not realise their significance. One year later, Wollaston discovers the elements rhodium and palladium.	
1805	Pierre Guinand develops the technique of using a fireclay rod to stir molten glass, making a much more even and reliable product for lens making.	

Date	Astronomical	General
1811	William Herschel proposes that stars are formed from clouds of gas that can then explode, resulting in a cloud of glass and a remnant star.	Avagadro proposes that at any given temperature and pressure any gas will always contain the same number of molecules. For 1 mole, this is about 6×10^{23}.
1814	Joseph Fraunhofer makes his first solar spectrum.	
1815	Fraunhofer produces a new solar spectrum of 324 lines.	
1818	Jean-Louis Pons discovers Encke's comet, which has the shortest orbital period known at the time at 3.3 years.	
1819	Francis Arago demonstrates that light from comet tails is polarized.	
1820	John Herschel and Charles Babbage, with others found the Royal Astronomical Society.	Augustin-Jean Fresnel invents his eponymous lens.
1821	The Catholic Church no longer bans teaching the Copernican idea of a heliocentric Solar System. Using observations of Uranus, Alexis Bouvard finds that there are discrepancies in the positions which lead to the discovery of Neptune.	Michael Faraday constructs the first two electric motors.
1823	Fraunhofer makes spectra of fixed stars and discovers dark lines that are different from the dark lines in the spectra of the Sun.	
1824	The first telescope mounted equatorially with a clock drive is built by Fraunhofer, known as a Dorpat refractor.	In the UK, the yard is defined as the length of the pendulum, which has a period of 1 second at Greenwich.
1825	John Herschel describes a device for measuring solar radiation.	George Cuvier describes his "catastrophe" theory, wherein catastrophic events cause large-scale extinctions.
1827	Calculations of the orbit of the binary star zeta Ursae Majoris demonstrates that Newton's laws of gravity control the stars.	John James Audubon starts publication of *Birds of America*.
1830	About 70 years after the achromatic lens for a telescope is developed, Joseph Lister develops an achromatic lens for microscopes.	
1831		Charles Darwin joins HMS Beagle.
1833	A meteor shower of unprecedented numbers over the United States raises questions as to how such showers originated.	

Date	Astronomical	General
1834	John Frederick Herschel starts a survey of the stars of the southern hemisphere.	Mercury/silver amalgam starts being used as a filling for teeth.
1835	Francis Bailey describes the bright spots visible around the edge of the Moon during a total eclipse. These become known as Bailey's beads. Beer and Madler produce a map of the Moon that remains in use for several decades.	The first species of lungfish is discovered, demonstrating a method of gaseous exchange that could be used by vertebrates to invade land.
1838	Friedrich Bessel measures the parallax of 61 Cygni, allowing him to determine the distance to a star for the first time.	The fundamental components of plants are recognised to be cells by Matthias Jakob Schleiden.
1839	Thomas Henderson measures the distance to Alpha Centauri by parallax measurements, the second time it has been carried out.	Louis Jacques Daguerre describes his photographic technique, which became known as the Daguerreotype.
1840	Through parallax, the third star outside the Solar System, Vega, has its distance measured, this time by Fredrick von Struve.	Giovanni Battista Amici invents the oil immersion lens for microscopy.
1842	Viewing a total solar eclipse, it is realised that the corona and other unusual features originate with the Sun and not the Moon.	Richard Owen coins the word "dinosaur".
1845	William Parsons, Third Earl of Rosse, completes his 72-in. (183-cm) reflector, sometimes called the Leviathan of Parsonstown.	*Scientific American* starts publication, founded by Alfred Beach.
1846	Using predictions of its position, Johann Galle discovers Neptune.	
1847	John Herschel completes his survey of the stars of the southern hemisphere. He has measured the brightness of the stars with great precision.	
1848	The eighth moon of Saturn, named Hyperion, is discovered by George Bond.	Hippolyte Fizeau suggests that light from a receding source will be redshifted in an analogous manner to the Doppler effect of sound.
1849	The *Astronomical Journal* starts publication, the first journal specifically for astronomy in the USA.	Hippolyte Fizeau measures the speed of light to within 5% of the accepted value.
1850	William Bond takes the best daguerreotype of the Moon so far.	

Date	Astronomical	General
1852		Elisha Otis invents the first lift (elevator) with an automatic break to stop the device even if all cables are severed. The first such lift is installed 2 years later.
1854	Hermann Helmholtz predicts the heat death of the universe.	
1855	William Parsons demonstrates the spiral nature of galaxies.	
1856	George Bond demonstrates that the magnitude of a star can be taken from a photograph.	William Henry Perkin makes the first aniline dye, mauve.
1857	Leon Foucault starts producing silvered glass mirrors for telescopes. James Clerk Maxwell shows that the rings of Saturn are not solid but made of discrete particles.	
1859	Richard Carrington discovers the rotation of the Sun is not uniform, the motion being faster at the equator.	*On The Origin of Species* is published by Charles Darwin.
1862	Alvin Clark and his similarly named son observe Sirius B, the dark white dwarf companion of Sirius. Leon Foucault accurately measures the distance from the Earth to the Sun. Anders Angstrom uses the solar spectrum to show that hydrogen is found in the Sun.	The American Civil War has the first naval engagement between ironclad ships, *Monitor* and *Merrimac*. Jordan Gatling develops the first machine gun.
1863	William Huggins uses spectral analysis to show that stars contain the same elements as on Earth.	
1865	Jules Verne publishes *From The Earth To The Moon*, in which four individuals are shot to the Moon from Tampa Town, Florida.	Gregor Mendel publishes his experiments in genetics. Friedrich Kekule works out the structure of benzene.
1866	Schiaparelli associates comets with meteor showers.	A telegraph cable is laid across the Atlantic Ocean.
1867		George Westinghouse invents the airbrake for railways.
1868	William Huggins shows that Sirius is moving away from us by using the doppler shift of the stars spectrogram. Janssen observes an unknown element in the Sun's spectra. Joseph Lockyer names it Helium.	
1869		Ferdinand de Lesseps completes the Suez Canal. Pere Armand David describes the Giant Panda.

Date	Astronomical	General
1873	Richard Proctor describes craters as being due to meteor impacts. Previously, craters were considered to be volcanic.	
1877	Schiaparelli claims to have seen canals on Mars.	
1881	Edward Barnard discovers a comet from a photograph.	
1882	David Gill introduces the idea of constructing star catalogues from photographs.	
1884	The Prime Meridian is agreed to run through Greenwich.	
1885	A supernova appears in Andromeda, which is just visible with the naked eye. Only repeated in 1987.	The dewar vacuum flask is invented by James Dewar.
1887	The 36-in. Lick refractor is installed on Mount Hamilton, California.	
1888	Johann Dreyer publishes *A New General Catalogue of Nebulas and Star Clusters* of 7840 entries. This creates the designation NGC.	Francis Galton describes statistical correlation of two variables. Dunlop introduces pneumatic tyres and Eastmann introduces a roll film camera.
1892	Edward Barnard find the fifth moon of Jupiter, the last to be found without photography.	
1894	Percival Lowell starts his observatory at Flagstaff Arizona.	Marconi constructs a radio that can ring a bell 10 m away.
1896	The Lick Observatory produces the first photographic atlas of the Moon	
1897	The Yerkes Observatory is organised by George Hale with a 1-m refractor.	Charles Parsons demonstrates the superiority of his steam turbine ship *Turbina*.
1903		The Wright brothers launch *Flier*, the best flight of the day lasts 59 seconds.
1904	Mount Wilson Observatory is set up by George Hale. Charles Perrine finds the sixth moon of Jupiter.	Emile Berliner invents the flat phonograph disc. Work begins on the Panama canal.
1905	Charles Perrine finds the seventh moon of Jupiter.	Einstein submits two papers on special relativity, the second one contains the mass/energy relationship $E = mc^2$
1906	William Wilson demonstrates that the Milky Way is a spiral galaxy.	An explosion at Tunguska, Siberia, is thought to be due to an extra-terrestrial body. Hydrogen is shown to have only one electron by J.J. Thompson.
1908	George Hale discovers the magnetic nature of sunspots, he also installs a 1.5-m reflector at the Mount Wilson Observatory.	Orville Wright takes to the air for an hour.

Date	Astronomical	General
1909	The Sun is thought to be part of the milky way and not central by Karl Bohlin.	Robert Peary reaches the North Pole, Bleriot flies across the English Channel and Bakelite is patented.
1911	The magnitude of a star and its mass are related together by Jakob Halm.	The first escalator is installed at Earls Court Underground Station in London.
1913	The Harvard Classification of stars is accepted as standard. Enjar Hertzsprung uses cepheid variables to estimate stellar distances.	Henry Ford introduces the first true production line.
1914	Arthur Eddington asserts that spiral nebulae are galaxies.	Robert Goddard starts investigating rockets. Ernest Rutherford discovers the proton.
1915	Investigations by Walter Adams on the very high surface temperature of Sirius B indicates it is a white dwarf.	Pyrex glass is produced by Corning Glass. Fokker introduce a fighter aircraft with a synchronised machine gun firing through the propeller.
1916	Edward Barnard discovers a star, Barnard's star, with a very large proper motion.	
1917	George Hale installs a 2.5-m refracting telescope. Karl Schwarzild predicts the existence of black holes.	Freezing food for preservation is developed by Clarence Birdseye.
1918	World War I ends	
1919	Observation of the solar eclipse, clearly photographed, demonstrate that Einstein's theory of gravity is correct.	
1920	Albert Michelson manages to measure the diameter of a star, Betelgeuse (Alpha Orionis), by interferometry.	The existence of an uncharged particle, the neutron, is suggested by William Harkins.
1921	Variation in the temperature of the Sun is described by Edward Milne.	R.U.R. by Karel Capek is published, introducing the Czech word robot into the language.
1923	Hermann Oberth suggests that a space-based telescope would avoid atmospheric distortion.	
1924	Arthur Eddington ventures the explanation that white dwarfs are made from matter in which the electrons have collapsed. Edwin Hubble shows that galaxies are independent structures made up of stars. Hermann Oberth describes the concept of escape velocity.	
1926	Robert Goddard launches the first liquid fuelled rocket. At 97 km/h and a maximum altitude of 56 m, it is a start.	

Date	Astronomical	General
1927	Georges Lemaitre suggests that the universe started from a cataclysmic explosion of a concentrated "egg" of matter. This is a precursor to the idea of the Big Bang.	Charles Lindbergh flies solo across the Atlantic without stopping. Werner Heisenberg postulates the Uncertainty Principle.
1929	Using Cepheid variables, Edwin Hubble calculates the distance to the Andromeda nebula. He also determines that the further a galaxy is, the faster it is moving away from the Earth. Robert Goddard launches a rocket carrying a barometer, thermometer and camera.	
1930	The coronagraph is invented by Bernard Lyot. Bernhard Schmidt corrects for coma, making Schmidt telescopes invaluable tools. Clyde Tombaugh discovers Pluto.	
1932	Carbon dioxide is discovered in the atmosphere of Venus.	
1933		The last known Tasmanian Wolf dies in captivity.
1934	Zwicky and Baade suggest that stars greater than 1.4 times the mass of the Sun will collapse to become neutron stars. Below this mass they can become white dwarfs.	Wernher von Braun launches a liquid fuelled rocket to 2.4 km altitude.
1936		The first scheduled television broadcasts begin in the UK.
1937	Fritz Zwicky uses a Schmidt camera to discover three supernovas.	The first jet engine is produced by Frank Whittle
1938	Hans Bethe and Carl Weizsacker independently propose stars produce energy from nuclear fusion.	A living Coelacanth is captured in the Indian Ocean. Lazlo Biro invents the ball point pen.
1939	Comparison of photographs taken over 30 years shows the Crab Nebula to be expanding.	German forces invade Poland and World War II commences.
1942	The first radio maps of the galaxy are made including individual sources.	
1944	It is discovered that Titan has an atmosphere.	Avery, MacLeod and McCarty demonstrate that the molecule of heredity is DNA.
1946	A V2 rocket is used to carry a spectrograph to study the Sun.	Willard Libby describes carbon dating. First meeting of the United nations.
1947	Lyman Spitzer suggests that space borne orbital telescopes could aid astronomy.	

Date	Astronomical	General
1948	The Hale 5-m reflector is finished at Palomar. Gamow, Alpher and Herman put forward the Big Bang idea for the origin of the universe.	Velcro is invented.
1949	Rocket testing starts at Cape Canaveral in Florida. A captured V2 rocket is launched from White Sands and reaches 400 km using a two stage system for the first time.	
1950	Jan Oort suggests that comets originate from a cloud of material beyond the orbit of Pluto.	
1952	Rudolph Minkowski and Walter Baade are first to relate radio sources to optically observable stars, including Cygnus A.	Josef Stalin dies.
1953	Measurements of the magnetic field of the Sun are made by Harold Babcock.	Watson and Crick determine the structure of DNA. Queen Elizabeth II is crowned. Everest is climbed.
1956	Herbert Friedman demonstrates solar flares to be X-ray sources.	Tjio and Levan show the normal human chromosome number to be 46.
1957	Sputnik I is launched by the Soviet Union. Sputnik II launches later in the year, carrying the first animal into space, Laika, a dog.	
1958	Eugene Parker demonstrates the solar wind. America launches its first orbital satellite. NASA is formally inaugurated.	
1960	Frank Drake attempts to find extraterrestrial life.	Theodore Maiman constructs the first ruby LASER (acronym).
1961	Yuri Gagarin is the first human to orbit the Earth.	
1962	John Glenn is the first American to orbit the Earth, taking the first pictures from space of the Earth. The radio source 3C273 was pinpointed in 1962 when it was occulted by the Moon. Photographs taken using the Hale telescope at Mount Palomar associated the optical image with unusual absorption lines with the quasi-stellar radio source.	
1963	Maarten Schmidt demonstrated the absorption lines of 3C273 were massively redshifted, indicating a huge recession velocity.	

Date	Astronomical	General
1964	The Kit Peak reflecting telescope of 213 cm becomes operational.	Peter Higgs suggests the existence of a particle that comes to be known as the Higgs boson.
1965	It is discovered that the rotation of Venus is opposite that of the Earth, the Sun rising in the west and setting in the east.	
1966	Lunar Orbiter I sends back detailed photographs of the lunar surface, even though one of its cameras fails. The Orbiting Astronomical Observatory is launched by NASA.	
1967	A bright nova is discovered by British amateur astronomer, George Alcock. Jocelyn Bell discovers the first pulsar, CP1919.	
1968	George Alcock finds another nova. NASA puts forward a plan for a Large Orbital Telescope, which will become Hubble.	
1969	The first visible star is found associated with a pulsar in the crab nebula. Celestron introduces a set of six Schmidt-Cassgrain telescopes for amateur use.	
1970	A 224-cm reflector is installed at Mauna Kea, Hawaii.	
1974	The 13th moon of Jupiter is discovered Charles Kowal. It is called Leda.	
1975	Kowal discovers a 14th moon of Jupiter.	
1976	A 6-m reflector at Mount Semirodriki in the Soviet Union is installed.	The Anglo-French Concorde begins a scheduled supersonic service, only 73 years after the first flight of *Flyer*.
1979	Work starts on the mirror for the Hubble Space Telescope.	
1981	*Columbia* is launched as the first reusable space vehicle.	
1983	The Large Orbital Telescope is formally renamed Hubble.	
1984	The European Southern Observatory in Chile reports a partial ring around Neptune. This had been suggested in 1981 when Neptune had been viewed passing in front of a star.	
1985	The Kek telescope in Hawaii is started. During an eclipse of Pluto by Charon, the diameter of the Pluto is determined at less than 3000 km.	

Date	Astronomical	General
1986	Space Shuttle Challenger explodes shortly after launch killing all on board.	
1988	The atmosphere of Pluto is directly observed for the first time.	
1990	Hubble Space Telescope is launched.	
1993	Corrective optics (COSTAR) are attached to Hubble, finally providing clear images.	
2008	The first image of an exoplanet, Formhault b, is published.	

During the second half of the 20th century, much development was made in X-ray and cosmic ray imaging of distant galaxies. The launch of the space telescope Hubble had started a renaissance in optical astronomy. Images taken from above the atmosphere have captured the public imagination and helped secure continuing funding for large telescope projects ever since.

Chapter 11
People in the Text

Abbe, Ernst (1840–1905) Born in Eisenach, Germany, Abbe became professor of physics at Jena in 1870 and director of the astronomical and meteorological observatories in 1878. He was partnered with Zeiss and took over responsibility for the company in 1888. He produced the Abbe condenser and the achromatic microscope lens in 1886.

Al-Battani (858–929) Little is known of his life, other than that he was born in Upper Mesopotamia, now in Turkey. He lived and worked for most of his life in Raqqa, Syria. One of his many successes was determining the length of the solar year.

Al-Farghani (c800–870) Little is known of the life of Al-Farghani before he became astronomer at the court of Baghdad. One of his achievements was calculating the diameter of the Earth.

Allen, Lew (1925–2010) Born in Miami, Lew studied at the United States Military Academy, West Point. He had a distinguished career in the armed forces until 1982. In that year, he took over the Jet Propulsion Laboratory as Director, where he stayed until 1990.

Antoniadi, Eugene Michel (1870–1944) Born in Constantinople (now Istanbul) by Greek parents, he is thought to have trained as an architect before turning to astronomy. He moved to France, when he was invited to join the private Camille Flammarion Observatory. He was an astute and accurate observer of Mars. Originally a supporter of Martian canals, after viewing Mars at the 1909 opposition, he concluded they were an optical illusion. Craters on both Mars and the Moon are named in his honour. He was also very accomplished international chess player and wrote a book in Greek on the architecture of Hagia Sophia in Istanbul.

Apollonius (260–190 BC) Born in Perga, Apollonius was a student in Alexandria and then taught there. One of his surviving books, *Conic Sections*, gave us the modern definitions of parabola, ellipse and hyperbola.

Archimedes (287–212 BC) Born in Syracuse, Sicily, Archimedes is regarded as Greek. He was a member of a wealthy family and studied in Alexandria before returning to Sicily. When the Romans finally took the city in 212 BC, Archimedes

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was killed. In his lifetime, he devised mathematical methods to determine areas and volumes of solids using geometry. He is widely thought of as the greatest mathematician of the ancient world and one of the greatest of any age.

Aristarchus (320–250 BC) Little is known of the life of Aristarchus. What we do know is that he proposed a heliocentric system and attempted to measure the distances of the Sun and moon by practical geometry. He reasoned that when the Moon was halfway through its cycle, it must form a right angle between the Earth and the Sun. The result was very inaccurate but regarded as significant by its method.

Aristotle (384–322 BC) Born in Stagira, northern Greece, he was the son of a doctor and a member of Plato's academy. Philip of Macedonia invited Aristotle to be tutor to his son Alexander. He retired to Euboea in 323 BC.

Arrest, Heinrich Louis d' (1822–1875) Born in and going on to study in Berlin, he was instrumental in discovering Neptune. Later, he worked at Leipzig Observatory, where he was an accurate and prolific observer of the skies. Asteroid 9133 d'Arrest, a crater on Phobos, and crater D'Arrest on the Moon are both named in his honour.

Aubert, Alexander (1730–1805) Born in London to wealthy parents, he was educated in Geneva. He returned to London in 1751. A year later, he became a partner in his father's company. In 1753, he became director of the company and late Govenor of the London Assurance Company. He was elected Fellow of the Royal Society in 1772. He built a private observatory that was wonderfully equipped.

Ayscough James (d. 1759) An optician and instrument maker who became famous for his microscopes. Little is known of his life. He made tinted spectacle lenses for some eye conditions. He married a woman named Martha, who was the subject of a legal case regarding achromatic lenses after the death of James.

Babcock, Horace (1912–2003) Born in Pasadena, Horace was an only child. He developed an early interest in astronomy. During World War II, he was engaged in radiation work at MIT and Caltech. From 1964 to 1978, he was director of Palomar Observatory. He also worked at Lick Observatory. He was a keen sailor of his own sail boat. Married twice, he had three children.

Badovere, Jacques (1575–1620) Sometimes called Giacomo Badoer, he had Venetian parents but was born in France and had a Huguenot upbringing. He converted to Catholicism and became a diplomat in the pay of Henry IV of France. He was reputedly homosexual, which resulted in him being the butt of many ribald poems.

Bass, George (1700s) Very little is known about George Bass, even though he is credited with the grinding of the first achromatic lens, although it was not his design. He worked in London around the middle of the 18th century.

Bayes, Thomas (1701–1761) The exact place of his birth is unknown, but we do know that in 1719 he went to the University of Edinburgh. On his return in 1722, he helped his father in his parish duties. In 1734, he moved to Kent and his own parish, where he was minister until 1752. He was elected Fellow of the Royal Society in 1742. His developing ideas of probability are what he is best remembered for.

Beer, Wilhelm (1797–1850) After making a considerable fortune as a banker, he built his own observatory with a 9.5-cm refractor in Berlin. His interest in astronomy led him, in conjunction with Madler, to map the Moon with great accuracy. There are craters on both the Moon and Mars called Beer in his honour.

Beg, Ulugh (1394–1449) This is the common name for Mīrzā Muhammad Tāraghay bin Shāhrukh, grandson of Timur (himself sometimes known as Tamerlane). Ulugh Beg was born in Persia and after the death of Timur settled in Smarkand, when at the age of 16 he became governor. He set about turning Samarkand into a scientific and cultural centre, to which end he had built the famous observatory. After the death of his father, he became involved in many wars and skirmishes until his eldest son ordered his beheading. |His remains were later interred in Samarkand with his grandfather, Timur.

Berkowski, Johan Julius Friedrich (1800s) There is some doubt as to the first names of Berkowski. Although he succeeded in taking the first coronal photograph of the Sun, he remains an unknown figure other than as a daguerreotype user local to Konigsberg Observatory.

Bevis, John (1695–1771) An English doctor who graduated from Oxford in 1715. In 1731, he discovered the Crab Nebula. In 1737, he observed an occultation by Venus of Mercury. In 1757, he published *The History and Philosophy of Earthquakes* and was elected Fellow of the Royal Society in 1765.

Bird, John (1709–1776) Born in Bishop, Auckland, he worked in London, starting his own business in 1745 in the Strand, London. He specialized in mathematical instruments and wrote two treatises on the subject—*The Method of Dividing Mathematical Instruments* (1767) and *The Method of Constructing Mural Quadrants* (1768). Bird also produced two standard yards (0.9144 m), an old imperial measure of length, one in 1758 and one in 1760. These were both destroyed in a fire at the Houses of Parliament in 1834.

Boyle, Robert (1627–1691) Born in Ireland, he was the youngest of 14 children of the Earl of Cork. He was tutored at home and the Eton. As a child, he was good at languages and algebra. He travelled widely in Europe and studied the works of Galileo. In 1654, he moved to Oxford and demonstrated Galileo's assertion that all objects fall at the same rate in a vacuum. Later, he demonstrated the direct relationship of air pressure to volume; this was the basis of his 1660 publication that we know as Boyle's law. He also founded the science of chemistry by putting to one side alchemical doctrines based on Aristotle's ideas of four elements. Boyle was a founder member of the Royal Society.

Brahe, Tycho (1546–1601) Tycho was a Danish nobleman born on Scania, the oldest of 12 siblings. At the age of 12, he joined the University of Copenhagen. In 1566, he went to Rostock University, where he lost part of his nose in a duel. He was forced to wear a prosthetic nose for the rest of his life. After a short urinary illness, he died and was buried in Prague. The nature of his sudden demise caused rumours of him having been poisoned. An exhumation in 1901 and further chemical analyses of samples in 2010, reported in 2012 showed that there was no basis for such claims. The lunar crater *Tycho* is named in his honour, as is the crater *Tycho Brahe* on Mars and the minor planet 1677 Tycho Brahe in the asteroid belt. The bright supernova SN 1572 is sometimes referred to as *Tycho's Nova.*

Braun, Wernher von (1912–1977) Born in Wirsitz, Germany to a titled family, Wernher developed an early interest in astronomy. He was also an accomplished pianist. From the age of 12, he attended boarding school. In 1930, he went to the *Technische Hochschule* in Berlin, where he developed a practical as well as a theoretical knowledge of rocketry. From there he attended Friedrich-Wilhelm University, also in Berlin, for postgraduate work. Although he was a Nazi party member, it is reported that his relationship was rather ambivalent. He immigrated to the USA in 1945 and continued his work on rockets for the military, moving to the newly formed NASA as first director of the Marshall Flight Centre. In 1972, he moved to work for Fairchild Industries. In 1947, he married a woman named Maria, with whom he had three children. He took USA citizenship in 1955.

Brearley, Harry (1871–1948) Born in Sheffield, he was the son of a steel worker of modest means. Harry left school at the age of 12 and became a steel worker himself. Later, he became an assistant in the company's chemical laboratory. He gained a reputation as a clear thinker and educated himself in the details of chemical analysis and metallurgy. In 1895, he married Theresa Crank, and when two steel companies set up the joint Brown Frith Research Laboratory Brearley led the group. It was here in 1913 that stainless steel was first produced as a result of looking for steels that could be used to line gun barrels and reduce the excessive wear associated with the high temperatures and pressures.

Brewster, Sir David (1781–1868) Born in Scotland, his father was a well-regarded teacher. David was the third child of six. At the age of 12 he enrolled at the University of Edinburgh, intending to join the clergy as a minister in the Church of Scotland. Although he became a licensed preacher, he was sidetracked and instead studied optics. In 1815, he invented the kaleidoscope, which made him well known to the general public. He was also elected to the Royal Society. He married his first wife Juliet Macpherson in 1810, with whom he had five children. In 1857 he married again, to Jane Purnell.

Burton, Charles Edward (1846–1882) Born in Cheshire of Irish parents, he had continuous poor health. Little else is known of his childhood. His astronomical interests started early, and by 15 he was experimenting with astrophotography. In 1864, the family moved back to Ireland, and in 1868, he graduated from Trinity College Dublin. He was appointed as assistant astronomer to Earl Rosse and learned to grind and polish reflectors, some of which were silvered glass. His ill health curtailed his employment in 1869, but he continued his observations of the night sky and astrophotography.

Busch, August Ludwig (1804–1855) Little is known of his life other than that he was the Director of Konigsberg Observatory and commissioned Berkowski to take a photograph of the 1851 eclipse. He was not present when the image was taken.

Calder, Nigel (1931–2014) Born into a titled family, his father was Lord Ritchie-Calder. Nigel went to Sidney Susssex College, Cambridge. He wrote for and edited *New Scientist* magazine from 1962 to 1966, after which he specialized in popular science, most specifically physics and astronomy. He was married and had two children.

Campani, Giuseppe (1635–1715) Little is known of Campani's life outside of his professional work. He was born in Umbria but at some point moved to Rome, where he started making lenses. He and his brother specialized in making long focal length lenses of high quality suitable for the then popular aerial telescopes.

Caravaggi, Cesare (1600s) Virtually nothing is known of Caravaggi other than his optical work, and that only from transient mentions in correspondences between Gallileo and his contemporaries.

Cassini, Giovanni Domenico (1625–1712) Originally Italian, Cassini became a naturalised French citizen. He was born in Perinaldo, northern Italy. In 1645, he was offered a post at the new Panzano observatory, where he also spent considerable time on astrological matters, a subject he dropped in later years. In 1661, he moved to Paris to help set up the Paris Observatory.

Cesi, Frederico (1585–1630) Born in Rome, he was the first of 11 male siblings. In 1614, he married a woman named Artemesia, who died 2 years later. In 1616 he remarried to a woman named Salviata. In 1618, he moved to Acquasparta and lived there until his death. At the age of 18, he invited friends to join him in founding the *Accademia dei Lincei*, Academy of the Lynxes, which was an important learned society.

Chance Brothers, Robert Lucas (1782–1685) and William (1788–1856) Robert bought the British Crown Glass Works in Birmingham in 1824. In 1832, it ran into financial difficulties and was helped by brother William, an iron merchant in Birmingham. In 1836, it became a formal partnership, Chance Brothers. The company glazed the Crystal Palace for the Great Exhibition of 1851 and the Houses of Parliament. Chance Brothers was the only company capable of making the opal glass for the four faces of the Parliament clock tower, which houses Big Ben. They also made the ornamental windows for the White House in the USA.

Charles II (1630–1685) The oldest son of Charles I. He lived in turbulent times; the English civil war was not to be resolved until he returned from exile, entering London in 1660. It was in November 1660 that the Royal Society was founded. In 1666, the Great Fire of London destroyed much of the city. Charles II died without legitimate issue, although he acknowledged many illegitimate offspring.

Clairaut, Alexis Claude (1713–1765) Born in Paris, Clairaut was a gifted mathematician, studying calculus at the age of 10. His mathematical researches were detailed and wide ranging, though it is said they suffered from his excessive socialising. He was elected a Fellow of the Riyal Society in 1737.

Clark, Alvan (1804–1887) Born in Massachusetts, he came from a line of Cape Cod whalers. He was a portrait painter and engraver, but at the age of 40 he became interested in telescopes. He started by polishing blanks from Chance Brothers in Birmingham and Mantois in Paris. His company, which included his son Alvan Graham Clark, made many very large refractors in the 19th century. There are Clark craters on the Moon and Mars named in his honour.

Common, Andrew Ainslie (1841–1903) Born in Newcastle. His father, a noted surgeon, died when Andrew was a child. He worked for most of his life in sanitary engineering and equipment, but ever since his childhood he had an abiding interest in astronomy. He was married in 1867. He also designed sighting devices for the Royal Navy and Infantry.

Cook, James (1728–1779) Born in Yorkshire, James was the second of eight siblings. At the age of 16 he moved to Staithes as apprentice to a grocer and haberdasher. This position lasted 18 months, at which point he moved to Whitby, where he became a merchant navy apprentice. In this position, he spent several years on coastal traders delivering coal from Yorkshire to London. He spent some years on other merchant fleets and in 1755 volunteered for the Navy. He married Elizabeth Batts in 1762 and had six children. None of the children had offspring before dying, so there are no direct descendants of James Cook.

Copernicus, Nicolaus (1473–1543) Copernicus was born in Poland and studied mathematics and medicine both there and in Italy. Most of his life was spent as a canon at Frauenberg Cathedral, mainly involved in administration. He was not a great observer and worked mainly from other works by other astronomers, but showed that mathematically a heliocentric cosmology fit the observations better than a geocentric one. His published description of this was published in *De evolutionibus orbium coelestium*, The Revolution of the Heavenly Spheres, completed in 1530 but not published until 1543.

Cox, John (1600s) Little is known of John Cox other than that he was a well thought of spectacle maker in London. He is referred to as having been contracted to make mirrors on two occasions when the finished surface was regarded as inadequate.

Daguerre, Louis (1787–1851) Born in France, he was apprenticed to a panoramic painter, Pierre Prevost. He was an accomplished theatre designer. In 1829, Daguerre joined Niepce, who had a basic system of photography. When Niepce died in 1833, Daguerre continued developing the technique, which became the daguerreotype. The technique was bought by the French government in exchange for a lifetime pension. The government then made it available to everyone by publishing the method. Daguerre has his name inscribed on the base of the Eiffel Tower—one of 72 names.

Defoe, Daniel (1660–1731) Originally Daniel Foe, he was born in London of Presbyterian Dissenter parents and educated locally before being educated at a boarding school in Surrey. He was married for 50 years and had eight children He worked as a merchant for many years and was also embroiled in politics, narrowly avoiding prosecution after the ill-fated Monmouth rebellion of 1685. In 1703, he was held in a pillory for 3 days and then taken to Newgate Prison, finally being released. He wrote many satirical and political pamphlets and tracts that are among the very first examples of journalism, although he is now primarily remembered for his full-length books. He is buried in Islington, London.

Demisiani, Giovani (?–1614) Born at Zakynthos, Greece, Demisiani was mathematician to Cardinal Gonzaga. He was a member of the *Accademia dei Lincei*, Academy of the Lynxes, and is best known for his coining of the word "telescope".

Digby, Sir Kenelm (1603–1665) Born in Buckinghamshire to a wealthy family. His Catholic background coloured his career. He went to Oxford at 15 but did not complete a degree. He was, however awarded a degree from Cambridge University very much later in his life. The range of his interests can be measured from him being granted a monopoly in sealing wax, writing books on philosophy, and improving the manufacture of wine bottles. He was imprisoned for his belief and lived for a time in exile. He was a founding member of the Royal Society and was a keen investigator of astrology and alchemy.

Dollond, John (1707–1761) John Dollond was the son of a Huguenot refugee silk weaver. He was born in Spitalfields, London, and followed his father as a silk weaver. He was elected Fellow of the Royal Society based on his detailed experiments in optics and construction of lenses. In 1752, he joined his son Peter making optical instruments. The business they started became Dollond and Aitchison, Opticians, which survived for 250 years before being absorbed into a chain of high street chemists.

Dollond, Peter (1731–1820) The son of the silk weaver John Dollond, Peter originally worked with his father as a silk weaver. In 1750 he quit the business and opened an optical instrument shop in London. Two years later, he was joined by his father. The Dollond company was recognised as producing the highest quality optical instruments, both on the basis of its optics and its mechanics.

Draper, John William (1811–1882) Born in Lancashire, the only boy of four siblings, he was home tutored until 1822, when he went to school, and then had another spell being home tutored until he went to University College London in 1829 to study chemistry. In 1831 he married Antonia, a Brazilian of Portuguese parents. Upon his father's death, the family moved to the USA and eventually settled in New York. There he helped found the New York University Medical School, where he was professor of chemistry. He was the first president of the American Chemical Society.

Dreyer, John Louis Emil (1852–1926) Dreyer was born in Copenhagen but took British citizenship in 1885. At 14 he became interested in astronomy and was a regular visitor to Copenhagen Observatory. He was educated in Copenhagen but in 1874 moved to Ireland to act as assistant to Lord Rosse at his observatory. In 1878, he moved to Trinity College Observatory, where he worked with R. S. Ball, and in 1882 he moved to Armagh Observatory as Director. He was married and in 1916 moved with his wife to Oxford. There is a crater on the far side of the Moon named in his honour.

Edward I (1239–1307) Eldest son of Henry III and Eleanor of Provence. In 1254, he married Eleanor of Castile. His son was Edward II.

Elmer, Charles Wesley (1872–1954) Born in New York, Elmer was a keen astronomer but was employed as a court reporter. In 1936 he met Richard Perkin, and they started Perkin Elmer.

Eratosthenes (270–190 BC) Educated in Athens, Eratosthenes became chief librarian at Alexandria. He was an astronomer and polymath, devising a method of separating prime numbers from composites. He became blind and when unable to read committed suicide.

Eudoxus of Cnidus (390–337 BC) All of his work has been lost, but there are reported fragments and many references to his work in later works. He was Greek and studied under Plato. He is widely acknowledged as second only to Archimedes as a mathematician.

Euler, Leonhard (1707–1783) Born in Basel, Leonhard was one of four siblings. He enrolled at University of Basel at the age of 13. He wrote a dissertation for which he was awarded a Master of Philosophy degree in 1723. He was obviously a talented mathematician, but was encouraged to study theology with a view of joining the priesthood. He moved to St. Petersburg and joined the Academy of Saint Petersburg as a mathematician. In 1734, he married Katharina Gsell and fathered 13 children, only five of which survived childhood. He worked in all areas of mathematics and is unique in having two numbers directly associated with his name, e (2.7182) and γ (gamma) (0.57721).

Flamsteed, John (1646–1719) Flamsteed was largely self-taught due to persistent ill health in his youth. It was not until 1670 that he entered Cambridge University. By 1675, Charles II had appointed Flamsteed as Astronomer Royal. He spent much of the rest of his life tackling the problem of accurate determination of longitude. His star charts contained almost 3000 stars and was published posthumously.

Forbes, George (1849–1936) Born in Edinburgh, George was the second son of Professor Forbes of St. Andrew's University. George went to St. Andrew's University and then Cambridge University. In 1873 he was appointed Professor at Anderson's University, Glasgow. He gave up this academic post and moved south, where he was instrumental in creating an electrified London Underground. In 1874, he was the lead astronomer in Hawaii for the transit of Venus. He predicted the existence of a trans-Neptunian planet 50 years before the discovery of Pluto. In 1887, he was elected Fellow of the Royal Society. In later years he became reclusive and died in an accident at home at Worthing.

Foucault, Leon (1819–1868) Born in Paris, the son of a Paris bookseller, he became a physicist at the Paris Observatory in 1855 and a Fellow of the Royal Society in 1864. He not only measured the speed of light but also demonstrated that it was lower in water than in air. In 1850, he used a pendulum to demonstrate the rotation of the Earth. He publicly demonstrated this in 1852 with a pendulum of 67-m length and a weight of 28 kg. This was hung in the dome of the Pantheon in Paris. It was the first direct demonstration of the Earth's rotation. Also in 1852, he invented the gyroscope.

Frederik VI (1768–1839) Frederik was King of Denmark from 1808 to 1839 and King of Norway from 1808 to 1814. He was a patron of astronomy, offering a gold medal to any astronomer discovering a new comet using a telescope. He was an ally of Napoleon, having been neutral until the bombardment of Copenhagen in 1807.

Galilei, Galileo (1564–1642) Born in Pisa, the son of a musician, Galileo studied music before moving to mathematics and physics. He took up a position of professor of mathematics at Pisa when he was 25. In 1591 he moved to Padua. Although as far as we know he never married, when he was 35 a Venetian girl, Marina Gamba, moved in with him. There were three children, two girls and a boy, but when he moved to Florence in 1610 they were left behind, Marina marrying soon afterwards. Coming into direct conflict with the Papal authorities, Galileo was at the age of 69 sentenced to house arrest. His life is filled with inventions and mathematical works of fundamental importance.

George III (1738–1820) Born in London, he was King of Great Britain from 1760 until his death. He had a long reign and life, despite repeated bouts of mental illness, sometimes suggested to be due to porphyria. In 1810, a regency was established after a final relapse. His son became regent until his father's death, when he became George IV. The reign of George III covered a period of immense scientific development, with the agricultural and industrial revolution starting in his reign, as well as the American war of independence (and look at what happened there!).

Glen, John Herschel (1921–2016) Born in Ohio, Glenn was fascinated by flying from an early age. He studied engineering but did not graduate. He had a long career flying fast jets before joining NASA. After leaving NASA he became politically active as a USA senator. In 1998, he became the oldest shuttle crew member at the age of 77. He married Anna Castor in 1943 and had two children.

Goddard, Robert Hutchings (1882–1945) Born in Massachusetts, Goddard became interested in science and engineering, through his reading as he was a child dogged by poor health. He was encouraged in his scientific investigations by his father. After school, where he did well despite long childhood absences, he enrolled in Worcester Polytechnic Institute and gained a degree in physics. He then moved to Clark University where he gained an MA in physics in 1910 and a PhD in 1911. He spent most of his career studying and designing rockets, including the first liquid fuelled rocket. In 1924 he married Esther Kisk.

Green, Nathaniel Everett (1823–1899) Born in Bristol, Green was an artist who at one point taught art to the Royal household, including Victoria. He was interested in astronomy and produced pencil drawings of Mars. He was also the first to suggest that the Martian canals were an optical illusion.

Gregory, David (1661–1708) Born in Aberdeen, David was the fourth of 15 children. He was the nephew of astronomer James Gregory. The family left Scotland to escape the threat of religious persecution. David graduated from Edinburgh University in 1683, where he immediately took up a position teaching mathematics. He was selected Fellow of the Royal Society in 1692 and in 1695 published *Catoptricae et Dioptricae Sphaericae Elementa* in which he addressed chromatic error and the possibility of its control using achromatic lenses. He was appointed to reorganise the Scottish mint after the Act of Union in 1707.

Gregory, James (1638–1675) The youngest of three children, Gregory was born in Drumoak, Scotland. He was originally home-educated by his mother and then later by his older brother. He then went to Aberdeen Grammar School and afterwards travelled extensively in Europe. On his return in 1668, he was elected Fellow of the Royal Society. Later that same year he became professor of mathematics at St. Andrews University and then Edinburgh University. He died at 36 after a stroke while demonstrating the Moons of Jupiter to a group of his students.

Guinand, Pierre Louis (1748–1824) Borne in Switzerland, Guinand started work as a woodworker but devised a method of making flint glass. This was a great improvement on previously unreliable techniques.

Hadley, John (1682–1744) Born in Bloomsbury, London, Hadley was the son of a prosperous family with estates in Hertfordshire. In 1717 he was elected to the Royal Society in 1717 and in 1721 exhibited a reflecting telescope. there In 1729, he inherited his father's estates. The lunar features Mons Hadley and Rima Hadley are named after him.

Hall, Chester Moore (1703–1771) Born in Leigh, Essex, Moore Hall was primarily a lawyer. At the same time, he was an accomplished mathematician. It was his studies of the human eye which persuaded him that an achromatic lens could be constructed if the right glass could be found.

Harriot, Thomas (1560–1621) Born in Oxford, he graduated from St. Mary Hall, Oxford, then travelled to America as part of an expedition where his knowledge of the Algonquin language was invaluable. On his return to England, he became a prolific mathematician. The 1607 sighting of Halley's comet turned his attention to astronomy. He had a prolonged illness, possibly cancer, and died 3 days after he made his will.

Harrison, John (1693–1776) Born in Foulby, Yorkshire, his family moved to Lincolnshire when he was young. When he was older he joined his father as a carpenter, making clocks in his spare time. He built his first long case clock at 20, the entire mechanism as well as the case being made of wood. He became a well-known clock maker, introducing several innovations that improved time keeping. He finally moved to Holborn in London. He married twice and had one son.

Herschel, Frederick William (1738–1822) Born in Hanover as one of ten children, he moved to England with his parents, his father being a military musician. He quickly learnt English and adopted the Anglicised version of his name, Wilhelm. After moving back temporarily to Hanover, William returned to England and went to Sunderland to join the Newcastle Orchestra. During this period he wrote a great deal of music. It was through music that he met an astronomer who fired his imagination. From Newcastle, he went to Leeds and Halifax and then Bath. His sister came over to join him and his brother in 1772, living at an address in Bath, where he took up astronomy. In June 1785, they moved to Old Windsor and finally to Slough. He was appointed Court Astronomer and elected Fellow of the Royal Society.

Hevelius, Johannes (1611–1687) Johannes was born of German-speaking parents and learned Polish at an early age. His father was a brewer, and although Johannes studied jurisprudence, it was as a brewer that he made his living. He eventually joined the brewer's guild and became its leader. He was also a councillor and Mayor of Danzig. He built an observatory on the roof of three adjacent houses that he owned and described ten new constellations. He married Katherine Rebeschke, who died in 1662, and in 1663 he married Elizabeth Koopman.

Hipparchus (170–125 BC) Born in Nicaea, now in Turkey, little is known of the life of Hipparchus, and few of his writings survive other than those copied for use. These influenced later mathematicians. He is credited with inventing trigonometry and discovering the precession of the equinox. His was the first star catalogue.

Holliday, Clyde (1912–1982) Little is recorded of his early career. He was staff engineer at John Hopkins University Applied Physics Laboratory, and besides designing cameras for the very first high altitude rockets, in 1967 he processed the first full-colour whole Earth images from space. He was married to Lois and had three children.

Hooke, Robert (1635–1703) Born on the Isle of Wight, he moved to London in 1660 and in 1662 helped found the Royal Society. During the 1660s, he formulated what we now know as Hooke's law, dealing with the elastic limit of materials, and realised a spiral spring could control a clock, although it was Huygens who produced the first working model. In 1665 he published *Micrographia* describing the compound microscope and coined the use of the word "cell" in the biological sense. He was unrivalled as an improver of instruments, such as the microscope, barometer and telescope. Although he was greatly respected, it is said that his cantankerous nature made him difficult to deal with.

Hubble, Edwin Powell (1889–1953) Born in Missouri, he moved with his family to Illinois in 1900. Early on, he was regarded to be more athletic than academic. Despite being interested in astronomy from an early age, under the influence of his father he studied law at the University of Chicago and then as an early Rhodes Scholar spent 3 years at Queen's College Oxford studying jurisprudence. On his return to the USA he taught Spanish, physics and mathematics at a school in Indiana. After a year as a teacher he went to study astronomy at Yerkes Observatory, Chicago University, where in 1917 he gained a PhD. Having enlisted, he was sent to Europe but never saw action, and in 1918 he started a year at Cambridge University. In 1919 he was offered a staff position at Mount Wilson Observatory, where he stayed until his death.

Huggins, William (Sir) (1824–1910) Born in Middlesex, he married a woman named Margaret in 1875, who was also keen on astronomy. He built a private observatory in south London at Tulse Hill. He was the first to use dry plate technology, which was new at the time, for astrophotography. He worked with the chemist William Miller on analysing star spectra. He was elected to the Royal Society in 1865. He died after an operation for a hernia.

Huygens, Christian (1629–1695) Born in The Hague, Huygens was a member of a wealthy family. His original studies were in law, but he quickly turned to physics and mathematics. His influence was considerable; many regard him as the greatest mathematician of the 17th century after Newton. Besides his astronomical investigations correctly describing Saturn's rings in 1655, in 1656 he described the dynamics of colliding elastic bodies. Although Galileo had described the consistency of a simple pendulum, it was Huygens who described it accurately and constructed the first accurate pendulum clock, later creating a compound pendulum to improve accuracy and reliability. His greatest achievement came in 1678 when he expounded a wave theory of light, including refraction and the prediction that light travels slower in a denser medium.

Huygens, Constantijn (1628–1697) Born in The Hague, Constanijn was the elder brother of Christian. He took his name from his father, a renowned Dutch diplomat. He studied in Leiden and around 1650 helped his brother Christian with his early studies of telescopes. Constantijn was a skilled artist and an art connoisseur.

Ibn Rushd (1126–1198) Ibn Rushd's name is sometimes Latinised as Averoes. He was born in Cordoba to a family of public servants and legal experts. In 1160 he became Qadi (Judge) at Seville, and later worked in Cordoba and Seville. During his life he wrote on medicine, physics, astronomy and psychology. He also wrote commentaries on Aristotle and Plato.

Janssen, Zacharias (c 1585–1632) The exact dates of his life are unknown. He was born in The Hague and grew up in Middleberg. He married in 1610, and the family moved to Arnemuiden in 1618 when he was accused of counterfeiting. In 1619 he was again accused of counterfeiting, so they moved back to Middleberg in 1621. His first wife died in 1624 and in 1625 he remarried, a year later moving to Amsterdam and the centre of spectacle manufacturing.

Kepler, Johannes (1571–1630) Kepler was the son of a mercenary and had smallpox at the age of 3, which damaged his eyesight and his hands. He studied theology at Tubingen but was interested in mathematics. After Tubingen, he taught mathematics at the protestant seminary in Graz, Austria. Due to religious persecution of Protestants, he was forced out of his teaching position in 1600. At this point he joined Brahe in Prague. Being unable to fit the consistent observations with Copernican cosmology, he formulated his idea of elliptical orbits. He was also an active astrologer, happy to cast horoscopes.

King, Gregory (1648–1712) Born in Lichfield, Staffordshire, he assisted his father from an early age in his surveying work. At 14 years of age, he became a student of heraldry. In 1672 King moved to London, where he set up shop as an engraver and surveyor. Later in his career he was associated with new taxes on births, deaths and marriages. In 1696 he produced estimates of population and wealth, describing the population in demographic terms.

Klingenstierna, Samuel (1698–1765) A Swedish mathematician who started out as a lawyer, he gave lectures on mathematics while still a student and became Professor of Geometry at Uppsala University, becoming progressively more interested in physics. In 1756, he became tutor to the Swedish Crown Prince, later King Gustav III.

Lagrange, Joseph Louis (1736–1813) Lagrange was born in Turin to a French father and an Italian mother. The family was well off, but while Lagrange was still young most of the fortune was lost. He took to mathematics early and by 19 was a professor at the Royal Artillery School, Turin. In 1766, he moved to the Berlin Academy of Sciences as Director, taking over from Leonhard Euler, and in 1797 he moved to Paris. He married twice, his first wife dying at a young age. In his younger days he was a prolific worker but had more or less given up mathematics by the time he reached 50. He worked with Lavoisier on weights and measures, helping to develop a useable metric system.

Lamarck, Jean Baptiste (1736–1813) Born in Picardy, he was the 11th child of an aristocratic family that had fallen on hard times. In 1760 on his father's death, he joined the French army. Upon his return, he was awarded a small pension ad started studying medicine, supporting himself by working for a banker. This lasted 4 years, after which he gave it up to study botany. In 1778 he published his flora of France. Also in 1778 he married a woman named Marie Anne, who mothered several children before dying in 1792. In 1781 he became a Royal Botanist, which allowed him to travel widely overseas. He was put in charge of the Royal Gardens in 1788 and changed the name during the French Revolution to distance the gardens from the Royal family. In 1793 he married a woman named Charlotte, who died in 1797. In his later years, he became blind and at his death was very poor. We now remember Lamarck for his misinterpretation of evolution, but this does him a disservice. He was an astute observer and a recorder; much of his work was of both great importance and significance.

Leighton, Robert Benjamin (1919–1997) Born in Detroit, he moved with his family to California, where Leighton lived and worked most of his life. He started by studying electrical engineering, but after graduating moved into physics. He was renowned for his practical problem solving. He worked at Caltech for most of his career, becoming head of division from 1970 to 1975. He was married to a woman named Margaret and had two sons.

Lieberkhun, Johann Nathanael (1711–1756) Lieberkhun was born in Berlin and initially studied theology before moving towards physics and mechanics. He then moved into medicine. In 1739, he moved to Leiden and soon afterwards moved to London and Paris. Later he moved back to Berlin, where he worked as a medical practitioner while making mathematical and optical instruments. He is most famous for his histological preparations, created by injecting wax into cavities to make faithful reproductions. The crypts of Lieberkhun found in the mammalian gut are named after him.

Liebig, Justus Freiherr Von Liebig (1803–1873) Liebig's father made paints and varnishes, which may have encouraged Justus in his interest in chemistry. He went to school in Darmstadt from age 8 to 14. From there he worked for a short time as an apprentice to an apothecary, returning prematurely to work for his father for 2 years. He then went to the University of Bonn, after which he moved University of Erlangen. He left Erlangen in 1822, moving to Paris on a grant from the Hessian government. In 1824, Liebig went from Paris back to Erlangen and became professor of chemistry at the University of Giessen after many years of internal rivalry within the university. In 1826, he married a woman named Henriette and fathered five children. In 1852, he joined Ludwig Maximilian University, Munich, where he stayed for the remainder of his career.

Link, Goethe (1879–1981) Born in Pike County, Indiana, Goethe graduated from the Central College of Physicians and Surgeons, Indianapolis in 1902. He became a specialist surgeon developing innovative surgical techniques. He was one of the founders of Indiana University Medical School. He won the National Balloon Race in 1909. Besides an intense interest in astronomy, he was a keen observer of hummingbirds and snakes. He has an asteroid named in his honour.

Lippershey, Hans (1570–1619) Sometimes known as Johann Lipperhey, he is famed for the first patent on a telescope, although it is unclear if he actually made the first one. Lippershey was born in Wessel, Germany but in 1594 moved to Middleberg, Zeeland, where he became a citizen of The Netherlands in 1602.

Lowell, Percival (1855–1916) Percival was born into a wealthy Boston (USA) family. Having graduated from Harvard, he travelled extensively. His interest in astronomy was kindled by the report of Schiaparelli on the *canali* of Mars in 1877. He was convinced that Mars was inhabited by an intelligent species. His most important work was carried out at the observatory he had built in 1894, where he predicted the ninth solar planet, although he never actually found it (Pluto) himself.

Madler, Johan Heinrich von (1794–1874) Born and educated in Berlin, his father died when Johan was just 19, leaving him to support his three younger sisters. Acting as a tutor, he met Beer, a banker with a private observatory. In conjunction with Beer, they produced the first accurate maps of the Moon.

Maestlin, Michael (1550–1631) Born in Goppingen, Maestlin studied at Tubingen and by 1580 had taken up the position of professor of mathematics at Heidelberg. He later moved back to Tubingen, where he taught for many years. One of his students was Kepler.

Mann, James (1706–1756) An optician and instrument maker working in the area of St. Pauls, London. He made very expensive spectacle for the wealthy as well as optical instruments such as telescopes and microscopes.

Mantois, Edouard (1848–1900) Mantois was the inheritor of the glass technology of Pierre Guinand in 1887. He was related by marriage to Guinand. In 1900, the name of the company was changed to Parra-Mantois, which became one of the premier glass manufacturers at the beginning of the 20th century.

Marshall, George Catlett (1880–1959) Born in Pennsylvania, George graduated from Virginia academy and retained his association with the military throughout his life, first as a soldier and then as a statesman. He was responsible for the Marshall Plan for the restoration of post-war Europe and in 1953 was awarded the Nobel Peace Prize. He was married twice: his first wife, Elizabeth, died from complications of surgery. His second wife Katherine was a trained actress.

Maskelyne, Nevil (1732–1811) Born in London, Nevil was the third son of the family. His father died when Nevil was 12, leaving the family in reduced circumstances. He attended Westminster School and was still a pupil there when his mother died. It was at school that he developed his interest in astronomy. He went to St. Catharine's College, Cambridge in 1749. He was ordained in 1755 and was elected Fellow of the Royal Society in 1758. Although pursuing an ecclesiastical living, he worked extensively in astronomy and associated science. He was for example part of the team testing time pieces for the accurate calculation of longitude. In 1765 he was appointed Astronomer Royal.

Medici, Leopold de (1617–1675) Born in Florence as a member of an influential and powerful family, he was widely educated. In 1638 he founded *Accademia Platonica*. He was an avid collector of books, art, coins and statues. In 1667 he was appointed Cardinal by the Pope.

Mersenne, Marin (1588–1648) Mersenne was born of peasant stock in central France. His early education was at Le Mans. Later he went to Paris to study theology and philosophy and was ordained in 1613. Between 1614 and 1618 he taught theology and philosophy at Nevers in France, returning to Paris in 1620. In Paris, he studied mathematics and music and met such luminaries as Pascal, Hobbes and

Descartes, also corresponding with Galileo. He is regarded as a polymath for his wide ranging work in mathematics.

Messier, Charles (1730–1817) Born in Badonville, France as the tenth of 12 children, he was interested in astronomy from an early age. In 1751 he was employed by Joseph Delisle, the astronomer to the French navy. In 1764 he was elected Fellow of the Royal Society. He produced the now famous list of Messier objects still used in astronomy.

Metius, Jacob (1571–c1630) The exact year of Metius's death is unknown. He was born and died in Alkmaar. Little is known of his life other than his 1608 patent application for a telescope.

Miller, William Allen (1817–1870) Born in Ipswich, he went to Kings College, London, eventually becoming professor of chemistry. He married Eliza Forrest in 1842 and was elected Fellow of the Royal Society in 1845. He worked with William Huggins to understand the spectral lines of stars. The Miller crater on the Moon was named in his honour.

Moliere (1622–1673) Jean-Baptiste Poquelin assumed the stage name of Moliere, by which he is best known. He was born in Paris into prosperous family. At the age of 21 he abandoned his position and became an actor, spending 13 years in that profession with a short spell in prison for debt. All the while he was polishing his skills at comedy and writing. His satires were well received, except by moralists and the Catholic Church, as they were often attacks on the hypocrisy of that institution.

Newton, Isaac (1642–1727) Born in Lincolnshire, he was broadly raised by his grandmother after the death of his father and his mother's remarriage. He went to Trinity College, Cambridge in 1661, where he became professor of mathematics in 1669 at the age of 26 and FRS in 1672. After writing *The Principia* in 1687, he turned more towards theology and alchemy. His scientific exploits were extensive and served as a testament to his intuitive and penetrating scientific thought.

Nunes, Pedro (1502–1578) Born in Portugal, he was a gifted mathematician who spent his entire life on the Iberian Peninsula. He published his scientific works in Latin, Portuguese and Spanish. He is mainly known for his attention to applying mathematics to navigation. He studied at Salamanca and Lisbon, where he graduated in medicine, having also become proficient in mathematics, for which he became most recognised.

Nur ad Din al Bitruji (unknown–1204) The name is sometimes Latinised to Alpetragius. Little is known of his life. He was the first astronomer to propound a non-Ptolemaic Solar System.

Oberth, Hermann (1894–1989) Oberth was born in Hermannstadt, Austro-Hungary (now in Romania). At the age of 11 he became interested in rocketry but in 1912 started his academic career studying medicine in Munich. During World War I, he began as a member of the infantry but then moved to a medical unit while continuing his interest in rocketry. By 1917 he had designed liquid-fuelled rockets, although he did not make them. In 1918 he married Mathilde Hummet, with whom he had four children. In 1919, the family moved to Germany so he could study physics, but after much work, his doctoral thesis was rejected. From 1924 to 1938 he taught mathematics and physics. The family moved to Switzerland in 1948 and then Italy in 1950. During the 1950s and 1960s, he moved between Germany and the USA. He retired in 1962.

Oldenburg, Henry (1619–1677) Born in Bremen, Oldenburg studied theology and was also a scientist. He was a tutor in the UK before returning as a professional diplomat. He moved in intellectual circles, being a friend of Boyle and correspondent of Spinoza, and also meeting Milton. As first secretary of the Royal Society, he is credited with introducing peer review.

Osiander, Andreas (1498–1552) Born in Gunzenhausen, he studied at University of Ingolstadt. In 1520 he was ordained a priest and went to Nuremburg, where he taught as a Hebrew scholar. Osiander eventually moved to Konigsberg, where he taught until his death. His niece married the future Archbishop of Canterbury, Thomas Cranmer. In 1543, he oversaw the publication of *De revolutionibus orbium coelestium* by Copernicus.

Pannekoek, Antonie (1873–1960) Panekoek studied math and physics in Leiden and became a committed Marxist. He was both an active observer of the heavens, travelling long distances to view solar eclipses, and a theoretical cosmologist. He received many awards for his work on the structure of galaxies and the history of astronomy. He is immortalised by the naming of a lunar crater, Pannekoek, and an asteroid, 2378 Pannekoek, after him.

Parkinson, Cyril Northcote (1909–1993) Born in York, northern England he was educated there and at Cambridge University. He completed his PhD at Kings College, London, after which he became best known as a naval historian. He was married with two children. He is best known for Parkinson's Law. This was elaborated in a humourous article in *The Economist* in 1955. Parkinson is buried at Canterbury.

Pellepoix, Antoine Darquier de (1718–1802) Born in Toulouse, he spent most of his life there. He was an astronomer known for his observation of the Ring Nebula M57. In 1777, he published *Astronomiques Faites a Toulouse*, a description of his observations made between 1748 and 1773. He is well known for a considerable catalogue of stars that he recorded.

Percy, Henry (1566–1632) The Ninth Earl of Northumberland, born in Tynemouth Castle, Northumberland, son of Henry Percy, the eighth Earl of Northumberland. He succeeded to the title on the death of his father in the Tower of London, apparently a suicide as he was being interrogated. Percy was brought up as a Protestant; he had estates in the North and South of England. He had a great interest in science and communed with many friends, including Thomas Harriot, while he was held in the Tower of London, having been implicated in the Gunpowder Plot by the associations of his relatives. On his release from the tower, he retired to Petworth House, Sussex.

Percy, Thomas (1560–1605) An English Catholic, he was the fifth member of the Gunpowder Plot. He went to Cambridge University, Peterhouse, but other than that little is known of his early life. He married in 1591, but he became estranged from his wife soon afterwards. He was a distant cousin of Henry Percy, ninth Earl of Northumberland and was described as tall and imposing. He was killed in a siege of Holbeche House in Staffordshire by the Sheriff of Worcester, who was trying to arrest Percy on a warrant with a force of men.

Perkin, Rihard Scott (1906–1969) Perkin developed an early fascination with astronomy, grinding his own lenses and mirrors. He spent a year studying chemical engineering before leaving and going to work in finance on Wall Street. In the 1930s he met Charles Elmer, and in 1937 they started Perkin Elmer. The lunar crater Perkin is named in his honour.

Perrotin, Henri Joseph Anastase (1845–1904) Little is known of his early life. He became the first Director of Nice Observatory from 1884 until his death. The Perrotin crater on Mars is named in his memory. Working with Thollon, he reported seeing the canals of Mars.

Plato (427–347 BC) Plato was born in Athens and lived for most of his life in the city with only short periods of absence. As far as we can tell, all of the works of Plato have been preserved and make up a considerable body of knowledge. He was the originator of philosophy as we know it in the narrow sense, but in one of his dialogues, the *Timaeus*, he deals with the physical world.

Ptolemy, Claudius (90–170 BC) Ptolemy lived in Egypt at the time of Greek rule and took the name Claudius upon becoming a Greek citizen. Little is known of his life; all we know comes from his four books. *Almagest* covers astronomy as it was known at the time, *Geography* gives a method of determining latitude and longitude, *Optics* detailes reflection and refraction and *Tetrabiblios* is about astrology.

Raleigh, Sir Walter (1554–1618) Born in Devon. His father was also called Walter Raleigh. Although he was a landed gentleman, little is known of his early life. He rapidly rose in the court of Queen Elizabeth I and was knighted in 1585. He was instrumental in the colonisation of North America. In 1591, after a secret wedding he and his wife were incarcerated in the Tower of London. This was a short imprisonment, after which he retired to his estate in Dorset. On the death of Queen Elizabeth I in 1603, he was imprisoned in the Tower again charged with plotting against James I. He was released from this imprisonment in 1616, at which point he went to South America in charge of a force that ransacked a Spanish enclave. On his return to England in 1618, he was executed to appease the Spanish.

Ramsden, Jesse (1735–1800) Born in Halifax, Ramsden was taught mathematics by his uncle before becoming an apprentice cloth worker in Halifax. He moved to London and in 1758 took up an apprenticeship as a mathematical instrument worker. He was so good at this that in 1762 he opened his own workshop. In 1765, he married Sarah, the daughter of John Dollond. He was elected FRS in 1786.

Ravenscroft, George (1632–1683) A businessman, he was born the second of five children. His parents were Catholic, and he started training for the priesthood in France, although he never completed it. He lived in Venice for a while, where it is suggested he learned the basics of glass manufacturer. When he returned to England, he became a wealthy man from the import and export of glass, as well as being a glass manufacturer. He developed the means of making flint glass as a reliable alternative to crown glass, paving the way for achromatic lenses.

Reeves, Richard (1640–1680) Sometimes called Reeve, little is known of his early life. Once established as an optical instrument maker, he is mentioned by

Samuel Pepys, who bought a microscope from him. His son, also Richard, took over the business and ran it until the early 18th century.

Rew, Robert (1700s) A brass worker who was closely associated with the Spectacle Makers Guild and the attempt to break the patent on achromatic lenses held by John Dollond.

Rheticus, Joachim (1514–1574) Joachim was a pupil of Copernicus when he started developing his trigonometric tables. He was born in Feldkirch, Austria, to wealthy parents, his father being a physician. His father was executed in 1528 for the extensive theft of money and goods from his patients. In 1552, Rheticus was convicted of sodomy and exiled from Leipzig for 101 years. The lunar crater Rhaeticus is named after him.

Sarpi, Paolo (1552–1623) Born in Venice, he was educated first by a teacher who was also his maternal uncle and then by monks. He joined the order in 1566, after which he moved to a monastery in Mantua, where he studied mathematics and oriental languages. He found himself in such disputes with the Pope that an assassination attempt was made on him, from which he recovered. He spent the remainder of his days in cloisters, studying science and corresponding as advisor to the Venetian Republic.

Scarlett, Edward (1688–1743) Born in London, Scarlett was an independent optician and instrument maker. In 1727 he was credited with inventing spectacles with curved earpieces. Prior to that date, spectacles were often referred to as "temples", as the straight sides pressed against the side of the head.

Schiaparelli, Giovanni Virginio (1835–1910) Born in Piedmont, he was educated in Italy, Germany and Russia. For 40 years he was Director of the Observatory at Milan. He demonstrated the orbits of meteors and the southern polar cap of Mars. He also saw the *canali* of Mars, which became the observation he is most remembered for.

Schott, Otto (1851–1935) Otto Schott invented borosilicate glass. He started his career studying chemical technology in Aachen, then Wurzberg, Leipsig and Jena. In 1879, he developed his borosilicate glass. This led him in 1884 to join with Zeiss and Abbe to set up Schott & Associates Glass Technology Laboratory in Jena.

Short, James (1710–1768) Short was born in Edinburgh and at the age of 10 was orphaned. He was very good at school and went to University of Edinburgh to study divinity. He was inspired to transfer to astronomy and mathematics. He was elected Fellow of the Royal Society in 1737 on the basis of his high quality telescopes. He became a professional telescope maker and amassed a considerable fortune from his reflectors.

Smith, Addison (d. 1795) Little is known of his early years, but he was apprenticed to an optician, Francis Watkins, and in 1744 went on to become an independent maker of glasses. In 1783 he gained a patent for a spectacle design incorporating lift-up-and-fold-down lenses. That same year, he published *Visus Illustratus*, in which he defined the current problems with spectacles as they were made at the time.

Smith, Robert (1689–1768) He was probably born at Lea in Lincolnshire. He went to Trinity College Cambridge in 1708, becoming master in 1742, having already attained the status of professor of astronomy. In 1719 he was elected Fellow of the Royal Society. He never married and lived with his unmarried sister at the Lodge of Trinity College.

Snellius, Willebrord (1580–1626) This is the Latinised version of his name, Snell. A Dutch physicist, he studied mathematics at many different universities and in 1613 became professor of mathematics at Leiden University, taking over the position from his father.

Spitzer, Lyman (1914–1997) Born in Ohio, Spitzer studied at Yale and then Princeton, both for an MA (1937) and his PhD (1938). In 1968 Spitzer, along with Donald Morton, was the first mountaineer to climb Mount Thor in Canada. He was married to a woman named Doreen and had four children.

Steavenson, William Herbert (1894–1975) Born at Quenington in Gloucestershire, William was the son of a vicar. He was interested in astronomy from a very young age but studied medicine as a profession, becoming a surgeon. All through his life he was involved in astronomy, becoming an expert in the history of the Herschel family. He was unusual in the 20th century for being President of the Royal Astronomical Society as an amateur astronomer.

Steinheil, Karl August Von (1801–1870) Born in Alsace, he originally studied law at Erlangen and then astronomy and physics at Gottingen and Konigsberg. Between 132 and 1849, he was professor of mathematics at the University of Munich. In 1854, he founded A. Steinheil and Sohne, an optical company specialising in astronomical equipment, building telescopes and spectrophotometers. In 1862, his sons took over running the company.

Talbot, William Henry Fox (1800–1877) Born in Wiltshire at Lacock Abbey, William (later usually referred to as Henry Fox Talbot) attended Eton school and Trinity College Cambridge, where he excelled at classics. He wrote extensively on mathematics and optics before working on photography. He was Member of Parliament for Chippenham from 1832 to 1835 and in 1840 High Sheriff of Wiltshire. He was also a keen archaeologist, helping to decipher cuneiform inscriptions from Mesopotamia. He was married to a woman named Constance and had three daughters and a son.

Tasman, Abel Janszoon (1603–1659) Born in Lutjegast, The Netherlands, Tasman joined the Dutch East India Company in 1632 or 1633 as an explorer and sailor. He was chosen by van Diemen, Governor-General of the Dutch East Indies, to explore the Southern Hemisphere. He became the first European known to have reached Van Diemen's Land, later Tasmania, and New Zealand.

Thollon, Louis (1829–1887) Born in Ambronay, France, he joined the Nice Observatory in 1881. In 1882, he went on an expedition to Egypt to view the eclipse. Working with Perrotin, he reported seeing the canals of Mars.

Utzschneider, Joseph von (1763–1840) An able administrator and adviser to Maximilian IV of Bavaria. He spotted the gifted Fraunhofer and recruited him for his optical works. This was one of the many industrial concerns he set up—another was a leather factory. In 1835, he became director of the Munich Polytechnic Central School, which became the Technical University of Munich.

Van Diemen, Anthoonij (1593–1645) Born in Culemborg, The Netherlands, he moved in 1616 to Amsterdam. He set up as a merchant but was declared bankrupt. He then joined the Dutch East India Company and went to Batavia. By 1626 he was Director-General. In 1630 he married and in 1631 returned to The Netherlands. Later he returned to Batavia, now Jakarta, and in 1636 became Governor-General.

Von Neuman, John (1903–1957) Born in Budapest, which was then part of the Austro-Hungarian Empire. He was the eldest of three brothers. A child prodigy, he could divide two eight-digit numbers in his head at the age of 6. He did not start school until he was 10 years old but also had private tutors as well. He gained a PhD in mathematics in the same year he graduated with a degree in chemical engineering. In 1930, he married Mariette Kovesi. They had one child and divorced in 1937. In 1938, he married Klara Dan. In 1933, he was offered a permanent position at the Institute of Advanced Studies, Princeton, where he stayed for his entire career. Interestingly, he was both keen and very knowledgeable on ancient history.

Wallace, Alfred Russel (1823–1913) Wallace left school at 14 and became first a surveyor and then a teacher in Leicester. It was here that he developed a passion for collecting insects and butterflies. He went on an expedition in tropical South America, intending to finance the trip by selling his collection on his return. Unfortunately, a fire at sea destroyed not only his specimens but the ship as well. In 1854, he started on another expedition, this time to Malaya. It was here that he started writing his proposals on evolution and species. His work was published in tandem with Darwin's own in 1858, and there was a great friendship between the two scientists. He became an advocate of women's rights and spiritualism.

Watkins, Francis (1723–1791) Francis was the youngest of his siblings. He became an apprentice to Nathaniel Adams, a spectacle maker in 1737. On completion of his indenture, he became a well-respected and important maker of optical instruments.

Webb, James (1906–1992) Born in North Carolina, he went to the University of North Carolina, Chapel Hill, receiving an education degree in 1928. After military service, he returned to study law at George Washington University, receiving a law degree in 1936 and being submitted to the bar that same year. In 1938 he married Patsy Douglas, and they had two children. Webb worked for his entire career in public service and in 1961 became administrator of NASA, a position he held until 1968, just before the first manned Apollo flight.

Wedgwood, Josiah (1730–1795) Born in Staffordshire, Josiah was the 11th and youngest child of Thomas Wedgwood. By 9 years old, he was a skilled potter and became apprenticed to his older brother, also Thomas Wedgwood. After surviving childhood smallpox, he was left with a week leg and unable to sustain the potter's wheel, so he took to design and working with skilled potters. He is credited with the industrialisation of pottery manufacture. He was the fourth generation of Wedgwood potters and also a prominent anti-slavery abolitionist. He developed a pyrometer for temperature measurement and was elected to the Royal Society in 1783.

Wren, Sir Christopher (1632–1723) Born in Wiltshire, Wren was educated at Westminster School and Wadham College, Oxford, distinguishing himself in mathematics and physics. In 1657 he became Gresham Professor of Astronomy, returning to Oxford in 1661 as Professor of Astronomy. While in London, he was instrumental in laying the foundations for the Royal Society. He was architect for many of the great buildings of Oxford, such as the Sheldonian Theatre and parts of Trinity College. He was architect of St. Paul's Cathedral after the Great Fire of London in 1666. He built more than 50 other churches in London, the style of which is quite distinctive. His designs extend to many secular buildings, including libraries and museums.

Wyche, Peter (1593–1643) Born in Oxford, Peter was a merchant and Ambassador to the Ottoman Empire in Constantinople (now Istanbul) from 1627 to 1641. He was knighted in 1626, and in 1641 he became a privy councillor. It is reported that at one point, he lent Charles I £30,000.

Zeiss, Carl (1816–1888) Carl Zeiss was born in Weimar on September 11, 1816, the son of a toy shop proprietor. He became apprentice to Friedrick Korner, *Hofmechanikus*, literally translated as official mechanic. At the University of Thumingen in Jena, Carl Zeiss learned many skills and went on to work with instrument makers in Stuttgart and Vienna. When he first started his workshop he was on his own, not only making instruments but also repairing them. By 1847, he had introduced a single lens microscope for sale. The single lens demonstrates his awareness of magnified aberrations in compound instruments as well as the essential portability of single lens devices. They were of course also easier and cheaper to manufacture. Business improved with time, and he moved on in 1858 and again 20 years later to even bigger ones. By this time, he was recognised for making the best lenses in Germany.

Zucchi, Niccolo (1586–1670) Zucchi was the fourth of eight children. He became a Jesuit Priest teaching mathematics. He wrote many books on science and met Kepler, with whom he kept up a correspondence.

Index

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