preoccupied with the solar system, some outside their ranks felt a need to understand the universe 'in the large'. The man who attempted to answer this need was then in the north of England, scratching a living as a refugee musician.

reading from:

"The Cambridge Illustrated History of Astronomy"

by Michael Hoskin

William Herschel and the Construction of the Heavens

William Herschel (1738–1822) grew up in Hanover, and came to England as a refugee in 1757, in the aftermath of the Seven Years War. There he struggled at first to make ends meet, but in 1766 his fortune changed when he was appointed organist to a chapel in the spa resort of Bath.

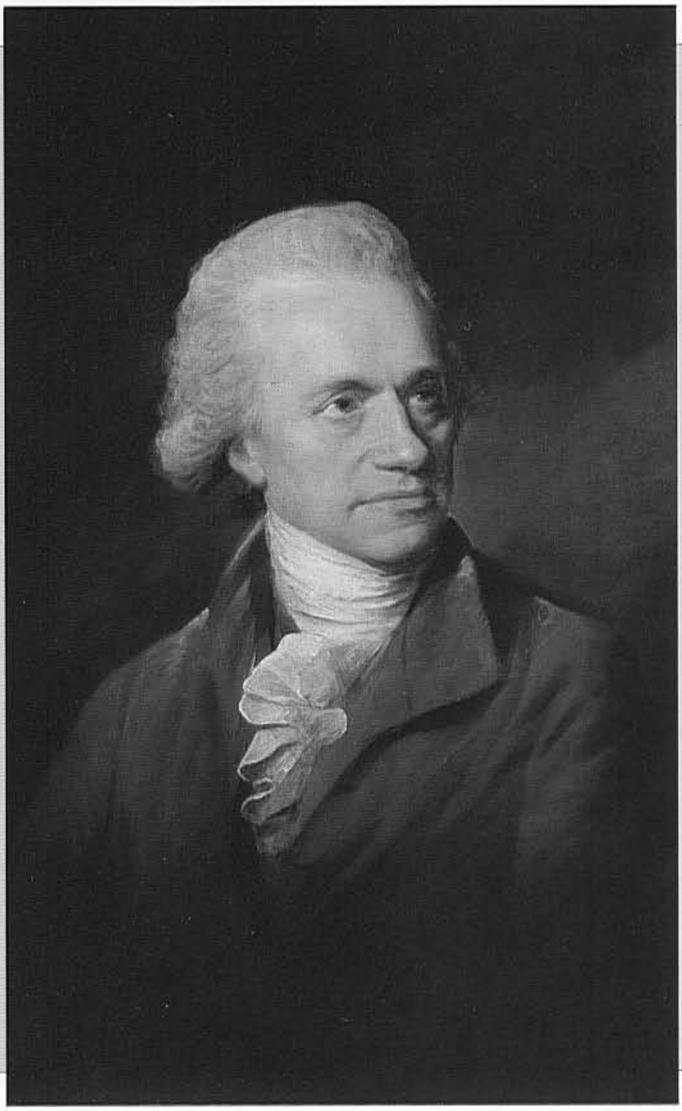
His new security gave him the chance to broaden his interests. He explored the classic two-volume textbook of *Opticks* by Robert Smith of Cambridge, a work that instructed the reader in the theory of optics and in the practice of constructing telescopes and microscopes. Smith had concluded his work with a chapter on 'Telescopical Discoveries in the Fixt Stars', and these few paragraphs served to focus Herschel's developing ambitions in astronomy.

William Herschel

Friedrich Wilhelm Herschel, known to history in his anglicized name of William Herschel, was born at Hanover on 15 November 1738. At the age of fourteen he joined his father in the band of the Hanoverian Guards. Following the French victory in the Seven Years War, Herschel (who as a boy was not under oath, and so free to leave) fled to England, where he scratched a living, first by copying music in London, and then as organist and teacher of music in the north of England.

In 1766 however he was appointed organist to the fashionable Octagon Chapel in Bath, and despite his varied musical duties he was then secure enough to develop his other interests, especially in astronomy. His main leisure effort went into the construction of reflectors large enough to bring into view distant and therefore faint celestial objects, as part of his ambition to study the universe in the large. The turning point came in 1781 when he chanced upon the unknown planet Uranus (see page 187), and recognized it as no ordinary star. This discovery gave friends the opportunity to persuade the king to grant him a life pension, so that he could devote himself to astronomy. In 1782 he moved to Datchet near Windsor Castle, and then, four years later, to nearby Slough, where he lived for the rest of his life.

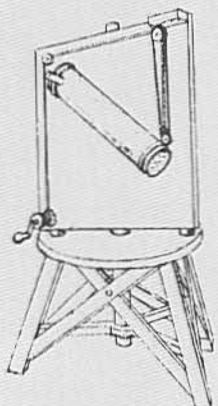
His loyal assistant in astronomy and, until his marriage in 1788, the mistress of his household, was his sister Caroline, who had joined him in England in 1772. In 1792 his only son, John, was born. William Herschel was knighted in 1816, and died at Slough on 25 August 1822.



In 1772, Herschel visited Hanover and persuaded his parents to allow his talented sister Caroline (1750–1848) to return with him to Bath. Caroline hoped for a career as a singer, but William was by now obsessed with astronomy, and her future role soon became evident: to be mistress of his household (until his eventual marriage in 1788), and his amanuensis and partner in the night watches at the telescope.

Next year Herschel bought a copy of *Astronomy Explained upon Sir Isaac Newton's Principles*, a best-seller by the leading popularizer of astronomy, James Ferguson (1710–76). It added little to his fragmentary knowledge of stellar astronomy, but it introduced him to some of the wider issues in cosmology. Ferguson, like many of his contemporaries, held that all planetary systems associated with stars are 'provided with accommodations for rational inhabitants'; and that even comets (once thought by William Whiston to be 'so many hells for tormenting the damned with perpetual vicissitudes of heat and cold') were probably peopled with beings capable of appreciating God's handiwork. Herschel was to extend this populating of the universe even to the Sun itself, which he came to believe was a cold body like a planet, but surrounded by clouds that protected the inhabitants from the exterior shell of fire; sunspots were glimpses of the clouds seen through gaps in the shell of fire.

Caroline Herschel



The 'comet sweeper' that William made for Caroline in 1783. 'Its distinctness is so perfect,' William later wrote, 'that it will shew letters at a moderate distance, with a magnifying power of 2000; and its movements are so convenient, that the eye remains at rest while the instrument makes a sweep from the horizon to the zenith'.

Caroline Lucretia Herschel was born at Hanover on 16 March 1750, and was brought to England by her brother William in 1772. She was his assistant in his astronomical work for half a century, the partnership ending only with William's death in 1822. In the early days she sometimes even put his food into his mouth, when he was grinding a mirror and dared not take his hands from it and allow it to cool. Later, on the nights when he was 'sweeping' for nebulae, she would sit at a table near the telescope, recording the descriptions as her brother shouted them out. So important was she to William's work that in 1787 the king awarded her a pension of £50.

She became a skilled comet-hunter in her own right, though her searches were restricted to what spare time she had. Despite this, she found her first comet in 1785, a second in 1788, and two more early in 1790.

The next year William made her a more powerful 'comet sweeper'. It was a sizeable instrument, of 9-inches aperture and 5-foot focal length, but it had the low magnification and wide field of view appropriate to comet hunting. Like its predecessor, it had a mounting that was simple, but effective for its purpose. Caroline could sweep the whole of one vertical 'slice' of sky without looking away from the eye-piece, simply by pointing the instrument to the horizon, and then turning a handle that enabled her to lower the tube from the horizontal to the vertical. She would then turn the instrument to face in a new direction, and sweep through the new slice of sky. In this way she was capable of searching the entire visible sky in four nights. She found her fifth comet late in 1791, her sixth (which had already been seen by Charles Messier) in 1793, her seventh (a reappearance of what is now known as Encke's Comet) also in 1793, and her eighth in 1797.

Caroline worked equally hard at her desk in the daytime, often preparing fair copies

Ferguson was not a Newton, dogmatically confident that Providence would intervene whenever chaos threatened, and restore the structure of the solar system or that of the universe of stars: the universe, he wrote, 'will last as long as was intended by its Author, who ought no more to be found fault with for framing so perishable a work, than for making man mortal'. Herschel learned the lesson well.

To view the objects described by Smith and Ferguson, Herschel first experimented with refracting telescopes. But the aperture of refractors was severely limited by the great difficulty (and cost) of manufacturing lenses of appropriate quality, and a lens of the size to match Herschel's ambitions was a technological impossibility. For his cosmological artillery Herschel therefore turned to reflectors, in which the light falls on a mirror at the base of the tube and is reflected back to a focus. Mirrors were altogether more promising, and he had Smith's book to tell him how to do the grinding and polishing.

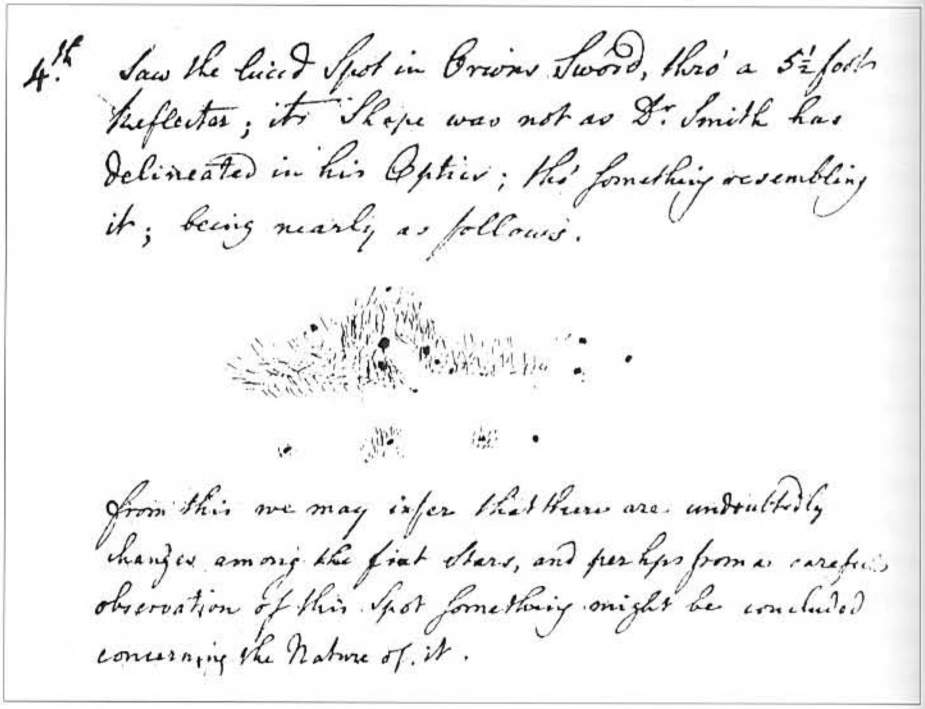
By November 1773, he had placed orders for a number of discs, one of which was for a reflector of $5^1/_2$-foot focal length. And it was when using this instrument, on 1 March 1774, that he decided to open a 'journal', or observing book. The first page of this

of the previous night's nebular observations. At William's request she improved the reliability of Flamsteed's 'British Catalogue' of stars, by compiling a list of stars observed by Flamsteed but omitted from his Catalogue (and a list of errata that included 'stars' never in fact observed). Her *Catalogue of Stars Taken from Mr. Flamsteed's Observations* was published by the Royal Society in 1798.

On William's death she returned to Hanover. Her last service to astronomy was to rearrange William's catalogues of nebulae into a form that her nephew John could use in his re-examination of them. For this she was awarded the gold medal of the [Royal] Astronomical Society. She died at Hanover on 9 January 1848, in her ninety-eighth year.

The only known portrait of Caroline Herschel as a young woman, this silhouette was painted before she left Hanover in 1772 to join William in England. It was later given to an English collector by a resident of Hanover.

An entry on the opening page of William Herschel's first 'journal' or observing book. On 4 March 1774 he observed the Orion Nebula, and compared what he saw with a sketch of its appearance many years earlier, as reproduced in Robert Smith's *Opticks*. The nebula, it seemed, had altered shape, and Herschel quickly realized that this fact had important implications for the understanding of its physical nature.



4th Saw the lucid Spot in Orions Sword, thro' a 5½ foot Reflector; its Shape was not as Dr. Smith has delineated in his Opticks; tho' something resembling it; being nearly as follows.

From this we may infer that there are undoubtedly changes among the fixt stars, and perhaps from a careful observation of this Spot something might be concluded concerning the Nature of it.

book (above) must be the most portentous beginning to any career in observational astronomy.

Six of the milky patches in the sky known as 'nebulae' had been listed by Edmond Halley in *Philosophical Transactions* in 1715, and these were discussed by Smith in his *Opticks*. The term 'nebula' referred simply to the object's milky appearance, and did not prejudge its physical nature.

On this there was a long-standing dispute. It was obvious that a distant cluster of stars would appear nebulous when seen in a telescope of insufficient power to 'resolve' the cluster into its component stars. The question was, were there also true nebulae, formed of some sort of diffuse luminous fluid; or were all nebulae merely apparent, nothing more than star systems whose true nature was disguised from the Earth-based observer by their great distances? Halley took the former view: nebulae 'in reality are nothing else but the Light coming from an extraordinary great Space in the Ether; through which a lucid *Medium* is diffused, that shines with its own proper Lustre'.

Observation could contribute to the debate in two ways. First, a more powerful telescope might succeed in resolving into its component stars a star system that had appeared nebulous when viewed with lesser instruments. Second, if a nebula was seen to alter shape from one decade to another, or even one century to another, then the nebula could not be a star system. After all, a star system so extensive as to appear to the observer as spread across the sky, and yet so distant that the component stars could not be detected, must be vast indeed – too vast to alter shape so rapidly.

Herschel was familiar with the crude sketch of the Orion Nebula that Smith had reproduced in his *Opticks*, from a drawing made by Christiaan Huygens in 1656. Looking at the nebula with his home-made reflector, Herschel decided it must have changed, and he at once saw the implications: '...from this we may infer that there are undoubtedly changes among the fixt Stars, and perhaps from a careful observation of this Spot something might be concluded concerning the Nature of it.'

But these were crowded years, and Herschel – organist, composer, conductor, and teacher of music – devoted most of the limited time he could spare for astronomy to improving his telescopes. But in 1779 he decided it was time he familiarized himself with the brighter stars, and so he systematically examined them one by one, using a portable reflector he had made himself of 7-foot focal length (see page 187). He then embarked on a second such 'review', much more thorough and this time with an additional goal: the identification of double stars that might be of use in the application of Galileo's method for the detection of annual parallax (see page 210).

Herschel harvested 269 double and multiple stars from this review, and a further 434 from a third review, thereby multiplying many times the number known to observers. He had introduced a new methodology into astronomy. Those who had received an orthodox education in the science knew that it was the job of an astronomer to study the familiar celestial bodies – Sun, Moon, planets and their satellites, comets, bright stars, each with its personal name and individual characteristics. Herschel, knowing no better, was beginning to play the natural historian, collecting specimens in great numbers, and counting and classifying

Attraction beyond the solar system

In his *Principia* (1687), Isaac Newton provided the strongest evidence that the force of gravitational attraction operated throughout the solar system, and the return of Halley's Comet in 1758 from beyond the outermost known planet was further confirmation of this. But Newton offered no evidence to show that attraction operated among the stars.

The first to do this was the Cambridge geologist and astronomer, John Michell (c. 1724–93). In a paper published in 1767, Michell used a mathematical argument to show that double stars were so numerous that they could not all result from mere accidents whereby the two stars lay in the same direction from Earth: most must in fact be physically connected pairs of companions ('binary stars'). The same applied to star clusters such as the Pleiades.

In 1802, William Herschel began re-examining double stars he had discovered two decades before. He found that in several of them, the two component stars had altered position relative to each other, in a way that showed they were indeed companions bound together by some attractive force.

But was the force that of Newtonian gravity? The necessary evidence was not available for another generation. At last, in 1827, the Paris astronomer Félix Savary was able to confirm that the two stars of Xi Ursae Majoris moved in elliptical orbits about their common centre of gravity, as required by Newtonian theory.

Black holes in the eighteenth century

The possibility of a celestial body that was invisible, because its mass was so great that its attractive pull prevented light from leaving it, was discussed several times in the late eighteenth century. The first to explore the question was John Michell. In a paper in *Philosophical Transactions* in 1784, Michell estimated that if a star of the same density as the Sun had a radius 500 times greater, 'all light emitted from such a body would be made to return towards it, by its own proper gravity'. However, such a body might betray its presence by the effects its pull was having on neighbouring bodies:

> yet, if any other luminous bodies should happen to revolve about them we might still perhaps from the motions of these revolving bodies infer the existence of the central ones with some degree of probability, as this might afford a clue to some of the apparent irregularities of the revolving bodies, which would not be easily explicable on any other hypothesis.

Taking up this theme and applying it on the cosmological scale, William Herschel in 1791 wrote of 'the great counteraction of the united attractive force of whole sidereal systems, which must be continually exerting their power upon the particles [of light] while they are endeavouring to fly off'.

The idea received wide publicity in 1796, when Pierre Simon de Laplace (1749–1827) included an estimate similar to Michell's in his *Exposition du système du monde*. But Laplace dropped the subject from the 1808 edition of his book, possibly because it conflicted with the general view that the speed of light was a constant; and the concept of what is now termed a 'black hole' was relegated to the status of a far-fetched speculation, where it remained until recent times.

them. Soon he would be ordering nebulae according to the stage they had reached in their life-cycle.

Meanwhile, word of this extraordinary organist was spreading in astronomical circles. Leading astronomers called on him, recognized his great talent, and did what they could to smooth his path. A Bath neighbour communicated papers of his to the Royal Society in London. But some Fellows of the Royal Society – mingling incredulity at his claims with contempt for his ignorance of basic procedures and conventions – declared him fit for the mad-house.

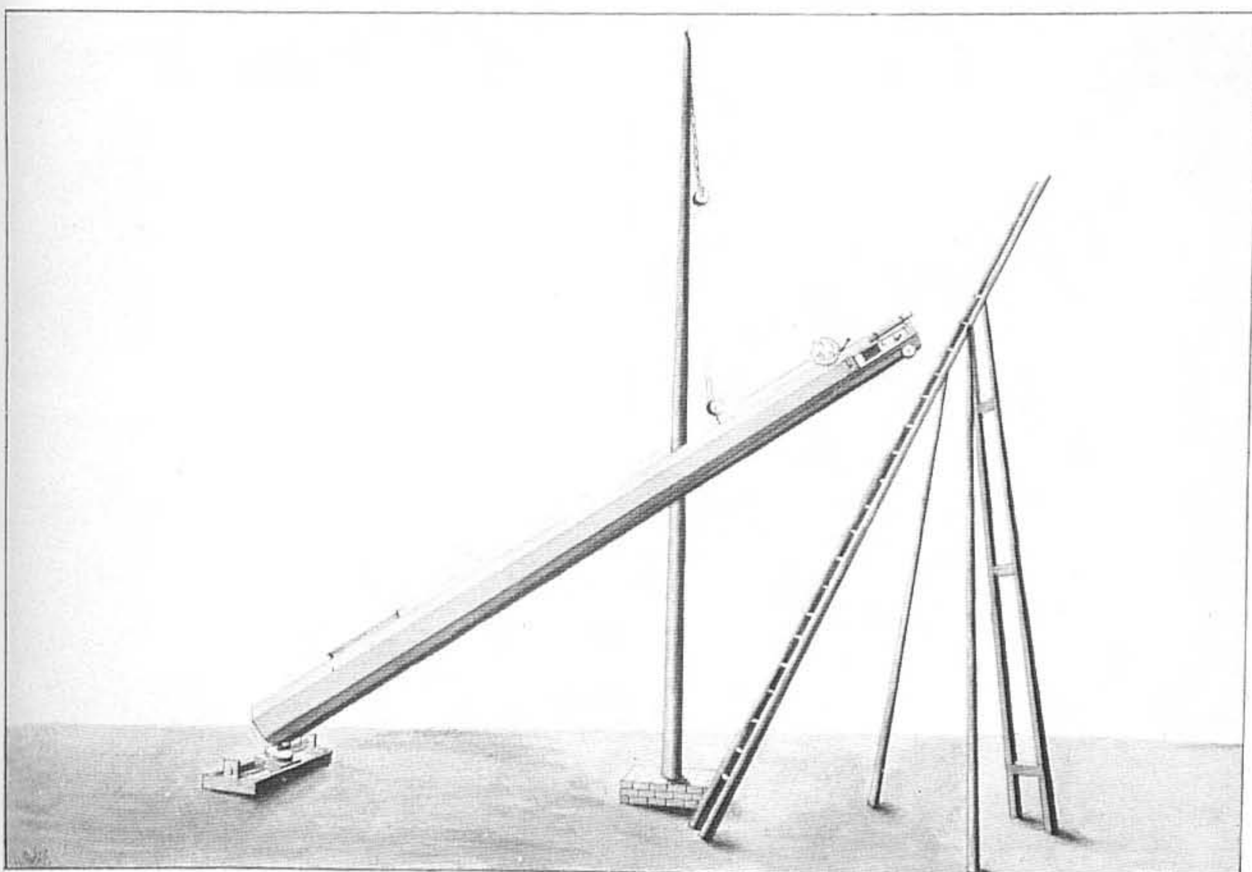
However, his discovery in 1781 of the planet Uranus (see page 187), in the course of his second review, was a triumph that none could gainsay, and soon every astronomer in Europe had heard of Herschel. King George III, himself a Hanoverian, granted him a life pension that would allow him to give up music and devote himself to astronomy.

Finding a new planet had been far from Herschel's mind on that fateful evening, but its discovery was no accident: he was systematically searching the sky, and his dual skills as telescope-maker and observer enabled him to recognize at a glance that the object was no ordinary star. Telescope-making would always be the foundation for his success as an astronomer, and he now became a professional maker, supplementing his pension by manufacturing reflectors for sale.

A successful reflector embodied three key components: first, a well-shaped mirror – in fact, two mirrors, so that one might be used while the other was being repolished to remove the tarnish caused by exposure to the night air; second, a range of eyepieces for magnification; and third, a stable yet adaptable mounting. Even when at Bath, Herschel's ambitions to have large mirrors of great 'light-gathering power', to permit the study of objects that were very distant and therefore faint, had outrun the capacity of local foundries to cast the blanks. Nothing daunted, in August 1781 he converted the basement of his own home into a foundry, and twice attempted to cast a 3-foot disc, which would have made this organist the owner of the largest telescopic mirror in the world. On the first occasion the mirror cracked while cooling; on the second, molten metal poured out onto the flagstones which, expanding, began to fly about in all directions. At this even Herschel admitted temporary defeat.

In the making of eyepieces, success seems to have come easily to Herschel. Indeed his magnifications – of hundreds and even thousands – were cited by him without special comment, although to many these well-justified claims were simply incredible.

It was in the mounting of large reflectors that Herschel proved most innovative. A 20-foot reflector he had made himself in 1776 had been slung from a pole, like



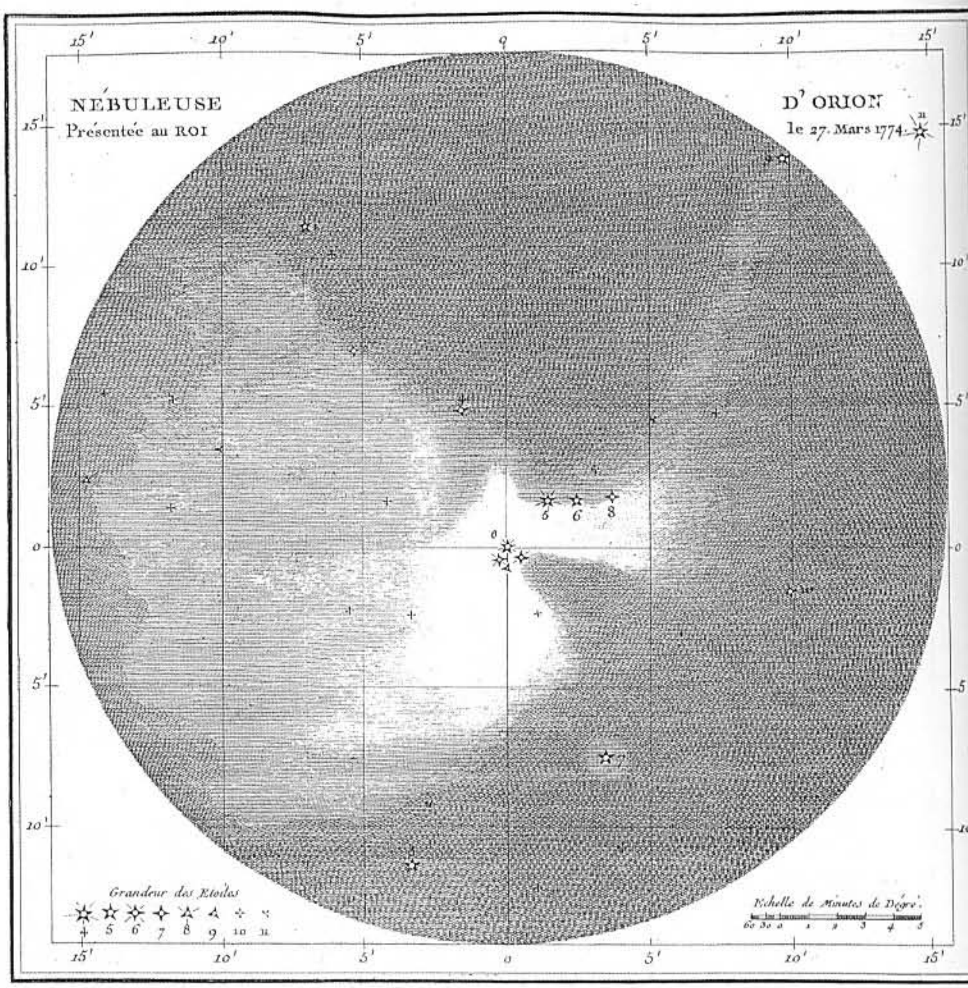
Herschel's 'small' 20-foot reflector, completed in 1776. The primitive mounting is reminiscent of the long-focus refractors of the seventeenth century (see page 142). It was however possible for Herschel to adjust the vertical angle through the ratchet-wheel on the upper side of the tube. He could also move the telescope a little to left or right by turning the small wheel below the eyepiece, but for major changes in azimuth he had to descend the ladder, move the base, and climb once more to the eyepiece.

Opposite: William Herschel's 'large' 20-foot reflector, completed in 1783. Its mirrors were bigger than those of the 'small' 20-foot, but the major advances were in the stable and secure mounting, and in the controls available to the observer. This telescope was used by William throughout his twenty years of sweeping for nebulae. It was later refurbished by his son John under William's supervision, and after William's death John used the modified instrument, first in England and then in South Africa (see page 250), to examine the entire heavens.

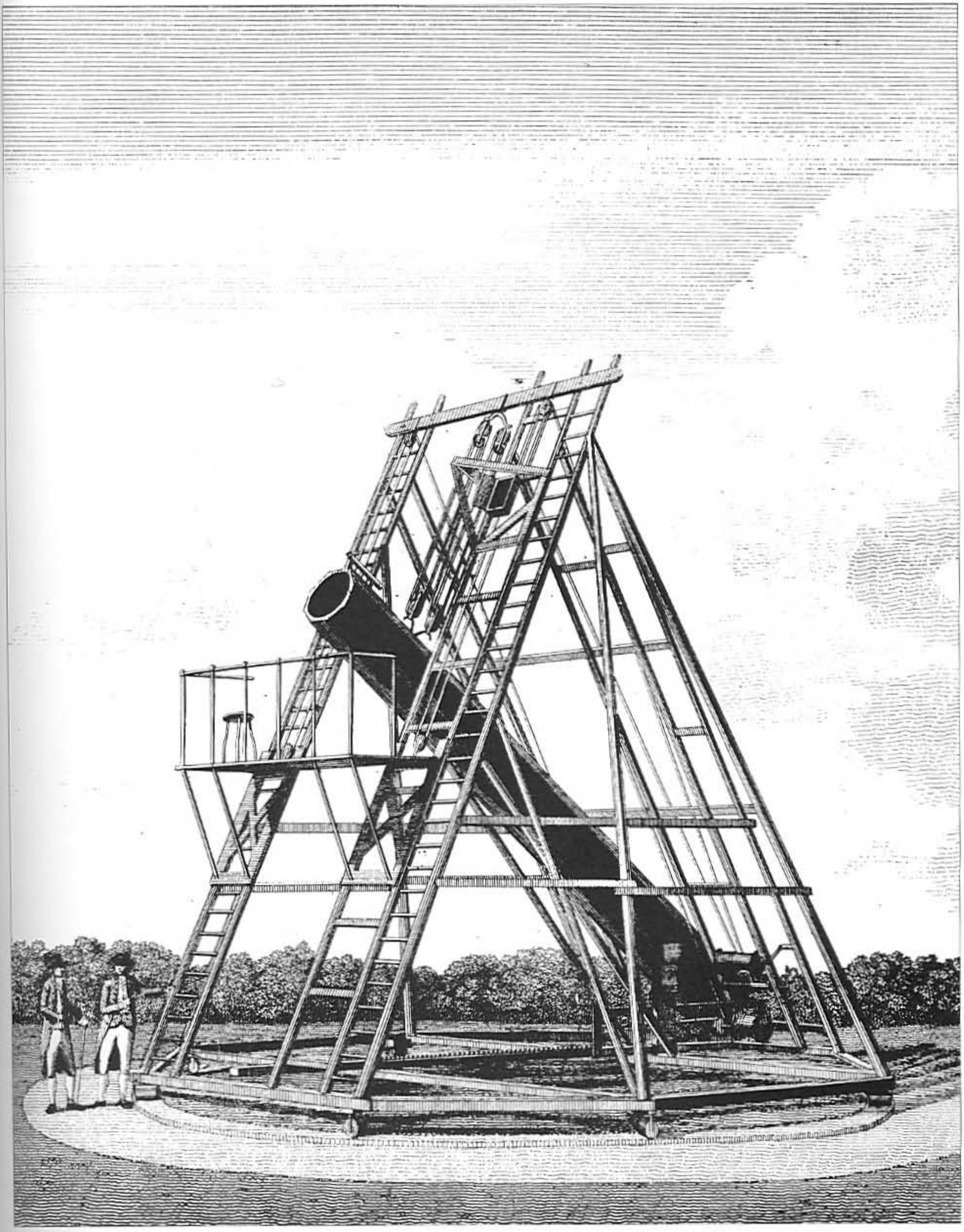
the very long refractors of past generations. But once he was free to devote himself to astronomy, it took Herschel only a year to build himself a new 20-foot. This time the mirrors were 18 inches in diameter rather than 12 inches; but more importantly, the mounting was stable, and the observer stood in safety on a secure platform.

Herschel was now equipped to tackle the riddle of the nebulae. Despite his early look at the nebula in Orion, by December 1781 he had seen only three more. It was then that he was given a catalogue of some sixty-eight nebulae and star clusters. It had been assembled by the French comet-hunter Charles Messier (1730–1817), who had found these diffuse objects an unwelcome distraction in his searches for comets. (In fact Messier had already published an enlarged catalogue with just over 100 nebulae, and this catalogue is used today by astronomers when they refer to a prominent nebula by an 'M', followed by its Messier number.)

Herschel made the momentous decision to use the new 20-foot to sweep the entire sky visible from England, in order to collect as many specimens of nebulae as possible. On nights when the 'seeing' was good, the telescope was turned to the south, and the tube raised to some particular angle. Herschel then let the sky drift past, so laying an ambush for any nebula that came into the field of view. When he saw one crossing the meridian, he would call out its description, which Caroline



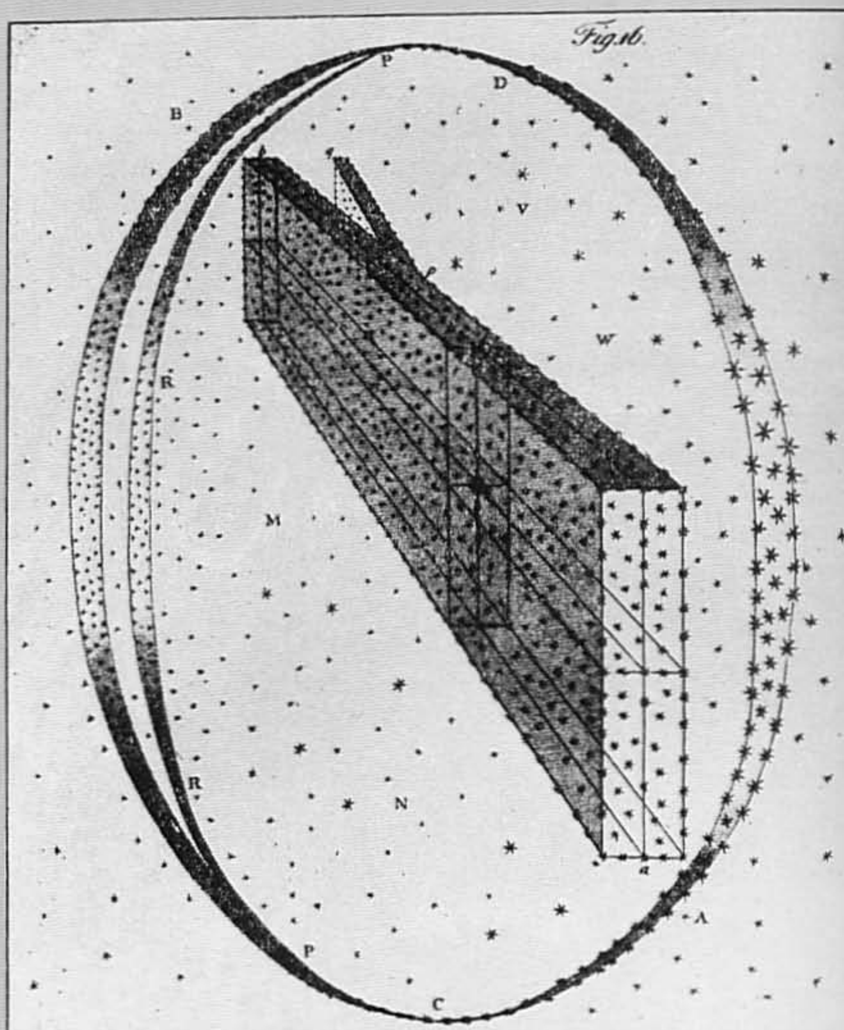
The Orion Nebula, drawn by Charles Messier early in 1773, at the Hôtel de Cluny in Paris. Like Herschel a year later (see page 234), he remarked on how much the nebula differed from its appearance in sketches by earlier astronomers, and he hoped that his drawing, made 'with the greatest attention', would allow future observers to decide whether or not it had in fact altered shape.



Herschel's map of the Galaxy

In a paper he published in 1785, Herschel pioneered the use of statistics in astronomy, by showing how the natural historian of the heavens can derive insights simply by counting stars. The problem he set himself was to determine the shape of our star system, the Galaxy.

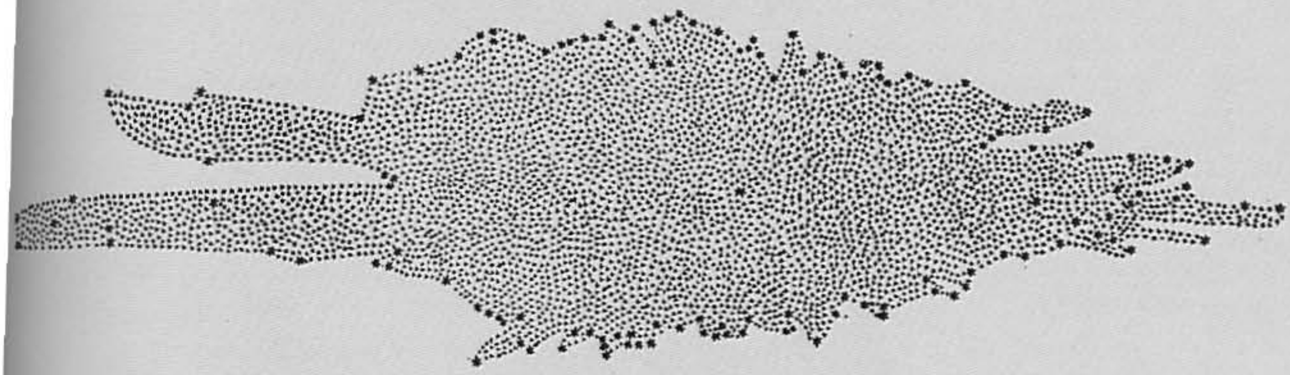
Like Wright, Kant and Lambert, he realized that the Milky Way was the optical effect of our immersion in a layer of stars.



The Milky Way and its explanation. According to Herschel, the Sun and the other stars form a stratum; and the Milky Way is the optical effect of these stars, when seen by an observer on Earth who is looking in directions within the stratum. The bifurcation is to account for the division in the Milky Way in Scorpius and elsewhere.

copied down, along with its angle from the celestial North Pole and the time. For two long decades the work continued. By 1802, the team of brother and sister had increased the number of known nebulae to 2,500.

But were all nebulae merely vast star clusters at great distances; or were some truly nebulous, and formed of a luminous fluid? Just before sweeping began,



But what was the precise shape of this layer? Clearly, Herschel could not attempt to answer this question unless he was allowed to assume that his telescope could reach to the limits of the Galaxy in every direction. But how then to proceed? Herschel decided that the way forward was to assume next that throughout the Galaxy, the stars were distributed uniformly: that the galactic space was uniformly stocked with stars. Obviously the assumption was not true in the literal sense; Herschel hoped it would be true enough for his purpose.

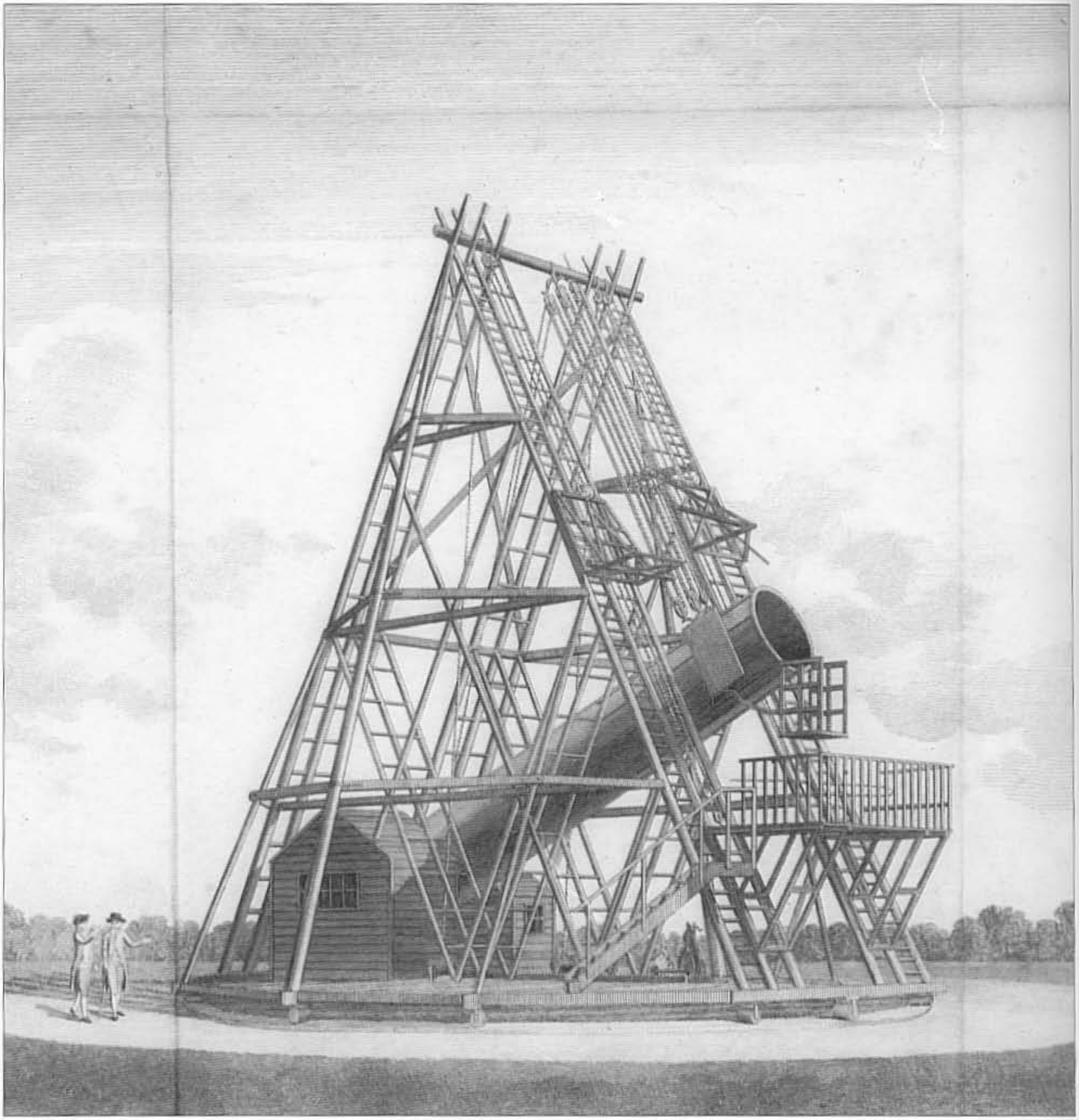
Granted this, the number of stars in Herschel's field of view in a given direction was proportional to the volume of galactic space within that field of view – that is, to a cone-shaped volume of space, whose vertex was at the telescope, and whose axis was the line of sight from the observer to the border of the Galaxy. Herschel would then count the stars to get a number proportional to the volume of the cone, and a simple calculation would then give him the (relative) length of the axis. Time did not permit him to implement this programme in full, but to illustrate his method he made the counts for a circle around the sky, and sketched the resulting cross-section of the Galaxy.

In later life he was to abandon both of the assumptions on which this famous figure was based: he found that the new, monster 40-foot reflector that he completed in 1789 brought many more stars into view, and so his 20-foot had not after all penetrated to the borders in every direction; and increasing familiarity with star clusters brought home to him how very non-uniform is the distribution of the stars. But astronomers, like Nature, abhor a vacuum. Herschel's cross-section might have been disowned by its creator, but for long there was nothing to take its place, and so we find it being reproduced in books late into the nineteenth century.

The cross-section of the Galaxy resulting from Herschel's star counts. The Sun is the star near the centre, and the (relative) distances to the stars shown bordering the Galaxy are inferred from the star counts: the greater the number of stars in a given direction, the greater the distance. Note the bifurcation to the left. Herschel was involved in sweeping for nebulae, and could spare only enough time to give this limited example of his method.

Herschel had confirmed (as he thought) the variability of the Orion Nebula, which he found 'surprizingly changed'; this, then, must be a true nebula. But how in general was one to distinguish true nebulae from distant star clusters?

Herschel had noticed that some nebulous-seeming objects had a uniformly milky appearance, while others were mottled. The former, he decided, were true



nebulae, while the mottled nebulosity of the latter indicated to him that they were 'resolvable' – in other words, they were clusters that with a sufficiently powerful telescope would be seen resolved into their component stars.

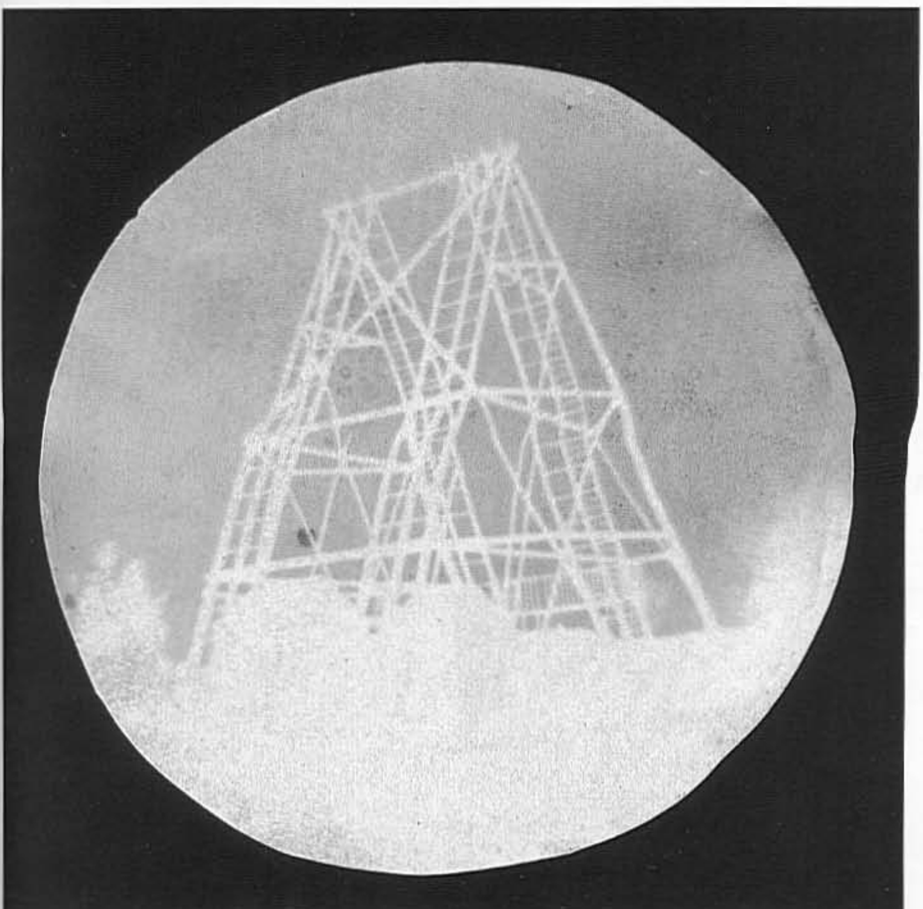
In June 1784, a paper outlining his current work on nebulae was read to the Royal Society. Within days, Herschel came across two nebulae that contradicted the very theory he had just published, for each seemed to contain both forms of nebulosity. Indeed, in one of them he believed he could also see stars mixed with the resolvable nebulosity. He interpreted the stars as being in the region of the nebula nearest to the observer, and the resolvable nebulosity as composed of stars that were further away, a little too distant to be individually visible. Must not then the milky nebulosity simply consist of stars at a still greater distance – rather than of the luminous fluid, or 'true nebulosity', that Herschel had hitherto postulated?

Ignoring the changes he believed he had earlier observed in the Orion Nebula, he now abandoned his belief in luminous fluid, and concluded instead that all nebulae were star clusters at great distances.

But clusters imply clustering, the assembling together of stars as a result of their gravitational pulls on each other. Accordingly, in an epoch-making paper 'On the Construction of the Heavens' published in *Philosophical Transactions* in 1785, Herschel examined the subject 'from a point of view at a considerable distance both of space and of time'.

He imagined a universe in which the stars were at first distributed with fair regularity; and he went on to outline how, in time, gravitational pulls would be likely to cause stars to assemble in places here and there, forming clusters of various types, examples of which he had already observed. He even envisaged the possibility that the continuing action of gravity might eventually lead to gravitational

Opposite: Herschel's 40-foot reflector, a cumbersome, scaled-up version of the 'large' 20-foot. It was completed in 1789, and remained unsurpassed in size until 1845 (see page 253). The second of its 4-foot-diameter mirrors weighed nearly one ton (1,000 kg), and to prevent it from bending under its own weight Herschel had increased the proportion of copper. As a result, the mirror tarnished easily.



An historic photograph of an historic instrument: the 40-foot in an advanced state of decay, photographed by John Herschel in September 1839. The tube had already been lowered for the last time, and the entire structure was to be dismantled during the winter. On New Year's Eve, 1839/40, John Herschel assembled his family inside the recumbent tube. *He then read a poem* written as an obituary for the instrument, before sealing the tube with his father's grinding and polishing tools inside. John Herschel was a pioneer of photography, and introduced the term into the English language.

The planetary nebula NGC 1514, which Herschel encountered in November 1790. The more distant planetary nebulae that he had earlier discovered and named were ambiguous in nature, but this object was clearly formed of a central star surrounded by a luminous atmosphere.

collapse, followed by some form of renewal. 'These clusters may be the *Laboratories* of the universe…wherein the most salutary remedies for the decay of the whole are prepared' – a far cry from the stable clockwork universe of the early years of the century.

In November 1790 Herschel was sweeping as usual for nebulae, when he came across 'a most singular phaenomenon! A star of about the 8th magnitude, with a faint luminous atmosphere...' It was in 1782 that he had encountered his first 'planetary nebula' – an object that was faint like a nebula but had the disc-shaped outline of a planet – and he had found several more since. What he had now encountered was in fact another of the class; but this one was unusually large in appearance, and he could see its structure and in particular its central star. The object must, he decided, be a 'nebulous star': a star surrounded by a cloud of (true) nebulosity, out of which the star was in the process of condensing. Faced with this new evidence, Herschel instantly reversed the position he had held since 1784, that all nebulae were nothing else but star clusters at great distances. Nebulosity existed after all, and it represented a pre-stellar stage in celestial development.

Herschel's final theory of the evolution of the universe therefore began with diffuse clouds of nebulosity, which gradually condensed here and there under gravity to form more concentrated nebulae, out of which in time individual stars began to form. These in turn would gather, at first into widely-scattered clusters, and then into more condensed ones. From the cataclysmic collapse of such clusters, and also from the light sent out into the universe from all luminous bodies, came the material to form new diffuse clouds of nebulosity, so that the cycle might repeat itself.

The status of our Galaxy was also changed by the 1790 observation. In the mid-1780s, Herschel had believed it to be a star system of known and therefore limited extent, and all nebulae to be similar star systems, though of varying shapes and sizes. The Orion Nebula, therefore, which he saw extended across the sky despite its being (supposedly) so distant that the individual stars escaped detection, had to be vast; indeed, it 'may well outvie our Milky Way in grandeur'. But in his post-1790 theorizing, the Orion Nebula reverted to being a nearby cloud of nebulosity located well inside our Galaxy, while the Galaxy became 'the most brilliant, and beyond all comparison the most extensive sidereal system'.

'A knowledge of the construction of the heavens', Herschel wrote in 1811, 'has always been the ultimate object of my observations…' Herschel had been able to make this into a true science because he combined to a unique degree the three talents necessary: those of instrument-builder, observer, and theorist. He built instruments that were ideal for his self-imposed task: they incorporated large mirrors, eye-pieces that magnified hundreds of times, stable mountings – all made with his own hands or under his direct supervision. With these instruments he played the natural historian of the heavens, collecting double stars by the hundred and nebulae by the thousand, in observational campaigns extending over many

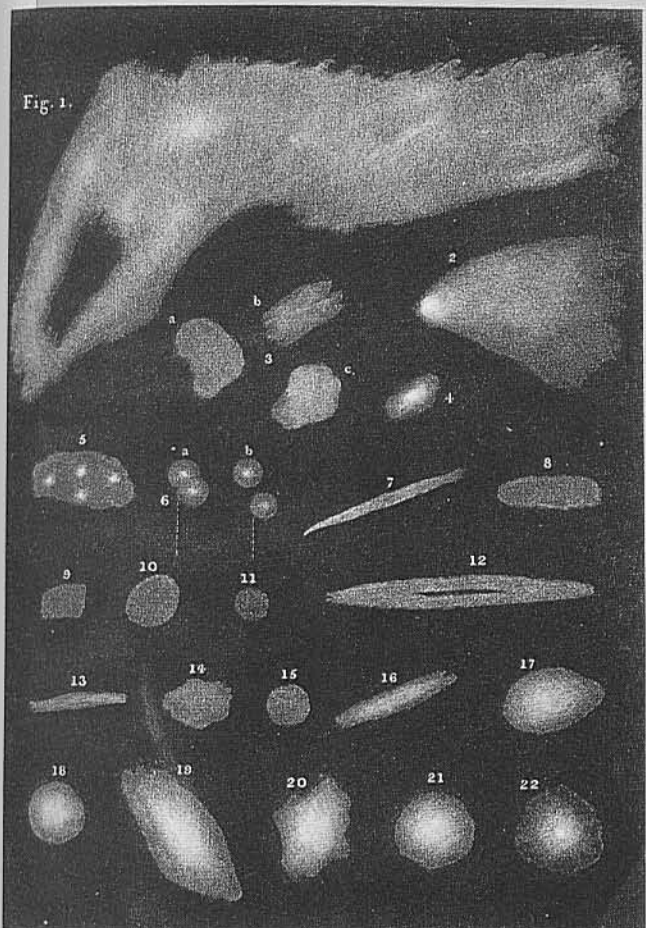
The life story of stars and star systems

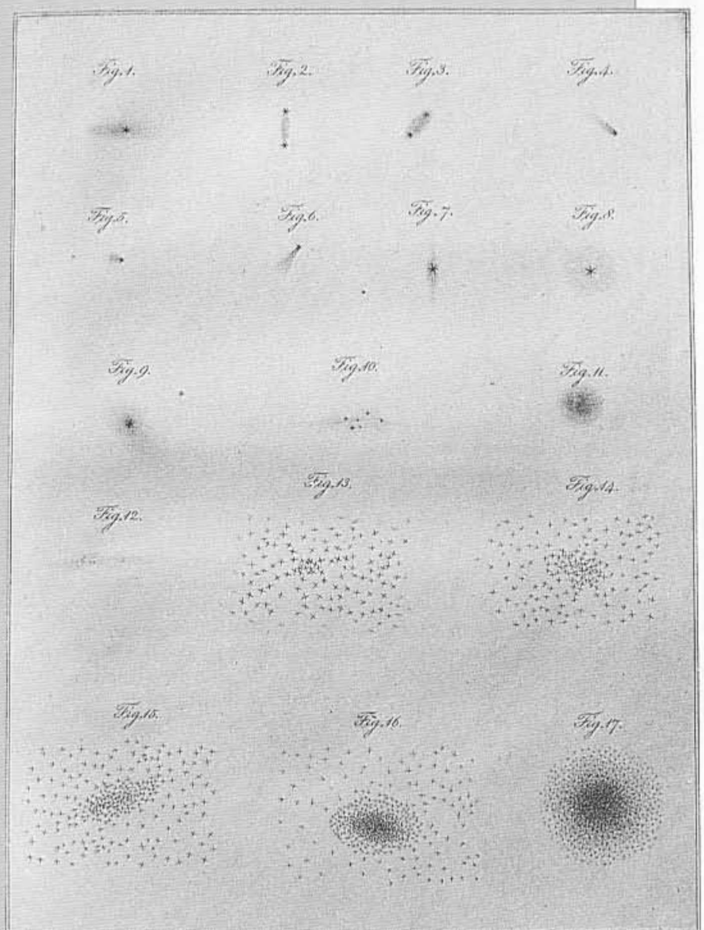
These sketches by Herschel show objects from his catalogues of nebulae and star clusters, arranged in sequence to illustrate (left) the stages by which nebulosity condensed into a star (or stars), and (right) the subsequent developments among the stars that led to the formation of condensed clusters.

In 1811, Herschel explained how astronomers – despite their own brief life-spans – might succeed in understanding the changes in nebulosity caused by gravitational attraction. They must select specimens of nebulae at different stages of development. They must then classify and order them by age (left): 'there is perhaps not so much difference between them [the nebulae in consecutive classes], if I may use the comparison, as there would be in an annual description of the human figure, were it given from the birth of a child till he comes to be a man in his prime.'

In 1814, Herschel published a second paper in which he continued the story, beyond the stage when scattered stars had been formed. In response to their mutual gravitational attraction, the scattered stars of a group would move ever closer together (right), until they formed a condensed cluster.

His son John would often be torn between scepticism, and the filial piety that made him hesitate to contradict the theories of his late father. In 1826, scepticism took control; how, he asked, could one argue from 'observed graduation' among nebulae and star clusters to 'concluding them to be in a course of progress from one state in the series to another'? 'So wide is the field for conjecture,' he concluded, '...that we shall do well for the present to dismiss hypothesis, and have recourse (perhaps for centuries to come) to observation.' Even the very existence of 'true nebulosity' continued to be a matter for debate. But John did come to adopt 'the theory of sidereal aggregation', according to which a star system passed through a period of collisions and disturbances, before eventually reaching a stable configuration.



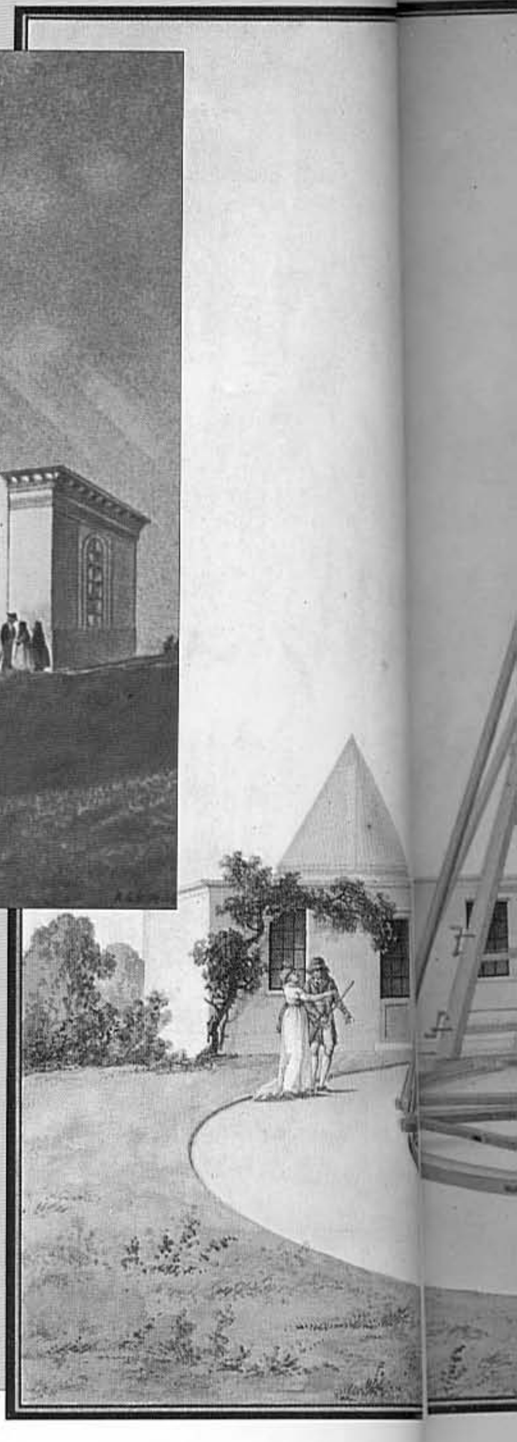


years. And, unusually for one so dedicated to assembling facts, he saw it as his clear duty to speculate too much rather than too little.

Among his contemporaries, Herschel's impact was mixed. The nebulae in particular were his private domain: no one else had telescopes to equal his, so no

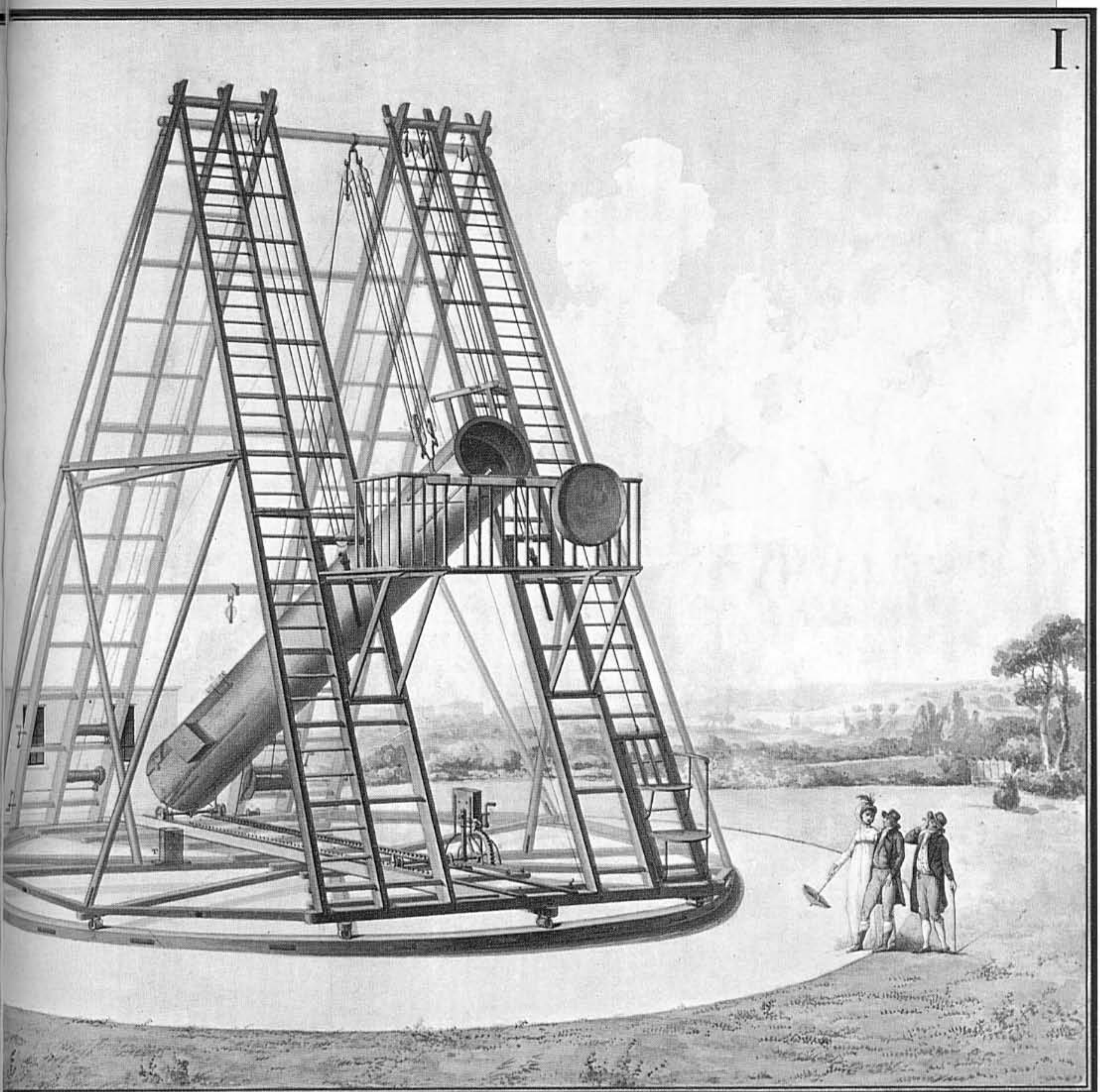
The national observatory of Spain

Madrid Observatory in 1848



Numerous observatories – most of them national, university, Jesuit, aristocratic, or the product of an amateur's enthusiasm – were founded in the eighteenth and nineteenth centuries. The observatory at Madrid (above), a national institution founded by the king of Spain in 1790, was equipped from the start with the usual transit instruments and clocks for positional measurements, but in 1796 two reflectors were commissioned from William Herschel. One was to be a small portable telescope of standard design (in the event, the observatory acquired two 7-foot instruments of slightly different mirror diameters), while the other was to be the largest instrument he ever made for sale, with 2-foot mirrors of 25-foot focal length. Right is the watercolour Herschel sent with the assembly instructions. This was perhaps his most successful telescope, more powerful than the 20-foot he customarily used but less cumbersome than his monster 40-foot. It was shipped to Spain in 1802 and erected in Madrid in 1804, only for the mounting to be destroyed by Napoleonic troops in 1808.

one else had access to the evidence. Few therefore knew what to make of him and his speculations. But his papers in *Philosophical Transactions* were readily available to the next generation of astronomers, who would be more receptive to his ideas. Prominent among them was his son, John.



John Herschel

John Frederick William Herschel was born on 7 March 1792 at Slough, near Windsor Castle, the only son of William. In 1809 he entered St John's College, Cambridge, where he was a leading figure in a campaign for the reform of British mathematics. He was elected to the Royal Society when he was only twenty-one, and in 1820 he took a leading part in the foundation of the future Royal Astronomical Society. He became perhaps the most prominent British scientist of his day, being knighted in 1831 and created baronet in 1838. So famous was he that a letter from abroad addressed to him in 'London' reached its destination.

After revising his father's observations of the skies visible from Slough, Herschel spent the years 1834-38 surveying the southern stars from the Cape of Good Hope. On his return he largely abandoned observational astronomy, though in 1864 he published a consolidated catalogue of over five thousand nebulae and clusters, the ancestor of the *New General Catalogue*, or 'NGC', that astronomers use today.

Herschel was of private means, though the source of this wealth is puzzling. Equally puzzling is his acceptance in 1850 of the post of Master of the Mint, which he filled for five unhappy years. He died at his home in Kent on 11 May 1871, and was buried in Westminster Abbey.

John Herschel and the Southern Skies

William Herschel had been a German-born provincial musician when he cut his astronomical teeth. His only son, John (1792–1871) – born when his father was already fifty-three – carried the most famous name in astronomy, and from his undergraduate days in Cambridge was a member of the scientific establishment. After a flirtation with law, John Herschel settled down to a teaching career in Cambridge. But in 1816 his father, whose strength was failing, prevailed upon him to return home, so that William could hand on his skills as a telescope-maker and observer before it was too late. 'My heart dies within me', wrote John as he left Cambridge. But, once he had made the sacrifice, the son saw himself as entrusted with a sacred mission, to complete his father's work and bring it to perfection.

Double stars were the most obvious place to begin: his father's telescopes had been designed as massive instruments of discovery, whereas the observation of double stars was best done with instruments of precision. Fortunately, among John Herschel's many scientific friends was James South (1785–1867). South's wealth through marriage had allowed him to give up surgery for astronomy, and he was a skilled observer and the owner of two exceptionally fine equatorials. From 1821 to 1823, though with interruptions, the two friends collaborated, often observing the same object with different instruments and then comparing notes. Their efforts resulted in a catalogue of 380 doubles, fully detailed, and conveniently ordered for the use of observers.

The principal legacy of Herschel's father, however, had been his studies of 'the construction of the heavens', and the catalogues of nebulae and clusters on which these studies were based. These catalogues listed the objects by class rather than

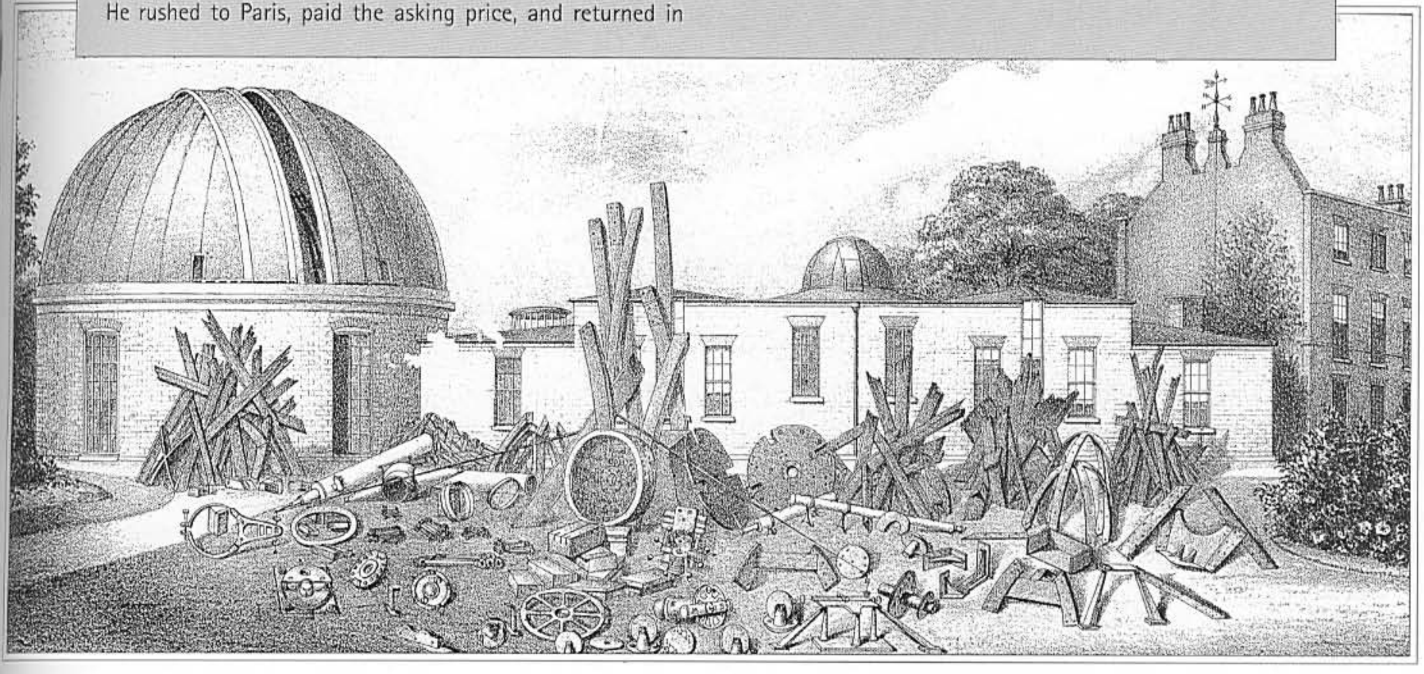
South's object glass: a price too high

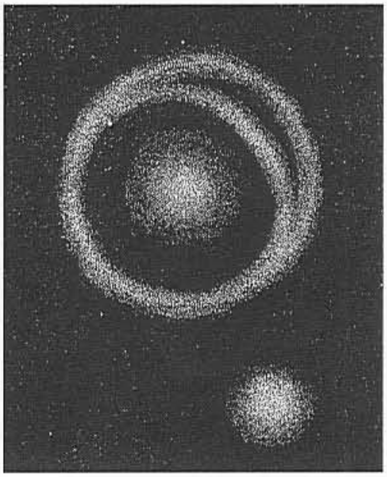
In the early nineteenth century there was intense competition among observers to obtain large, high quality object glasses, for only rarely was one successfully made. The observer whose refractor was equipped with such a glass would have a clear advantage over his rivals.

Around 1830 the Paris maker Robert A. Cauchoix (1776–1845) produced three such glasses, all between 11¾ and 14 inches in diameter. One was bought by the Duke of Northumberland for the Cambridge Observatory – the Northumberland telescope was the instrument used by James Challis in his fruitless search for Neptune (see page 193). Another was acquired by Edward J. Cooper for the observatory on his estate at Markree Castle in northwest Ireland. The third was bought by James South for his private observatory at Camden Hill in London.

South was a leading observer of double stars, rivalled only by Wilhelm Struve, who had the Dorpat refractor (see page 217) at his disposal. In 1829 South heard that French astronomers were haggling with Cauchoix over the price of the lens. He rushed to Paris, paid the asking price, and returned in triumph with the precious glass. He then commissioned Troughton & Simms, the firm of the leading London maker, Edward Troughton (1753–1835), to make the mounting, without which the lens would be useless. South wished for a scaled-up version of the mounting of his 5-foot equatorial, but Troughton had other ideas.

Before long matters turned sour. South was notoriously impulsive and irascible, and he declared himself dissatisfied with the mounting supplied and refused to pay for it. Troughton & Simms took him to court, and after an expensive lawsuit lasting from 1834 to 1838 (during which time Troughton died) obtained judgment in their favour. Within months South, unhinged with rage, had smashed the polar axis to pieces and auctioned the fragments (engraved below). Three years later he auctioned the brasswork, advertising the sale with a poster of legendary vindictiveness. The lens, however, he preserved, and near the end of his life he presented it to Dublin University. But its moment had passed, and South's own career as an observer had been destroyed.



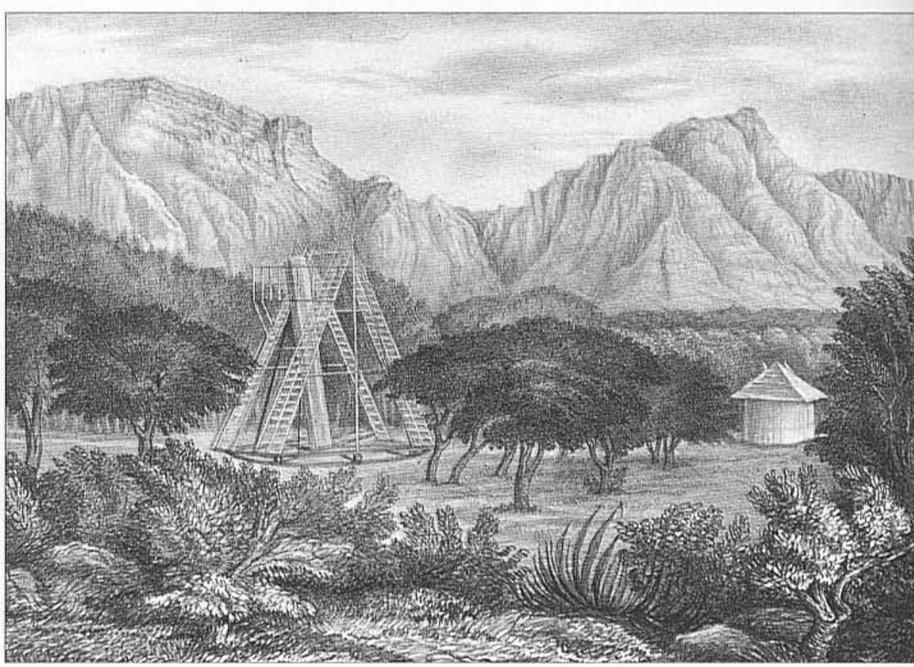


The nebula M 51, as drawn by John Herschel in 1828. An observer in the central cluster would see bright stars scattered all round the sky, and a fainter, bifurcated 'milky way' – much as we ourselves do.

position, and were therefore highly inconvenient for other observers to use. In addition, there had been ample scope for error when Caroline had copied down the observations shouted out by her brother, as the various nebulae came into view. Fortunately, John had himself refurbished his father's 20-foot reflector under the old man's supervision, so he possessed the ideal instrument with which to re-examine (and re-order) his father's nebulae. 'These curious objects…I shall now take into my especial charge', he told Caroline in 1825, 'nobody else can see them'. His immediate efforts resulted in a catalogue of 2,306 nebulae and clusters, published in 1833 in *Philosophical Transactions*; it became the standard reference work, and helped transform the study of nebulae from one of the maverick William's exotic pursuits, into a component of mainstream astronomy.

So far John Herschel's experience of nebulae had been little different from that of his father: the same skies, and much the same instrumentation. Not surprisingly, his theoretical stance was also the same. Only one significant new item of evidence had come his way: he had several times had a good view of the nebula M 51, which he saw as being composed of stars in the form of a central cluster surrounded by a divided ring. The sky as seen by an observer within the central cluster would, as he immediately realized, be strikingly similar to the sky we see from Earth: on all sides a number of nearby (and therefore bright) stars and, in and near the plane of the ring, a divided milky way of innumerable faint stars. 'Perhaps', he remarked, 'this is our Brother System'.

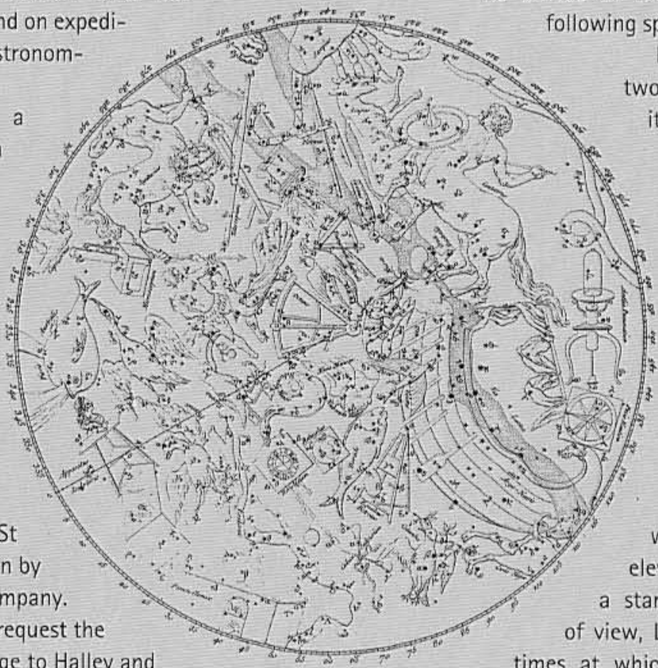
His father had seen only the skies visible from England, and to complete his father's work John Herschel would need to set up his telescopes south of the equator. And so, declining official offers of financial support, he set sail in November 1833 for the Cape of Good Hope. For deep-sky exploration he had the



The refurbished 20-foot reflector, at John Herschel's temporary observatory at Feldhausen, a few miles from Cape Town. In the sea air, a telescopic mirror tarnished in a matter of days and needed repolishing, during which time it was out of action. Anticipating this, John had brought with him three matching mirrors, one made by William, one by John, and one by the two in collaboration.

Early observations of the southern skies

The southern skies have much more to offer the observer than their northern counterparts, for they contain the brilliant Milky Way star clusters that lie in the direction of the galactic centre, as well as such wonders as the Magellanic Clouds. However, because astronomy developed in Europe, and travel south of the equator was difficult in past centuries, it is only in our own day that they have been given their due share of attention. No public observatory existed in the southern hemisphere until Fearon Fallows (1789-1831) arrived in 1821 at the Cape of Good Hope as His Majesty's Astronomer. Until then, knowledge of the southern skies had depended on sailors' lore, and on expeditions by two remarkable astronomers, Halley and Lacaille.



Edmond Halley made a reputation for himself in Royal Society circles when no more than a youth. Early in 1676, and still not yet twenty years old, he was corresponding about suitable sites for an expedition south of the equator; but some of these sites were in foreign hands, and his choice eventually fell on the south Atlantic island of St Helena, used as a waystation by the (British) East India Company. The King was persuaded to request the Company to give free passage to Halley and his colleague, and Halley's father agreed to contribute to the costs of the expedition.

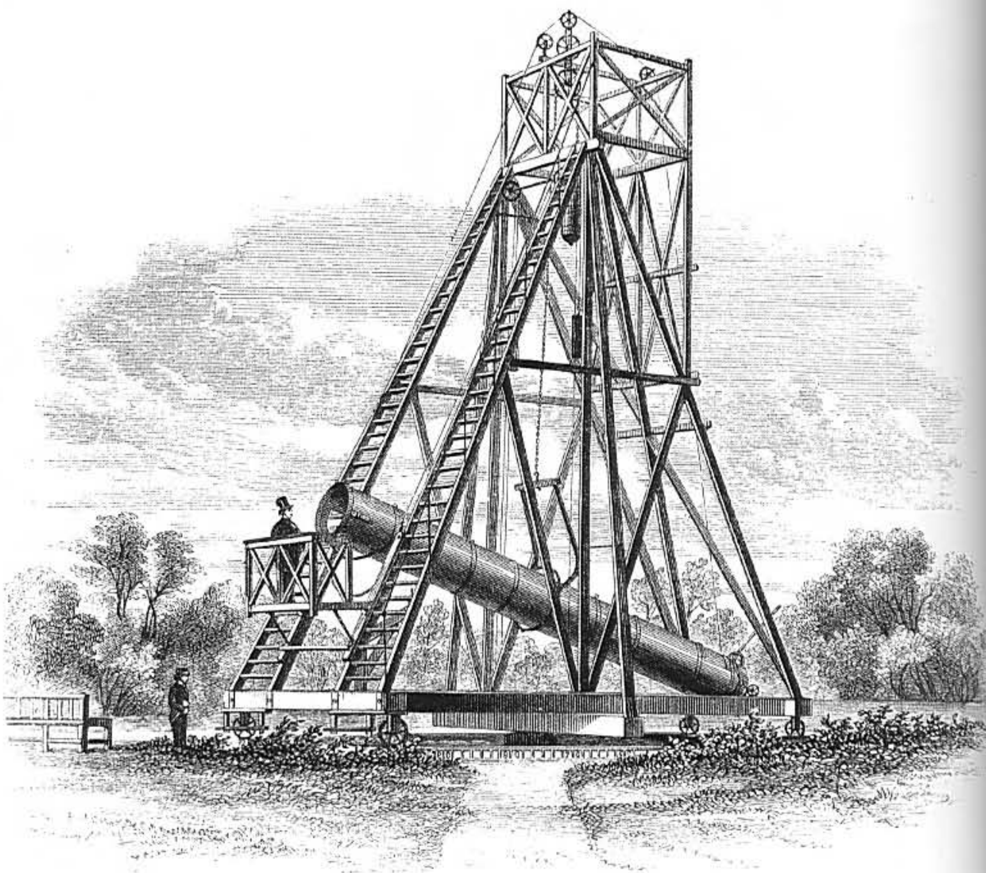
Halley arrived at the island in February 1677, and stayed for nearly a year. He was equipped with a range of instruments, prominent among which was a sextant of $5^{1/2}$-foot radius with telescopic sights, for measuring the angular distance between pairs of stars. The climate was less favourable than Halley had hoped, but he managed to compile a catalogue of some 350 stars, listing their positions relative to two of Tycho Brahe's fundamental stars.

He also observed three 'nebulae', including the scattered cluster of stars known as M 7, and the fine spherical ('globular') cluster Omega Centauri. The Magellanic Clouds, he wrote, 'reproduce exactly the whiteness of the Galaxy, and, examined through a telescope, they exhibit here and there small clouds and a few stars, from the concourse of which their white colour, like that of the Galaxy, is now believed to be produced'. On 28 October he saw Mercury move across ('transit') the face of the Sun.

It was to be the middle of the next century before the southern skies again came under scrutiny. In 1750, the abbé Nicolas-Louis de Lacaille (1713–62), who had built up a formidable reputation as an observer, secured government support for an expedition to the southern hemisphere, and he arrived at the Cape of Good Hope the following spring.

In a stay lasting less than two years, he measured the positions of nearly ten thousand stars. He achieved this extraordinary level of productivity by attaching a small telescope of wide aperture to a mural quadrant (a graduated quarter-circle mounted against a north–south wall), and placing a rhomboidal diaphragm in the field of view of the instrument. The telescope would be fixed at a particular elevation in the meridian. As a star drifted through the field of view, Lacaille noted the (sidereal) times at which it entered and left the rhombus; the average of the times gave one of the star's co-ordinates and the difference in the times gave the other. He also assembled information on no fewer than forty-two nebulous objects, and assigned names to southern constellations, most of which are in use today (see his 1752 chart, above).

In 1757 Lacaille published the positions of nearly 400 of the brightest of the southern stars, so establishing the framework for southern-hemisphere astronomy. His observations of 10,000 southern stars appeared posthumously, in 1763. However, he left the majority of his position measurements in their raw ('unreduced') state, and a definitive catalogue of his southern stars was not published until 1847.



The reflector with 3-foot mirrors, built in 1839 by the future Lord Rosse using the type of mounting developed by William Herschel. The first mirror was assembled in sixteen segments, but in 1840 Rosse, with the help of local labourers, successfully cast a solid mirror. Rosse persuaded himself that the telescope had 'resolved' a number of nebulae into their component stars, and that a larger instrument would resolve many more.

20-foot; for precision measurements, he had an equatorial he had bought from South; and for a preliminary reconnaissance, he had the largest of the 'comet sweepers' his father had made for Caroline (see page 232).

Over the next four years, and with no Caroline to help him, John explored the southern skies with a dedication surpassing even that of his father. The resulting volume, *Results of Astronomical Observations Made During the Years 1834, 5, 6, 7, 8 at the Cape of Good Hope*, appeared, after considerable delays, in 1847. Arguably the greatest single publication in the whole history of observational astronomy, it bore a proud subtitle: 'Being a completion of a telescopic survey of the whole surface of the visible heavens, commenced in 1825', for John Herschel was and would remain the only astronomer in history systematically to examine the entire sky with a major telescope. The book listed over 1,700 nebulae and clusters and over 2,100 double stars, as well as thousands of star counts, extensive sequences of the comparative brightness of stars, and much else besides.

In March 1838, his duty to his father's memory nobly discharged, Herschel took ship for England. His future work in astronomy would be done sitting at a desk. In any case, within a year or two the Herschel monopoly of great reflectors would come to an end, and with it the period in which, as Wilhelm Struve put it, the study of the nebulous heavens had seemed 'almost the exclusive domain of the Herschels'.