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(*b*. Hannover, Germany, 15 November 1738; *d*. Observatory House, Slough, Buckinghamshire, England, 25 August 1822)

astronomy.

Friedrich Wilhelm (William) Herschel was the third of the six surviving children of Isaac Herschel. In 1753 William Herschel joined his father's regimental band as oboist and in 1756 traveled with the band to England, where he learned the language and established musical contacts that were to prove invaluable: in 1757 Hannover was occupied by the French after their defeat of the duke of Cumberland's army, and Herschel, who because of his youth had not been formally enlisted, escaped to England with his brother Jacob.

In England, Herschel supported himself, first by copying music and later by teaching, performing, conducting, and composing. In 1766 he settled at Bath after being appointed organist to the fashionable Octagon Chapel there. By this time Herschel's inquiring mind had moved from the practice of music to its theoretical study in Robert Smith's *Harmonics*, and from there to Smith's *Opticks*, with its extensive account of the construction of telescopes and its summary of the wonders of the heavens. By 1772, when Herschel brought his sister Caroline to England, he was becoming obsessed with astronomy; and over the next decade these interests encroached increasingly on his busy sequence of musical engagements. In 1773 he was hiring telescopes and assembling others from component parts, and in September of that year he bought some secondhand equipment and began to grind his own mirrors. Throughout the rest of his astronomical career Herschel used reflecting telescopes, which avoided the problems of chromatic and spherical aberration and offered the possibility of almost indefinite increase in size.

This possibility was to become of prime importance when, after a few years of desultory observations, he directed his efforts toward understanding "the construction of the heavens," the nature and distribution of distant stars and nebulae, rather than to the study of the nearby members of the solar system, which preoccupied most astronomers of the day. He seems quickly to have realized that in order to investigate very distant (and therefore faint) objects, he would need telescopes with considerable light-gathering power, for a telescope directed to a faint object must not only magnify it but also collect enough light for the magnified image to be visible to the observer. As he put it in 1800, light-gathering power is "the power of penetrating into space." His need was therefore for reflectors with large mirrors; and as his ambitions grew, he found himself forced to undertake an increasing share of the labor of construction himself. In the grinding and polishing of large mirrors, and in the working of exquisite eyepieces, Herschel was soon without peer; and when in 1782 one of his telescopes was taken to the Royal Observatory for comparison with the instruments there, Nevil Maskelyne, the astronomer royal, conceded superiority to Herschel. For the rest of his life Herschel enjoyed the possession of telescopes which were incomparably the most powerful of the period for the study of faint objects, although he never attempted the carefully mounted and graduated instruments required for exact positional astronomy.

By 1779 Herschel had undertaken his first review of the heavens, in which he examined stars down to the fourth magnitude. In August of that year he began a second review, more systematic and extensive than the first, and concentrated (for reasons discussed below) on the discovery of double stars. On 13 March 1781, during this review, he encountered an object which his experienced eye could tell at a glance was not an ordinary star. Yet it was not one of the planets known since the dawn of history, and Herschel supposed it to be a comet. His "Account of a Comet" was read to the Bath Philosophical Society, to which he had been introduced following a chance encounter with William Watson; Watson also communicated the paper to the Royal Society. It is proof of the lead which Herschel had established between himself and other observers that he could recognize the unusual nature of the object at a glance, while they could identify it only by its slow movement relative to neighboring stars. Examination of its orbit by other astronomers showed that the object was actually a primary planet of the solar system; Herschel called it Georgium Sidus to honor George III, but it became known by the more conventional name of Uranus, proposed by J. E. Bode.

The discovery of Uranus marked a turning point in Herschel's career. His scientific isolation had already been reduced by his membership in the Bath Philosophical Society and by the visits of Maskelyne and others. But now he was world-famous as the first recorded discoverer of a planet, even if not everyone would acknowledge the magnifications he claimed for his telescopes. He was awarded the Copley Medal of the Royal Society and elected to fellowship; in May 1782 he was received by the king, and on Watson's prompting he applied for and was granted a royal pension of £200 per annum. He was to live near Windsor Castle, and his only duty was to show the heavens to the royal family from time to time.

Herschel was now able to give up music and devote his full energies to astronomy. In August 1782 he and Caroline moved to Datchet, but the land surrounding the house was flooded when the Thames overflowed. In 1785 they rented a property in Old

Windsor; the landlady proved a tyrant, and the following year they moved to Slough to live in what became known as Observatory House. It was there that Herschel spent the rest of his days.

Because Herschel's pension, supplemented in 1787 by £50 per annum for Caroline's services as his assistant, was barely sufficient for his needs, he manufactured a large number of telescopes for sale; but few of these were used for serious astronomy. The work did, however, allow him to make innumerable experiments on polishing by machinery. His own favorite telescope, completed in 1783, was a reflector with a mirror of eighteen-inch diameter and twenty-foot focal length, but he made two efforts to equip himself with a larger instrument. The first attempt had taken place in 1781, when Herschel set his heart on a reflector with a mirror of three-foot diameter and thirty-foot focal length. He intended, as usual, to polish the mirror himself; but he found on inquiry that even to cast the rough disk was beyond the capacities of the local foundries. Undaunted, he converted the basement of his house into a foundry and made many experiments with metals of different compositions. A mold was prepared from horse dung, and on 11 August Herschel and his brother Alexander "cast the great mirror"; but the mold leaked and the mirror cracked on cooling. On the second attempt, with an improved composition, the molten metal ran over the flagstones, and the brothers were lucky to escape with their lives.

In 1785 Herschel successfully requested the king to finance a fresh attempt to build a large telescope. "It remained now only to fix upon the size of it, and having proposed to the King either a 30 or a 40 feet telescope, His Majesty fixed upon the largest." Four years of labor followed for Herschel and his team of workmen, during which the original grant of £2,000 was doubled and an annual allowance of £200 was also made. The mirrors of forty-eight-inch diameter were cast in London, but all other work was carried out at Slough under Herschel's direction. In mounting the mirror in the tube Herschel tilted it slightly to one side so that the observer might peer through the eyepiece directly at the mirror, without the need for additional mirrors (the "Herschelian" arrangement). The monster telescope was completed in 1789 and immediately revealed a sixth satellite of Saturn. But it was never fully satisfactory: the mirrors tarnished quickly, the structure was cumbersome to turn, and when Herschel in 1790 altered his opinion of the nature of nebulae, he thereby answered the very question the telescope's great light-gathering power may have been intended to settle. Yet it became one of the wonders of the world and a visible testimony to Herschel's mechanical ingenuity and to the scale of his cosmological ambitions.

Herschel's second review of the sky, which extended to stars of the eighth magnitude and resulted in a first catalog (1782) of 269 double and multiple stars, had been concluded late in 1781; and he at once embarked on his third and most complete review, using a higher magnification and examining all Flamsteed's stars and thousands of others besides. This review was vigorously prosecuted once Herschel was established at Datchet. Released at last from his musical duties, "I employed myself now so intirely [*sic*] in astronomical observations, as not to miss a single hour of star-light weather, for which I used either to watch myself or to keep up somebody to watch; and my leisure hours in the day time were spent in preparing and improving telescopes" (*Scientific Papers*, J. L. E. Dreyer, ed., I [London, 1912], 37). The review was completed in January 1784 and resulted in a second catalog (1785) of 434 double and multiple stars.

But now Herschel's interests were changing. There was for the present little more he could contribute to the study of double stars, and in December 1781 Watson had aroused his curiosity in the milky patches in the sky known as nebulae, by presenting him with a newly published catalog of nebulae by Charles Messier. Herschel realized that he was the privileged possessor of the most powerful instruments for the study of these mysterious objects; but Messier's catalog, even when later extended, listed little more than 100 nebulae, and Herschel decided he must again play the natural historian. And so, in October 1783, with his newly completed twenty-foot reflector, he embarked on an intensive twenty-year program of "sweeping" for nebulae and eventually raised the total of those known to 2,500. Even the move from Old Windsor to Slough was achieved without the loss of a single night's viewing.

As a professional musician, and then as an astronomer, Herschel had always thrown himself into his work with single-mindedness; there is no hint that he contemplated marriage until after the death in 1786 of a neighbor, John Pitt. Early in 1788 Herschel became engaged to Pitt's widow, Mary, and they were married in May. Herschel was nearly fifty years old. To Caroline, who had been William's constant companion in his astronomical investigations, this displacement in her brother's affections came as a bitter blow; but in time she was won over by Mary's kindliness. Herschel's daily routine continued as before, but with more frequent holidays and with reduced financial anxiety. In 1792 his only son, John Frederick William, was born. As the years passed, Herschel began to feel the physical effects of his years of unremitting toil; it was not until 30 September 1802, when Herschel was sixty-three, that the program of sweeps came to an end. In 1808 he was desperately ill; but although he never recovered his full health, he continued in his remaining years to struggle with the polishing of mirrors, to carry on his observations, and to develop his cosmogonical theories. He was knighted in 1816, and that year John left Cambridge to become his father's assistant; in this way the aged astronomer's unrivaled experience was transmitted to the next generation. Herschel died peacefully at his Slough home in 1822.

Astronomy of the Nearby Stars . The fundamental problem in sidereal astronomy, in the eighteenth century was to determine the distances of stars, for this knowledge was basic to a study of their distribution in three-dimensional space. It had long been realized that the stars are self-luminous, like the sun; but all attempts to make trigonometric determinations of their distances from measurements of the apparent annual movements of stars which reflect the actual movement of earth about the sun had failed: claims to have measured these apparent movements had always proved mistaken. Yet it was clear from this failure that the apparent movements were minute and that the distances of even the nearest stars were correspondingly vast, and estimates of these distances had been made on the hypothesis that the sun and the stars are equally bright in themselves and differ in appearance only because of their different distances from the observer. Throughout his career Herschel made use of this hypothesis, which had the important merit of offering a method that might well prove practicable not only for the nearest stars but also for objects so distant that there was little hope of ever detecting their apparent annual movements.

But in his early years as an astronomer Herschel had hoped it would be possible for him to make trigonometric determinations of distances and so avoid the need for this assumption; and since he lacked the accurately positioned and graduated instruments normally thought necessary, he followed a suggestion of Galileo and other observers that a watch be kept on pairs of stars very close to each other in the sky in the expectation that the fainter member of each such "double star" would be so distant as to be, for practical purposes, a fixed point from which the apparent annual movements of the brighter (and presumably less distant) member might be measured. It was for this reason that Herschel's second sky survey was mainly in search of double stars, and his catalogs of double stars (1782, 1785, 1821) list 848 examples.

The double-star method of determining stellar distances depended upon considering the two stars' proximity in the telescope as the optical effect of a chance alignment, and it would fail if the two stars were companions in space and thus equidistant from earth. John Michell had pointed out in 1767 that since the number of double stars in the sky was too great for chance alignments to be the usual explanation, most of them must be physical companions; and in 1783 he repeated this with explicit reference to Herschel's work. And so it proved to be. In 1802 Herschel began to reexamine his doubles, and he found that in several of them the two stars had altered position relative to each other in a way that showed they were companions held together by attractive powers. After Herschel's death it was confirmed that the power was, as expected, gravitational attraction, the first proof that gravitational attraction extended beyond the solar system. It is notable that Herschel ignored the implication of his own discovery, for in some cases the two companions were of different apparent brightness although at the same distance from earth; in other words, the differences in brightness were attributable to the stars themselves, in contradiction to the hypothesis that the stars are equally bright, on which rested Herschel's chief hopes of investigating stellar distances. Herschel was not prepared to abandon the hypothesis despite this conclusive evidence to the contrary, and indeed his career in sidereal astronomy can be seen as a prolonged rearguard action in defense of the hypothesis in the face of ever increasing counter evidence.

This hypothesis did indeed offer a theoretical solution to the problem of stellar distances, but it led to practical difficulties: how was one quantitatively to compare the apparent brightnesses from which distances were to be inferred? Surprisingly, an approximate technique for comparing the sun's great brightness with that of stars had been established in 1668 by James Gregory, and the real difficulty lay in the comparison of one star with another. Newton and others had avoided the problem by making the additional assumption that the traditional magnitudes directly represented relative distances, so that a star of, for example, the sixth magnitude was six times further than a star of the first magnitude. Although this assumption could be tested against the plausibility of the resulting stellar distribution, Herschel needed it for most of his career and shrank from exposing it to the potentially destructive test. But in 1817 he developed a method of comparing the light of two stars whereby he directed similar telescopes at each star and masked the aperture of one telescope until the two stars appeared to be of equal brightness; a comparison of the apertures could then be translated into a comparison of the apparent brightnesses. Herschel could at last risk the destruction of his now redundant magnitudes hypothesis, and he easily showed that it led to an absurd stellar distribution.

One notable contribution by Herschel to the study of the stars in the vicinity of earth owed nothing to his skill as an observer and depended entirely on data freely available: his investigations of the motion of the sun and solar system through space. In 1783 Herschel published an analysis of the "proper" or individual motions of a handful of stars as listed by Maskelyne, showing that if the sun was assumed to be moving toward a point in the constellation Hercules, most of these proper motions would be explained as apparent rather than real, reflecting the movement of the observer rather as the daily movement of the stars reflects the daily rotation of the observer on earth. His result is remarkably close to modern estimates.

In 1805 and 1806 Herschel returned to the problem, this time intending to investigate not only the direction but also the velocity of solar motion. To estimate the velocity he needed to know the velocities of neighboring stars relative to the sun (these velocities to be regarded as wholly or partly a reflection of the solar velocity); and he could arrive at some knowledge of the relative velocities of these stars only by taking for each its observed proper motion (angular velocity) and multiplying it by the star's distance. Since Herschel determined the distances of stars from their apparent brightness and for this used his customary hypothesis (which in fact is not even approximately true), he obtained highly disparate results; and only with difficulty did he propose a velocity which reduced this disparity to a minimum. Even so, he was forced to explain why some bright stars appear to have no proper motion and to be at rest relative to the sun despite their presumed nearness: Herschel claimed that they were moving in company with the sun, although this resulted in his assigning these additional motions as the result of an investigation originally intended to have the opposite result, reducing the number of proper motions of stars by showing them to be optical effects only. The complexity of his two-part study defeated his contemporaries, who were unable to unravel his confused argument.

Aside from his catalogs of double stars, Herschel's main contribution to the natural history of the sun's neighbors in space took the form of catalogs of the comparative brightness of stars (1796–1799), in which each star of such a catalog was placed within a delicate sequence of stars ordered in decreasing brightness. By this means a star which was later observed to be no longer in its correct position in the sequence could be identified as variable. Evidence concerning variable stars was desirable because these variations presented a puzzle to which different physical solutions had been proposed, and several of Herschel's early papers discuss particular variable stars. In 1796 he showed from his catalogs that α Herculis varied with a period of about sixty days and so was intermediate between the very long period and very short period variable stars already known. In the same paper he joined himself to those who explained all variations as due to the rotations of stars on their axes.

The Construction of the Heavens . Herschel's most important single achievement in astronomy consisted in his development of far-reaching theories of "the construction of the heavens." Newton, Bentley, Halley, and Loys de Cheseaux had discussed whether the number of stars is finite or not; questions had been asked as to the nature of the nebulae; Thomas Wright, Kant, and Lambert had offered explanations of the Milky Way; and Kant and Lambert had speculated about higher-order systems of stars; but the necessary basis of observational evidence was almost totally lacking. It was Herschel's achievement to assemble a mass of evidence and make it the basis for bold theorizing, thus founding observational cosmology.

Galileo had confirmed earlier speculations that the Milky Way itself is composed of great numbers of stars whose light merges to give the milky appearance: and by 1781, with the publication of Messier's second catalog, the number of known nebulae or milky patches in the sky had risen to just over 100. Herschel, as we have seen, increased this number to 2,500 by twenty years (1783–1802) of systematic "sweeping"; but even before his sweeping began, the gift in 1781 of Messier's earlier catalog had aroused his interest in the problem of the nature of nebulae. According to one view, each nebula was simply a star cluster, the light of the innumerable stars merging to give the milky appearance; according to the other view, some nebulae were star clusters but others were truly nebulous and formed of a self-luminous fluid. Because of the unrivaled light-gathering power of his big telescopes, Herschel was better placed than any other astronomer to decide this question; and he quickly "saw, with the greatest pleasure, that most of the nebulae....yielded to the force of my light and power, and were resolved into stars." In fact Herschel had succeeded in resolving some nebulae and had convinced himself that others were "resolvable" and would be resolved with a larger telescope; from this he quickly generalized and claimed that all nebulae are star clusters.

As he considered his growing collections of nebulae, Herschel not surprisingly saw these alleged clusters as evidence of the continuing activity of clustering or attractive powers; and in three important papers (1784, 1785, 1789) he developed a cosmogony in which the universe began with stars scattered throughout infinite space: with the passage of time, and under the action of these attractive powers, the stars began to condense toward regions where their initial density had been above average; and with the further passage of time the loose, large associations of stars which had been formed gave way to fragmented and tightly packed clusters. Herschel considered that groups of nebulae which he discovered represented the fragments of larger associations of stars, and he took a similar view of the star clusters of the Milky Way.

In the 1784 and 1785 papers Herschel also inaugurated the scientific study of the Milky Way. Whether he was then aware of previous speculations concerning the structure of the Milky Way star system is uncertain. Thomas Wright of Durham in 1750 had correctly suggested, in *An Original Theory or New Hypothesis of the Universe*, that the appearance of the Milky Way as a zone of light encircling the sky is the result of our immersion in what approximates (but for Wright, only locally) to a flat layer of stars, the milkiness appearing when—and only when—we look out along the layer; but Wright had then grafted this insight onto his fundamental belief that the stars are symmetrically arranged about a supernatural center. Herschel may have encountered Wright's book during his years (1760–1766) as a performer and music teacher in the north of England; it is unlikely that by 1784, when he published his own first study of the Milky Way, he was aware of the view of Kant and Lambert that the Milky Way star system to which the sun belongs not only approximates locally to, but actually is, a flat, finite layer of stars.

Herschel adopted a similar view but went on to ask how he might chart the outline of this layer. Obviously he must first assume that his telescopes could reach the stars at the borders of our system in every direction, since otherwise the task was impossible. To go on to determine the distance to the border in any given direction, Herschel could in principle have examined the faintest star in that region and, on his customary assumption that differences in apparent brightness are entirely the result of differences in distance, calculated the distance of the star from its apparent brightness. But the measurements involved were impracticable; and instead Herschel made use of information which was actually accessible to him, the different numbers of stars visible in different fields of view. Making the assumption that within the borders of our star system the stars are spread out regularly, he included in his early sweeps a number of "gages" or star counts and with a simple mathematical formula interpreted high counts as evidence of large distances to the border in the relevant directions. Time was precious and he carried out this program only for a great circle in the sky, but the map of a cross section of our star system which resulted (1785) was proof of the power of this new technique of stellar statistics.

In later years Herschel's preoccupation with star clusters brought home to him the gulf between the observational evidence and his assumption of uniform distribution, and the completion of the forty-foot telescope revealed stars which had been inaccessible in his earlier instruments. He therefore had to abandon each of his two assumptions and the map based on them, and he admitted that in some directions at least the star system seemed "fathomless."

Herschel's identification of nebulae with star clusters provided the foundation for his theory of the construction of the heavens published in the 1780's; for if stars could not be detected in a particular nebula, it must be because of the great distance of the nebula. In this way Herschel believed himself to have some understanding of the distances, and therefore the sizes, of nebulae; some nebulae, he believed, "may well outvie our milky-way in grandeur" (1785). He chose simply to ignore evidence of changes in certain nebulae which by their rapidity showed that the nebulae in question must be small, and therefore near. However, on 13 November 1790 he observed a nebula (NGC 1514) which he realized consisted of a central star surrounded by a luminous shell which could not be composed of stars; he admitted the existence of "true nebulosity" in a paper published the following year.

It was no longer possible for Herschel to discuss with confidence the construction of the heavens. An "unresolved" nebula might be near, small, and nebulous; or it might be a distant, vast star system. But he was able to adapt to the new evidence his earlier account of the life history of a star cluster and thus add further emphasis to the temporal element in his theorizing. Believing NGC 1514 to represent a star condensing out of the luminous "matter, he published in 1811 and 1814 a theory of the development of a star cluster, beginning with "extensive diffused nebulosity" which gradually condenses into stars which in turn cluster together ever more tightly. Illustrated with many examples at every stage, these papers showed brilliantly how dynamic changes can be inferred from virtually static evidence; and Herschel concluded by characterizing the Milky Way in its present stage of dissolution as "this mysterious chronometer."

The Solar System . Although Herschel's contributions to the study of the sun, moon, planets, and comets are less significant than his investigations of the sidereal universe, he constantly interrupted his observing programs to examine these nearby objects, and nearly half of his published papers are devoted to the solar system. Herschel was no mathematician and he could not advance the mathematical analysis of planetary motions on Newtonian principles, nor did his instruments have the precision necessary for positional astronomy; but his skill as an observer and the excellence of his telescopes enabled him to contribute to the knowledge of the physical constitution of most of the principal members of the solar system.

The Sun. Herschel's interest in the sun was naturally stimulated by the realization that, of all the stars, it alone is close enough for detailed examination. He was aware of the various existing theories of the physical constitution of the sun. In a long paper published in 1795 he mentions some of them before listing his own observations and arguing that what we actually see is not the sun itself but its luminous atmosphere, which surrounds the planetlike body of the sun. Mountains on the sun, which protrude through the luminous atmosphere as dark spots, are occasionally glimpsed as sunspots. He claims that rays from the sun's atmosphere produce heat only when they act upon "a calorific medium"—which is why mountaintops on earth are cold—and so the sun itself can and does support life, and by analogy the same is true of the other stars.

In 1801, in a second long paper in which he arranged his observations according to relevant physical questions, he modified his earlier account of the sun to include in its constitution an interior layer of dark clouds not unlike our own, this layer serving to shield the solar inhabitants from the exterior, luminous layer.

By this time Herschel had extensive experience of the use of "various combinations of differently-coloured darkening glasses" in observing the sun. "What appeared remarkable," he wrote in March 1800, "was, that when I used some of them, I felt a sensation of heat, though I had but little light; while others gave me much light, with scarce any sensation of heat." This suggested experiments with a prism and thermometers which showed that radiant heat is refrangible, but in such a way that its maximum is very different from the maximum of illumination: ".....the full red falls still short of the maximum of heat; which perhaps lies even a little beyond visible refraction." In hundreds of further experiments, Herschel confirmed the existence of invisible, infrared heat rays, and showed that heat, whether solar or terrestrial, obeys laws of reflection and refraction analogous to those of light.

In a less happy venture into the physics of light, Herschel devoted three papers (1807–1810) to investigating the cause of colored concentric rings ("Newton's rings"). Ignoring the explanation already given by Thomas Young whereby the rings result from interference between light waves, Herschel criticized Newton's theory and attempted one of his own. He brought down on his head a storm of criticism, and this may have been a cause of his poor health at this period.

The Moon. In the winter of 1779–1780 Herschel calculated the height of several lunar mountains by adapting the method of Galileo and others. This involved measuring the angular distances between the mountain and the boundary of the illuminated part of the moon, at the time when the sun's rays first reached the peak of the mountain. To make the delicate measurements Herschel used a bifilar micrometer, which he calibrated by applying it to known terrestrial objects. He concluded that the height of lunar mountains had been exaggerated and that "the generality do not exceed half a mile in their perpendicular elevation."

Herschel makes no secret of his belief that argument from analogy shows that there is "great probability, not to say almost absolute certainty," of the moon's being inhabited, and in 1787 he used analogy to interpret certain observations of three volcanoes on the moon. In the eclipse of 22 October 1790 he saw at least 150 "bright, red, luminous points," but for once refused to speculate on their cause.

Mercury. Transits of Mercury and Venus across the sun offer a means of determining the distance of the earth from the sun, a fundamental quantity in astronomy, and so the transit of Mercury on 9 November 1802 was carefully studied and timed by astronomers.

Herschel restricted himself simply to observing the appearance of the planet. He reported that "the whole disk of Mercury is as sharply defined as possible; there is not the least appearance of any atmospheric ring." He added that the planet offered a perfectly round outline, so that it was unlikely to be materially flattened at its poles.

Venus. In 1793 Herschel published a lengthy paper entitled "Observations of the Planet Venus," which was provoked by the extravagant claims made the previous year by J. H. Schröter. Schröter claimed to have observed on Venus mountains of immense height, and to have noticed that one cusp appeared blunt because of the shadow of a mountain.

In his paper Herschel demolished these claims by quoting from his own numerous observations going back to 1777 (when he had hoped to resolve a controversy over the period of rotation of the planet), and especially from the series he carried out in the spring of 1793 specifically to test Schröter's assertions. Herschel concluded by agreeing with other astronomers that Venus has a considerable atmosphere and (rightly) dismissed Schröter's mountains. He admitted that this atmosphere had defeated his attempts to determine the period of rotation of the planet (as it defeated astronomers until our own day), in contrast to the less cautious claims of Schröter and others to have established a period of about twenty-three hours.

Mars. The clearly defined markings on Mars enable the period of rotation of the planet to be determined with accuracy. Herschel's observations, published in 1781, gave by his calculations a value of $24^h\ 39^m\ 21.67^8$, which closely confirmed earlier estimates; but they would have brought him within some three seconds of the modern value of $24^h\ 37^m\ 23^8$ if he had not neglected to apply certain corrections.

In 1784 Herschel published a lengthy paper on Mars, in which he reprinted numerous observations on the shape of the planet and on the polar regions to establish the inclination of its axis. He made an elaborate study of the white regions at the polar caps and concluded "that the bright polar spots are owing to the vivid reflection of light from frozen regions; and that the reduction of those spots is to be ascribed to their being exposed to the sun," a view which is still accepted today.

The Asteroids. Ceres, the first known celestial body in orbit between Mars and Jupiter, was discovered early in 1801, but it was soon lost in the glare of the sun and was not rediscovered until the end of the year.

Herschel first saw Ceres on 7 February 1802, and it was a week before he could detect a visible disk such as is characteristic of the appearance of a planet; evidently Ceres was very small. With his lucid-disk micrometer for comparing celestial bodies with lamps of controlled characteristics, he carried out careful observations of Ceres and then of the newly discovered Pallas, calculating their diameters to be under 200 miles and believing them to have considerable comae. As they differed so much from the known planets and comets, Herschel felt a different term would be appropriate for them, and proposed "asteroid" because even in a good telescope they resembled stars. He also forecast that more would be discovered, a prediction fulfilled with the discoveries of Juno in 1804 and Vesta in 1807.

Jupiter. Herschel's main contribution to the study of Jupiter took the form of a long paper, published in 1797, on the planet's four known satellites. As usual he began by reprinting his earlier observations. He then used his findings to argue that each satellite always returns to its original apparent brightness after every orbit around the parent planet, and that (like our moon) it will rotate on its axis in the time it takes to complete one orbit.

Saturn. Saturn exercised a special fascination for Herschel, and between 1789 and 1808 he devoted seven papers and part of an eighth to the planet, its ring, and its satellites.

On 19 August 1787 Herschel suspected he had found a sixth and previously unknown satellite, but he was not able to confirm this until 28 August 1789, when his forty-foot telescope came into commission. A few days later he found a seventh satellite. For some months he carefully tracked the satellites, establishing for Mimas and Enceladus periods within seconds of the modern values, and giving evidence to show that Iapetus rotates in its period of revolution.

He also made careful observations of the rings, which he believed to be solid. As the earth happened to be in the plane of the ring structure at the time, he compared the thickness of the ring when seen edge-on with the diameter of Jupiter's satellites; and although his estimate exceeds modern values, his method showed that the thickness did not exceed a few hundred miles.

Like other astronomers before and since, Herschel was puzzled by "luminous points" which he observed in the rings. He at first thought they were caused by irregularities in the surface of the rings, but changed his mind in 1789 when "one of these supposed luminous points was kind enough to venture off the edge of the ring, and appeared in the shape of a satellite." He tried to relate the observations of luminous spots to the movements of the known satellites, but found that numerous observations remained unaccountedfor. About twenty of these could be explained by the revolution in just over ten and a half hours of a satellite within the ring system, and in 1791 Herschel assigned this period to the rotation of the ring system (specifically to the outer ring); a result which, although substantially correct, seems to be based on illusory data.

In 1791 Herschel examined the dark region between the inner and outer rings to decide whether this region could be a genuine gap between the rings. He had already observed the southern face of the region, and now it was the northern face that was visible. Careful observations showed that the region appeared to be entirely uniform. Since (as he believed) the ring system was rotating rapidly, the evidence for uniformity was as complete as one could hope for, and he categorically asserted that a gap existed between two rings. But the conclusive test which he suggested, as to whether a star might on occasion be seen beyond and between the two rings, was not successfully made until long after his death. In the same paper he also gave micrometer measures of the breadth of each ring and of the gap.

Herschel's observations of the globe of Saturn were reported in six different papers. He discussed the belts and also the shadow of the rings (but overlooked the "Crepe Ring"), and he showed that the planet is compressed at the poles; this suggested Saturn was rotating. By a remarkably bold argument based on fluctuations in the appearance of the belts, he proposed in 1794 a rotation period of $10^h\ 16^m\ 0.4^s$, which is very close to the modern value of $10^h\ 14^m$.

Uranus. In addition to his account of the discovery of Uranus on 13 March 1,781 and a letter naming the planet Georgium Sidus, Herschel published five papers on the planet and its satellites.

His search for possible satellites was not successful until 1787, when he adopted the “Herschelian” arrangement of tilting the telescopic mirror slightly in the tube and looking at it through the eyepiece directly. The resultant light-gain enabled him to discover two satellites; his determinations of the shape and size of their orbits are in close agreement with modern values. In 1788 he was able to give their synodic revolution periods, again in excellent agreement with modern values; and he also gave the first determination of the mass of the planet.

His two long papers of 1798 and 1815 were devoted almost entirely to satellites. In 1798 he made the astonishing announcement that the motion of the two known satellites of Uranus was retrograde. He also believed, as the result of numerous difficult observations, that he had discovered four additional satellites, but their existence has not been confirmed.

Comets. The discovery of comets was the prerogative of Caroline Herschel rather than her brother, but William did publish extended accounts of his observations of the great comets of 1807 and 1811, with a view to elucidating their physical nature. In discussing the 1811 comet, he suggested that such a comet had an atmosphere and, within this, nebulous matter gathered about the head of the comet. When the comet approaches the sun the nebulous matter is rarefied and suspended in the atmosphere, where it is exposed to the solar heat.

....and if we suppose the attenuation and decomposition of this matter to be carried on till its particles are sufficiently minute to receive a slow motion from the impulse of the solar beams, then will they gradually recede from the hemisphere exposed to the sun, and ascend in a very moderately diverging direction towards the regions of the fixed stars.

Physical Speculations . In 1780 and 1781 Herschel read numerous papers to the Bath Philosophical Society, dealing with a variety of subjects including electricity and the nature of matter. Prompted by what he had read of the ideas of John Michell and R. J. Bošković in Joseph Priestley’s *Disquisitions Relating to Matter and Spirit* (1777), Herschel supposed that each particle of matter was endowed with a system of centrally acting forces (unlike Bošković’s theory of distinct zones of attractive and repulsive forces); he argued that phenomena such as the absorption and reflection of light were caused by the joint effect of the different forces. This is an extension of the Newtonian theory of atoms as surrounded by envelopes of forces.

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M. A. Hoskin