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The Cosmology of William Herschel

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Abstract. William Herschel was an amateur astronomer for half his life, until his discovery of Uranus earned him a royal pension. He then set himself to study "the construction of the heavens" with great reflectors, and discovered over 2,500 nebulae and star clusters. Clusters had clearly formed by the action of gravity, and so scattered clusters would in time become ever more compressed: scattered clusters were young, compressed clusters old. This marked the end of the 'clockwork' universe of Newton and Leibniz.

In the time of Newton and Leibniz, God was seen as the great clockmaker, and the planets cycled eternally around the Sun as the hands of a clock rotate eternally over the clockface. Newton believed that in the long term the gravitational pulls of the planets on each other would threaten the stability of the system, but then God would intervene to restore order: the Great Clockmaker had a servicing contract with his Creation. The stars formed a backcloth to the motions of the planets, but they were virtually unchanging — "fixed", as the ancient Greeks had termed them — and therefore of little interest. According to Newton, the stars were more-or-less motionless in space because each was pulled gravitationally by roughly equal stars to one side and to the other; but here too God would intervene whenever the stability was threatened.

The world we live in today could hardly be more different. The solar system is a minority interest among astronomers. And, far from being unchanging, everything in the universe has a life-story: stars are born and die, and even the universe itself began with a Big Bang and has evolved ever since. If Newton lived in a mechanical universe, we might be said to live in a biological one. The transformation has been as profound as any episode in the history of science. And the man who did more than any other to bring about this transformation was William Herschel.

Herschel was born in Hanover, Germany, in 1738, the third son of a humble bandsman in the Hanoverian Guards. When he was 14 he left school and followed his father Isaac and his elder brother Jacob into the band of the Guards. At the time the ruler or Elector of Hanover was also King George II of Britain, and in 1756 the Guards sailed to England to reinforce the country against a possible invasion by the French. They returned home at the end of the year, only for the Hanoverians and their allies to be defeated by the French near to home, at the Battle of Hastenbeck in July 1757. Isaac sent his two sons to England as refugees, and for two years they made a precarious living as musicians in London and the Home Counties. Then peace was restored, Jacob returned home, while

William went to the north of England where there was less competition among musicians than in London. There he made a comfortable living performing and teaching music, and he wrote a large number of symphonies and concertos.

Isaac had always encouraged his boys to interest themselves in matters of the mind, and William used some of his leisure to study the book on *Harmonics* by the Cambridge professor, Robert Smith. He liked it so much that he later bought Smith's other work, the two-volume *Opticks*. This taught him a lot about how to make telescopes and a little of what to see with the completed instruments.

At the end of 1766 Herschel accepted an invitation to become organist at a private chapel in the spa resort of Bath in the west of England, the most profitable place for a musician outside London. It was now that — perhaps under the influence of Robert Smith — he began to develop a passion for astronomy. In 1770 he was joined there by his younger brother Alexander, a musician with an exceptional talent for clockwork and other gadgetry, and in 1772 by their sister Caroline who proved to be brilliant as an amanuensis. In time the three of them were to form the greatest partnership astronomy has ever seen.

Some astronomers down the centuries have excelled in the construction of instruments; others have excelled as observers; a few have excelled as theoreticians. Herschel, uniquely, was to excel in all three.

First, the construction of instruments. With the aid of Smith, Herschel taught himself to build reflecting telescopes, devising the tube and stand made of wood, casting and grinding and polishing the mirror, and fabricating eyepieces that astonished professional opticians. In his Bath days these were mostly small precision instruments for the study of the planets and nearby stars, but later in his career he built monsters with large mirrors designed to collect enough light from distant and faint objects for them to become visible to the eye of the observer. These were to be the foundation of his investigations into cosmology, for the study of what he termed "the construction of the heavens".

In his Bath days it was the 7-inch mirror he made in 1778 for his 7-ft reflector that was of first importance, for this mirror was quite simply the finest in the world. With it he began systematically to examine each of the brighter stars to see which were single and which were double, that is, two stars so close together that at first sight they appear as one. The first double he identified was the Pole Star, but so exceptional was his telescope that it was months before any other observer could confirm his claim. He went on to publish in 1782 a catalogue of 269 double stars, followed by a second catalogue in 1785 of a further 434 doubles. It was evident to the astronomical community that a telescope-maker and observer of exceptional talent and dedication had appeared on the scene, and those with influence in Royal Society circles began to look for ways by which Herschel could be freed from the need to earn his living from music and enabled to dedicate himself full-time to astronomy.

Their opportunity came in March 1781, when Herschel's systematic examination of the brighter stars took him to a star-like object that he recognized instantly was not a normal star. When he went back to it four nights later, he found that it had already moved: it was therefore nearby to Earth, a member of the solar system. Herschel assumed it must be a comet, but it proved to be a planet, the first to be discovered since the dawn of history. Herschel's friends encouraged him to dedicate it to the king, George III, in the tradition of patronage whereby Galileo had long before named the moons of Jupiter the Medicean Stars, in honour of the ruling family of Tuscany. Herschel named his planet the Georgian Star, but we know it as Uranus.

Just as the Grand Duke of Tuscany had been expected to reward Galileo financially for the dedication, so George III was required to reward Herschel, by making him a professional astronomer, and allowing him to give up the daily grind of the musician. It was not obvious to the King just how this was to be achieved, but eventually, in the autumn of 1782, he offered Herschel a salary to come and live near Windsor Castle, with the sole duty of showing the heavens to the Royal Family and their guests when asked to do so; otherwise his time was his own. A year later the King placed with Herschel an order for the construction of five reflectors, thus launching him on a profitable career as telescope maker.

Hitherto astronomy had been mainly the study of individual bodies well-known to everyone: the Sun, the Moon, the various planets and their satellites, and the occasional comet. The stars provided a background to the motions of these familiar bodies, motions that taxed the minds of the greatest mathematicians of the eighteenth century. Herschel was self-taught, and no-one told him that this was what astronomers were supposed to do. He instead set his heart on exploring the universe of stars, and he did so by introducing into astronomy the methodology of the natural historian.

We see this already in his search for double stars. These stars he classified according to how close the two stars of the double were, and by the date of discovery, much as a butterfly collector organizes his specimens — indeed Herschel had learned this methodology from his younger brother Dietrich, who spent a couple of years in Bath and who was a professional musician and an amateur butterfly collector. But the double stars were intended to shed light on a major problem of stellar astronomy, namely the distances that separate the solar system from the nearer stars. We on Earth are orbiting the Sun every twelve months, and as we observe a star from this moving platform, the star should appear to move, the more so the nearer it is. The difficulty was that the stars are so distant that the movement in question is minute and very difficult to detect — it is in fact no more than the width of a coin at a distance of several kilometres. And the movement takes place over an annual cycle, months during which all sorts of complications can interfere with the instrumentation and with the measurements themselves. A contemporary of Galileo had proposed that if two stars lie in the same direction from Earth — that is, if they form a double star — and if one is very distant and the other near, then the distant one will serve as a quasi-fixed reference point against which we can measure the apparent movement of the nearer star. Because the two stars will be equally affected by any changes in the instrumentation and so forth, measuring the motion of the nearer relative to the more distant would avoid these complications.

However, this method assumes that double stars are made up of two independent bodies at very different distances from Earth, and that they lie in the same direction purely by chance. But it had been pointed out by John Michell in 1767 that the number of double stars is much too high for chance to be the usual explanation: in most doubles it must be that the two stars *appear* to be companions because they *are* companions, neighbours in space bound to each other by attractive forces, no doubt Newtonian gravity. Luckily, Herschel knew nothing of Michell's paper until his search for double stars was well advanced.

But once he did learn of it, he then had reason to believe that Newtonian gravity operates among the stars, and this was to become the fundamental insight underlying his cosmology.

In his Bath days, Herschel's largest telescope was of 20-feet focal length and had mirrors 12 inches in diameter. But it was simply slung from a pole, and the observer was perched at the top of a tall ladder, in mortal danger. As soon as he was established in the Windsor area, he began construction of a second reflector of 20 feet, but this time it had 18-inch mirrors and — more importantly — had a stable wooden-frame mounting. If the telescope was fixed in the meridian like a transit instrument, the observer might prefer the observing chair, but if Herschel needed to track an object by pulling the tube from side to side, he would have to use the observing platform. This instrument was the foundation of Herschel's success as a cosmologist, and after his death his son John was to take a matching instrument south to the Cape of Good Hope to extent his father's work to the southern skies.

Herschel had not been long in the Windsor area before he was planning with his allies, notably the President of the Royal Society, to petition the King to fund a reflector of a size the world had never seen. And in 1785 King George made a grant of £2000 for a 40-ft reflector with mirrors 4-ft in diameter.

It was to prove a disaster. First, although it was a scaled-up version of the 20-ft in many respects, it was too cumbersome. Whereas the 20-ft could be moved by a single workman, the 40-ft required two, and it took a long time to get it ready and pointed in the required direction. Second, the construction called for an army of workers, and the design of the instrument and the supervision of the workers occupied endless hours when Herschel was in his prime and had other things to do. Third, it proved much more expensive than Herschel had estimated, and although the King gave a second grant of £2000 rather than have the enterprise end in total failure, he greatly resented having to do so, and relations between him and Herschel never recovered. Fourth, the first mirror was so heavy that it lost shape when tilted in the tube. To prevent this, the second mirror was made of a different alloy, and it tarnished quickly. To lift this one-ton mirror out of the tube for repolishing was a huge and unwelcome task for Herschel and his brother Alexander in later life, yet the succession of royal and aristocratic visitors sent from Windsor Castle was never-ending, and to keep these visitors happy the instrument had to have the appearance of being in working order. But fifth, as we shall see, the theoretical question that the instrument was designed to answer was settled soon after the reflector was completed, and so the monster lost its primary purpose.

Herschel therefore was outstanding in the first aspect of greatness in an astronomer. He was soon the world's leading builder of reflectors large and small, and the kings and emperors of Europe competed to persuade him to accept a commission. And we have seen something of his greatness in the second aspect, that of an observer: his catalogues of double stars. His outstanding achievement as an observer, however, and the foundation of his cosmology, lay in his catalogues of nebulae and clusters of stars; and in this his sister Caroline played an essential role.

It was a few months before the time of Herschel's move to Windsor that the French comet hunter, Charles Messier, published his definitive catalogue of one hundred or so nebulae and clusters that we still use today. Caroline's career as a singer was now at an end, and her brother supposed she had time on her hands, so on their arrival at Windsor in the autumn of 1782 he gave her a little refractor and told her to look for anything of interest, such as comets or nebulae. She quickly came across some of the Messier objects that Herschel himself had never seen, and then early in the new year she began to discover nebulae that hitherto had been unknown to science. It was an astonishing achievement for a novice observer equipped with what was little more than a toy, and her brother was impressed. He too "began to sweep the heaven for nebulas and clusters of stars", using a small achromatic refractor for the purpose. It then occurred to him that the whereas newly arriving comets had to be searched for as a matter of urgency with small telescopes that had a large field of view, the nebulae were permanent and would await leisurely scrutiny with a big reflector — and his new 20-ft was nearing completion.

The 20-ft came into service in October 1783, and Herschel at once embarked on a search for nebulae and clusters. But the objects he was searching for were faint, at the limits of visibility, and when he went into artificial light to make written notes, it would be minutes before his eyes were once more adjusted to the dark. And so at the end of the year he abandoned these solo attempts and organized instead a team operation. The telescope would always be facing exactly south, in the manner of a transit instrument, and William would watch the sky as it rotated overhead, constantly bringing new regions under examination. Caroline sat at a desk at a window with reference books (one compiled by herself), a clock, and so forth. When her brother saw a nebula or cluster, he pulled a string as a signal. Caroline opened the window, copied down his shouted observations, and identified the stars he was using as reference points to define the position of the nebula. Next day she would write up a fair copy of the night's observations, and in due course she would assemble a catalogue of newly discovered nebulae and clusters for publication in *Philosophical Transactions* — one thousand in 1786, a second thousand in 1789, and 510 in 1802, at which time Herschel lost interest and terminated the search with some small areas of sky still to be examined. These 2510 objects — to be compared with the hundred or so of Messier — were re-examined by William's son John in the 1820s, and organized into a systematic, unified catalogue that could be used by observers — for William Herschel was a natural historian of the heavens and his catalogues were organized by type and date and so of little use to other astronomers. John Herschel then went to the Cape of Good Hope and swept for nebulae in the southern skies his father had never seen, and in 1864 he consolidated all known observations of nebulae and clusters into a catalogue that is the immediate ancestor of the New General Catalogue that we all use today.

Herschel, then, was a great telescope builder and a great observer, but equally he was a bold and innovative theorist: in 1811 he declared in *Philosophical Transactions*, "A knowledge of the construction of the heavens [that is, cosmology] has always been the ultimate object of my observations", and already in 1785 he had warned his readers that he would try to keep a balance between speculating too much and too little, "but if I should deviate from that, I could wish not to fall into the latter error". What, then, were the issues in cosmology that so concerned him?

Since the time of Descartes in the mid-seventeenth century, it had been understood that stars are distant suns and our Sun merely our local star, and it was thought that the stars are physically similar to each other. It was this principle that led Newton to the conclusion that Sirius is about one millions times further from us than is the Sun (because its light is one million million times fainter than the Sun's). There had been surprisingly little interest in the Milky Way, which was the preserve of theological speculators in the mid-eighteenth century. But the nebulae, the cloudy spots of light listed by Ptolemy long ago and much better understood as the eighteenth-century dawned, were of some controversy. Clearly a cluster of stars that was so far away that the individual stars could not be distinguished by the best telescopes of the day would appear nebulous. But were *all* nebulae simply clusters of stars, or were some of them true nebulae, 'gaseous' as we would say?

One test was whether a new and more powerful telescope proved able to 'resolve' into stars nebulae that hitherto had resisted resolution. But such a test would only be persuasive rather than compelling, because no doubt there would always be *some* nebulae that so far had resisted resolution, and it might therefore be dangerous to generalize.

A more interesting test would be whether any nebula had changed shape in only a few years. For if a nebula was a cluster of stars so distant that telescopes could not distinguish the individual stars, its size in kilometres must be enormous, and so it could not change shape in a short space of time. A nebula that was known to change must therefore be near, small, and truly nebulous. The problem was that a nebula will look different to different observers armed with different telescopes and using them under different seeing conditions. When, therefore, will an apparent change reflect an actual change in the nebula itself?

It seems that Herschel understood the significance of authentic changes in nebulae right from March 1774 when he opened his first observing book. He knew of the sketch of the Orion Nebula that Smith had reproduced, in fact from Huygens in 1656, and Herschel made his own sketch and remarked on the difference. He comments: "from this one 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." In his remaining eight years in Bath he observed only three other nebulae, but the Orion Nebula he observed seven more times and sketched twice, on the second occasion remarking "there is a visible alteration in the figure of the lucid part".

Arrived in the Windsor area, he slowly enlarged his familiarity with nebulae, and he even showed two of them to King George. The changes he believed he had seen in the Orion Nebula had convinced him that it was a small, nearby cloud of true nebulosity, and therefore there were in the heavens both true nebulae, of which this was an example, and star clusters that appeared nebulous because of their great distance. How was he to distinguish the two?

He was sometimes encountering examples of smooth, milky nebulosity, and sometimes uneven, mottled nebulosity. He decided, plausibly enough, that the smooth nebulae were true, nearby clouds of nebulosity, whereas the mottled nebulae were star clusters at great distances. And this was the theory he advanced in his first paper on "the construction of the heavens", published in 1784. But no sooner had the paper been sent to the Royal Society than Herschel came across two nebulae in each of which the two forms of nebulae coexisted. This convinced him that he had been fundamentally mistaken, and that in each of the two nebulae the mottled nebulosity indicated the presence of stars in the middle distance, while the milky nebulosity was the effect of stars at greater distances. Closing his mind to the changes he had earlier supposedly detected in the Orion Nebula, he argued in his 1785 and 1789 papers on the construction of the heavens that all nebulae are star clusters — that there is no such thing as 'true nebulosity'.

The existence of clusters proved that Newtonian attraction (or some similar force) was at work among the stars, as Michell had argued: stars pulled each other, and so gradually moved closer and closer together, to form the clusters. Some clusters were scattered, while others were condensed and tightly packed. But as time goes on, the stars of a scattered cluster will continue to pull each other closer and closer together, and the cluster will then become condensed. In other words — and it is impossible to exaggerate the importance of this insight in the history of cosmology — scattered clusters are young, and condensed clusters are old.

The human life-span is too short for us to live to see a star cluster going through its own life cycle, but Herschel could give us an equivalent experience, by putting before us examples of young clusters, and then middle-aged clusters, and then clusters in old age. And this is exactly what he did. It would take generations before astronomers generally accepted this revolutionary new way of looking at the universe, but Herschel had rung the death-knell of the clockwork universe, and introduced the new, evolutionary cosmogony.

How did the evolution of a cluster end? Herschel had long ago come across examples of a puzzling new type of object. It had the disk of a planet, but the pale light of a nebula, and so he called these objects 'planetary nebulae'. In the 1780s he thought that these might be highly condensed star systems about to suffer what we would call 'gravitational collapse'. Perhaps Tycho's nova of 1572 was itself an example of such a cataclysmic event.

And then, in November 1790, he was sweeping for nebulae when he came across "a most singular phaenomenon! A star of about the eighth magnitude, with a faint luminous atmosphere...". It was in fact another planetary nebula, the one we know as NGC 1514, but this time it was near enough for Herschel to see the central star with its luminous atmosphere. For him it was a nebulous star. And he accepted the obvious implication: it was a star condensing out of a cloud of true nebulosity. He recognized at once that he had been mistaken in thinking that all nebulae were star clusters: true nebulosity really did exist.

This required him to taken his cosmogony further back in time, before the formation of stars. In the universe light was circulating, and under gravity it was forming itself into clouds of nebulosity. Under gravity these clouds became more and more condensed, until stars began to form. These stars pulled each other together to form scattered clusters, and then more tightly packed clusters, perhaps leading to gravitational collapse and the generation of light that would help start the whole cycle over again.

But what about the Milky Way? Galileo had shown that it was a vast system of stars, and more recent speculators had realized that it was probably a layer or stratum of stars in which we are immersed. We see the milky effect of innumerable stars when we look around within the layer, but when we look outwards we see only a few near and therefore bright stars before our gaze penetrates into outer space. But what is the exact shape of the layer of stars that make up the Milky Way?

Herschel realized that he could answer this question if he made two assumptions. The first, obviously, was that his biggest telescope could penetrate to the borders in all directions, for unless this was so his attempt was doomed from the start. The second was more controversial. Herschel assumed that the space within the Milky Way is more-or-less uniformly filled with stars, so that the more stars we see in a particular direction, the further the Milky Way extends in that direction. In a pioneering exercise in stellar statistics, Herschel systematically turned his 20-ft reflector around a great circle of the sky, and counted the stars, and in his 1785 paper he converted this information into a diagram that showed a cross-section of the Milky Way.

Since the Orion Nebula, and the Andromeda Nebula, and the other great nebulae in the sky, were star systems (as he believed at the time), and since they were so far away that he could not distinguish the individual stars, in size they must be enormous, and (as he put it) "they may well outvie our milky way in grandeur". In others words, the solar system belongs to a galaxy known to be of finite extent, and it seems that some of the other nebulae are even larger galaxies.

Later he realized that both assumptions were false. His new 40-ft brought many more stars into view, and he could no longer justify the claim that he could see to the borders of our Galaxy in every direction. For all he knew, it was without limits, "fathomless". And as he studied star clusters, year after year, he realized that the stars within our Galaxy are nowhere near uniformly distributed. And so he had to abandon the attempt to map our Galaxy. And since he now accepted that true nebulosity existed, he had no way of deciding whether the Orion Nebula was a true nebula, near and small, or a galaxy — but if it was a galaxy, it was evidently of finite extent, which is more than could be said of our own Galaxy.

Herschel therefore began by believing that true nebulosity existed, and that some nebulae were star clusters whereas others were truly nebulous. He then decided in 1784 that all nebulae were star clusters, and in this simple context he saw that some clusters are young and others old, and that clusters therefore go through a life-cycle. When in 1790 he found a nebula that looked to be a star condensing out of true nebulosity, he carried his cosmogony back in time, to when light condenses into clouds of nebulosity, out of which stars are born, to form clusters that are ever more concentrated, and perhaps reach a final cataclysm, after which the cycle begins again. The Milky Way he saw as a stratum of stars of which we are part, and in 1785 he attempted to map this stratum. At this stage he saw other nebulae as star clusters, and some of them were galaxies larger than our own. Later he realized that our Galaxy appeared to be without limits, while the other possible galaxies may in fact be no more than nearby clouds of luminous fluid.

His thoughts on our Galaxy and on the existence of other galaxies therefore ended in some confusion. But he had demonstrated that the universe of stars is a rich field for study, and that in it there is life and death, coming-to-be and passing-away. It was a far cry from the clockwork universe of Newton.

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