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WILLIAM HERSCHEL AND THE NEBULAE, PART 1: 1774–1784

MICHAEL HOSKIN, Churchill College, Cambridge

Introduction

The prehistory of the mysterious milky patches in the sky known as nebulae goes back to Antiquity, but eighteenth-century writers often took their lead from the short paper that Edmond Halley published in 1715, "An account of several nebulae or lucid spots like clouds".[1] Halley listed six nebulae: those known to us as M11, M13, M22, M31 and M42, together with ω Centauri which is too far south to be visible from England. They are, Halley declared, "Light coming from an extraordinary great Space in the Ether; through which a lucid *Medium* is diffused, that shines with its own proper Lustre".

But a star system so distant that existing telescopes were not powerful enough to 'resolve' it into stars would also appear nebulous, and there could be little doubt that such systems existed. The question, therefore, was whether *all* nebulae were simply star clusters disguised by distance, or whether Halley was right and some were formed of a "lucid medium", or "true nebulosity" as William Herschel (1738–1822) preferred to call it.

Herschel was introduced to astronomy in 1772–73 by two authors, both of whom drew on Halley's paper. What they had to say about Halley's lucid spots immediately captured his attention. Herschel's own theorizing on nebulae falls into three periods. For a decade, 1774–84, Herschel had good reason to believe in true nebulosity; then, in 1784, new observations led him to reverse his opinion and he now equated nebulae with star clusters — only in 1790 to come across evidence that compelled him once more to accept the existence of true nebulosity. Here we investigate in detail the first of these periods, while in Part 2 we study the second and third.

1774–1781: Does the Orion Nebula Alter Shape?

"A knowledge of the construction of the heavens has always been the ultimate object of my observations", wrote William Herschel in 1811 when commencing his final series of papers on this subject.[2] Nearly four decades earlier, when Herschel first developed his passion for astronomy and in particular his fascination for cosmology, he was one of the two leading musicians in the fashionable spa resort of Bath in the west of England.[3] As an astronomer he was entirely self-taught, learning his telescope-building from the formidable two volumes on *Opticks* by the Cambridge professor Robert Smith,[4] and his astronomy from the popular *Astronomy* by the former shepherd boy, James Ferguson.[5]

Smith began his brief chapter on "Telescopical discoveries in the Fixt Stars" by informing his readers that the Milky Way was

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> nothing else but a prodigious number of very minute stars, so close to one another that the naked eye can only perceive a whitish mixture of their faint lights. This was *Galileo*'s discovery, who found also that those faint stars, which Astronomers call *Nebulosae*, appeared through his telescope to be small clusters of very minute stars.[6]

In 1656 Christiaan Huygens had seen "a whitish cloud" in Orion's Sword, and Smith reproduced Huygens's sketch. According to Huygens, he tells readers,

> the three little stars very near one another (marked θ by *Bayer*), together with four more, shone out as it were through a whitish cloud, much brighter than the ambient sky: which being very black and serene caused that lucid part to appear like an aperture, that gave a prospect into a brighter region.[7]

An article in *Philosophical transactions* in 1715, Smith continued, had reported five more of these "lucid spots", where it seemed that there was "perpetual uninterrupted day".

Ferguson had more to say. He lists five of these six "lucid spots" under this same heading; of the Andromeda Nebula, M31, he says intriguingly that it "is sometimes invisible", in which case it could not be a vast star system.[8] The sixth, the Orion Nebula, he lists under a separate heading, "Cloudy stars". These "look like dim Stars to the naked eye; but through a telescope they appear broad illuminated parts of the Sky; in some of which is one Star, in others more".

> But the most remarkable of all the cloudy Stars is that in the middle of *Orion's Sword*, where seven Stars, of which three are very close together, seem to shine through a cloud, very lucid near the middle, but faint and ill-defined about the edges. It looks like a gap in the sky, through which one may see (as it were) part of a much brighter region. Although most of these spaces are but a few minutes of a degree in breadth, yet since they are among the fixed Stars, they must be spaces larger than what is occupied by our Solar System; and in which there seems to be a perpetual uninterrupted day among numberless Worlds, which no human art ever can discover.[9]

Herschel was only a beginner in astronomy but this was a challenge that aroused his curiosity. Were some of the nebulae indeed lucid spots, perhaps with embedded stars? Or were they all like Galileo's *nebulosae*, "small clusters of very minute stars"?

Of five of the lucid spots Herschel had little more than a simple list, and one of them was below his horizon; but of the sixth, the Orion Nebula, he had a crude sketch of how it looked in 1656, and the account in Ferguson of its more recent appearance. Unlike the professional astronomers of his day, the Bath violinist focused on the fact that because a vast star system could not possibly alter shape in only a few years, a nebula that had demonstrably altered shape *must* be a lucid spot. And so, on 1 March 1774, when he decided he had reached the stage when he might open his first observing book, one of the two objects he observed was the Orion Nebula.

That night the seeing was poor, but it was better three nights later. And sure enough, the nebula looked quite different from the sketch in Smith: it had apparently altered shape since the time of Huygens. "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."[10]

As a novice observer Herschel did not realize the extent to which changes in seeing conditions or in the instrumentation can affect the appearance of a nebula, and in any case the sketch by Huygens was crude. He decided that by observing the Orion Nebula at regular intervals, he might establish whether or not it was in fact altering shape. True, the ghostly form of the luminous spot was nearly impossible to record, and his skills as a draughtsman were limited; but if he kept meticulous records of the configuration and brightnesses of the embedded stars, and their relationship to the luminous spot, he might find evidence of change. In his remaining years in Bath, therefore, he returned time and again to the nebula. On 11 November 1776 he made elaborate notes of its appearance. On 25 January 1778 he repeated the exercise, and continued the following night; for example, he records that embedded stars "6.2.1 make a straight line". On 7 and 25 February and 12 March he looked for but found no changes in the January configuration, and the same was true on 15 December, when stars 6, 2 and 1 again lay in a straight line. But on this occasion he felt sure "there is a visible alteration in the figure of the lucid part". He confirmed this on 7 October the following year: "the figure of the lucid part is much altered." On the same night he noted that "the line 6.2.1 is a little convex towards 5". On 5 December he decided "6.2.1 concave ... the concave part turned to the south". On 22 January 1780, however, "6.2.1 instead of seeming concave towards the north appear convex"; but he could not be sure. On 19 and 26 February 1780 he looked again, and now began to measure the angles separating pairs of stars; and on 22 October 1781 we find him recording the colours of the stars.[11] But by now he was emerging on the world-stage as the discoverer of a 'comet' that some thought (correctly) might be a planet, and in the resulting upheaval it would be nearly a year before he could find time to think once more about nebulae.

Ferguson had given brief details of the locations of the four remaining nebulae listed by Halley that were visible from England. In his Bath years Herschel was a busy musician; most of the time he could give to astronomy he spent improving his armoury of reflectors, and when he found time to observe, his concerns were mostly nearer home: Saturn's ring, signs of the Lunarians who Ferguson believed inhabited the Moon, measurements of the height of lunar mountains, scrutiny of the brighter stars to determine which were in fact double. But he found occasions to view three of the four, and they provided him with evidence of the bewildering variety of forms to be found among the nebulae. M11 is a galactic star cluster, and Herschel had no problem in resolving it: 12 Sept 1779, "nebula seems to be a prodigious number of small stars surrounded with luster and glare"; 7 Aug 1780, "a great many stars"; 25 June 1781, "an amazing number of small stars"; 26 July 1781, "great number of

Stars". M13, by contrast, is a globular cluster and could not be resolved by the small instruments then at Herschel's disposal: 22 Aug 1779, "without stars in it"; 29 Aug 1779, "there is no star in it". M31, the Andromeda Nebula, is of course a galaxy and far beyond the resolving power of any instrument of the Herschel era: 6 Aug 1780, "Nebula, in Andromeda, has no Star in it"; 27 July 1781, "no star visible".

Herschel also came across five other nebulae in his Bath years. On 2 Aug 1780 he noted that χ Persei (the galactic cluster NGC 884) is "An astonishing number of small stars". On 30 Sept 1780 he found near λ Aurigae "a very rich Spot", and this will be the galactic cluster NGC 1857. On 15 July 1781, "over β [Serpentarij] is a fine cluster of small stars", and this is the galactic cluster IC 4665 now in Ophiuchus. In addition, on 24 Aug 1780 he came across two nebulae with stars, one in Sagittarius and the other in Ophiuchus; but the locations he gives for them are vague.

1776–1784: Reflectors and the Quest for More Light

For his first observations of the Orion Nebula Herschel had used a home-made Newtonian reflector of $5\frac{1}{2}$-ft focal length. He was a man for whom 'more' and 'larger' were always 'better', and he did not need Smith to tell him that a telescope with greater aperture will bring into view faint objects that were previously invisible — and will allow higher magnifications to be brought to bear on objects already in view. On 1 May 1776 he used a 7-ft reflector (aperture 6 inches) for the first time, and a few days later a 10-ft (aperture 8 inches).[12] Within a couple of years the 7-ft and the 10-ft were to be mounted in simple, practical wooden stands. The tube of the 20-ft with 12-inch mirrors that he completed in July 1776, however, was crudely slung by ropes from a vertical pole; the unfortunate nighttime observer had to perch precariously alongside on the top of a huge ladder, at the risk of life and limb. Although Herschel devised a fine-tuning mechanism by which the observer could alter its vertical and lateral motions, it must have been a nightmare to use — as he noted ruefully on 17 April 1777, "The air being changed and a high wind arose, I found it impossible to continue my obs. so long as I proposed ... the uneasy posture and cold prevented farther observ:".[13] At Bath he used it very occasionally to observe Mars, Jupiter or Saturn (although never Lunarians or the mountains on the Moon), but there was no possibility of his sketching the layout of the stars of the Orion Nebula in the dark at the top of a 20-ft ladder.

The 10-ft with its modest 8-inch aperture was not an instrument that would satisfy the ambitions of any committed student of the construction of the heavens: James Short, the eminent maker who had recently died, used to offer for sale Gregorian reflectors with 18-inch mirrors.[14] But Herschel was currently preoccupied with earning his living as a musician, and when eventually he did have time to devote to systematic observations he wisely concentrated on the nearer stars, using the superlative mirror for the 7-ft that he completed in November 1778. This mirror, the finest of its size in existence, gave him an advantage over all other observers, and would lead to his discovery of the planet we know as Uranus. But he hankered after a reflector with

huge mirrors that would allow him to examine the fainter nebulae, and he may have been spurred into action by the news early in 1781 that the founder employed by John Michell had successfully cast a speculum disc of nearly 30 inches diameter. Michell was a former Cambridge professor of geology, now rector of a parish in Yorkshire, and he alone of Herschel's English contemporaries was a dedicated student of the construction of the heavens — although, curiously, Michell was to make no use of his great telescope to contribute to the subject, despite the promptings of friends.[15]

On 12 August 1780 Herschel had written to Joseph Priestley to ask about Michell's plans, and on 21 January 1781 Michell sent news of the casting direct to Herschel's Bath ally Dr William Watson, Jr.[16] That same January Herschel embarked on the construction of a giant reflector, with mirrors that he eventually decided should be 3-ft in diameter — bigger even that Michell's. But whereas Michell had located a founder capable of work on this scale, Herschel ended up having to cast the mirrors himself in a foundry installed in the basement of his own home.[17]

In August 1781 he twice tried to cast the great mirror, and twice failed; and for the time being he gave up the attempt. As 1782 opened, he still had grandiose plans for a large reflector,[18] but he was now preoccupied with the fall-out from his discovery of Uranus. His admirers in London, already hugely impressed by his collection of double-stars — only after great efforts was any astronomer, professional or amateur, able to confirm his claim that the Pole Star is double[19] — shrewdly saw in the planet the excuse to lobby King George III for the patronage that would allow Herschel to devote himself full-time to astronomy. And so it was that in August 1782 Herschel and his sister Caroline moved from Bath to Datchet near Windsor Castle, where Herschel was to be astronomer to the King.

King George was a serious student of astronomy — indeed, he had established Kew Observatory so that he might observe the 1769 transit of Venus — and as part of his duties Herschel was required to transport his 7-ft to Windsor Castle on demand. And so it was that at the end of August 1782 he showed the King "several nebulae, that in Andromeda [M31] and that in Scut. Sob. [M11]". By October Herschel had devised some sort of tripod support for his 10-ft, no doubt so that it too could be transported to the castle, and on the 12th he was able again to show M11 to the King — but this time with a mirror of nearly twice the 'light-gathering power'.[20] And so the King experienced for himself the benefit of larger mirrors.

The 20-ft was much too large to transport, but George was keen to view it, and so on 1 December the King made the journey to the Herschel home. But the precarious observing ladder was no place for royalty. He was consoled with a view of Herschel's planet, now named the Georgium Sidus in honour of the King, through the 10-ft.

The King did not observe again until 28 April, when Herschel took the 10-ft to the castle and again showed him his planet, along with the scattered cluster in Gemini, M35. By this time Herschel was making progress with the construction of what was to prove one of the most successful telescopes of all time. It was another 20-ft, but its mirrors were to be 18-inches in diameter. This was only a modest improvement on

the existing 20-ft, and far short of the 30-ft with 3-ft mirrors that he had attempted in Bath; but this time the technology was within easy grasp. Experience with the existing 20-ft had taught him the crucial importance of a convenient and safe mounting, and the new instrument was to be housed in a ladder structure that carried an observing platform complete with guard-rails. From the platform Herschel would be able to manhandle the tube from side to side. Alternatively, if the instrument was to be kept facing exactly south (so acting as a transit instrument), he could use an observing chair securely attached to the ladder structure. The 'large' 20-ft with its 18-inch mirrors was completed in October 1783, and by the close of the year Herschel had recruited Caroline to be his amanuensis in a two-decades-long observing campaign with the 20-ft that was to add an astonishing 2500 nebulae to those previously known.[21]

But the 18-inch mirrors had only one-quarter the light-gathering power of 3-ft mirrors such as he had tried and failed to cast in Bath, and at the start of 1784 the question of the existence or otherwise of true nebulosity was as open as ever. Unfortunately, Herschel's salary from the King was less than half his earnings as a Bath musician, and he had drawn on his savings to pay for the 'large' 20-ft. To build a reflector that would dwarf even Michell's would be possible only with funding from King George, and by the summer of 1784 his campaign to secure this funding was well under way. That August we find Watson writing to him to ask, "above all, has the King set you about the magnum opus, the great speculum?"[22] The omens were good, for Herschel had the enthusiastic backing of Sir Joseph Banks, president of the Royal Society and a man with the ear of the King; and George had seen for himself the benefits of large mirrors.

1782–84: The Great Untruth

A transformation in Herschel's desk knowledge of nebulae had taken place back in December 1781. Until then he had known of the existence of only a handful of these mysterious objects — those listed by Smith and Ferguson, plus the very few others that he had happened upon by chance. But that month Watson had sent him a catalogue of no fewer than 70 nebulae and clusters of stars that the French comet-hunter Charles Messier had compiled.[23] Some had been discovered by Messier himself with his $3\frac{1}{2}$-inch refractor, some by other observers, and Messier had assembled the list because at first glance a nebula looked like a comet and the distraction was costing him valuable time.

When the catalogue arrived from Watson, Herschel had in his garden a 20-ft reflector whose 12-inch mirrors were large by Messier's modest standards; surely he would take the earliest possible opportunity to use it on Messier's nebulae and see whether the description of some of them as nebulae without stars, "nébuleuses sans étoiles", survived a more rigorous examination. And this, he tells us in his 1784 *Philosophical transactions* paper on the construction of the heavens, is exactly what he did:

> As soon as the [catalogue] came into my hands, I applied my ... reflector of 12 inches aperture to them; and saw, with the greatest pleasure, that most of the

> nebulae, which I had an opportunity of examining in proper situations, yielded to the force of my light and power, and were resolved into stars. For instance, [he lists 29 Messier objects], all of which are said to be nebulae without stars, have either plainly appeared to be nothing but stars, or at least to contain stars, and to shew every other indication of consisting of them entirely.[24]

Regrettably, this is the very opposite of what really happened. Between the arrival of the gift from Watson in December 1781, and Herschel's move to Datchet in August 1782, he did not look at one single nebula: he had more urgent things on his mind, and Messier's catalogue he simply put on one side. Only after he was established as Court astronomer did Herschel — very occasionally — observe a nebula.

People tell lies for a reason. In 1784 the aperture of his largest reflector was eighteen inches, and Herschel wished the King to fund a reflector with aperture forty-eight inches. By then Herschel was frustrated with the modest light-gathering power at his disposal, as we see from his observing books: "more power & light will probably resolve it" (M79, 28 Sept 1783); "I think a great deal more of light and a much higher power would be of service" (M17, 31 July 1783); "This speculum has not light enough" (M31, 2 Aug 1783); "wants more light to attack it properly" (M32, 2 Aug 1783); "I want light" (M27, 2 Aug 1783); and so on.[25] The monster reflector would be very expensive and Herschel needed to conjure up the most persuasive justification. And so he invented a plausible untruth: the dramatic new insights that had (or more correctly, would have) resulted two years before, when (or rather, if) the objects examined by Messier with a $3\frac{1}{2}$-inch refractor had been re-examined with the twelve-inch reflector.

Even in the months after his arrival at Datchet, Herschel had in fact devoted most of his observing time to his very productive search with the 7-ft for double stars (a search that was to continue until September 1783). As a result, as late as the end of March 1783 he had seen only nine Messier objects unknown to him in his Bath days, all of them viewed with the 7-ft. We are well informed on such matters because we have both his rough observing notes and the fair copy that Caroline wrote up next day; we have too the file she later compiled listing the Messier objects and the dates when Herschel first observed them.[26] A full fifteen months had then elapsed since the arrival of the gift from Watson, and Herschel had still not examined a single Messier object with the 'small' 20-ft.

By then Caroline's success in finding nebulae in 'sweeps' with the little refractor her brother had given her had opened Herschel's eyes to the great number of nebulae awaiting discovery. He impulsively began himself to sweep with a small refractor, before he accepted that nebulae were permanent objects in the night sky and deserved to be examined at leisure with the biggest telescope available.[27] The 'large' 20-ft was approaching completion (it came into operation on 23 October 1783), and during the summer Herschel indulged himself by giving whatever time he could spare from double stars to examining objects in the Messier list — or rather lists, for around the end of May he acquired a copy of Messier's third and final catalogue of 103 objects,

the one we use today.[28] It was during these summer months of 1783 — and not the winter of 1781/82 — that Herschel viewed most of the Messier objects cited in his 1784 paper.[29] Once the 'large' 20-ft was commissioned, he embarked on his great campaign to sweep the whole of the visible sky for nebulae;[30] and from then on Messier objects took their turn with the rest.

Of the Messier objects that Herschel viewed from Datchet prior to the commissioning of the 'large' 20-ft, seventeen were declared by Messier to be clusters of stars and Herschel could do no more than confirm this: M4, M6, M7, M11, M18, M20, M21, M23, M25, M26, M29, M34, M35, M36, M38, M73, M103. With another five objects Herschel had to admit defeat: M17 (a gaseous emission nebula, seen in the 'small' 20-ft on 2 August 1783 as "A curious train of light. I cannot resolve it"); M32 (an elliptical galaxy, seen in the 7-ft the same night as "Like a nebulous star"); M43 (a gaseous emission nebula, seen in the 20-ft on 20 September 1783 as "nebulous"); M78 (a gaseous reflection nebula, seen in the 20-ft the same night as "2 large stars ... with nebulosity"); and of course the Orion Nebula, M42. At Datchet Herschel abandoned his earlier caution in pronouncing on changes in the nebulosity of M42: on 31 Jan 1783 he recorded that "the nebulous part is quite different from what it was last year" (7-ft); on 20 Sept 1783 it "has evidently changed its shape since I saw it last" (20-ft); a week later he was writing of "the new division in the Nebula of Orion" (20-ft?); and the following night he declared, "Nebula in Orion is surprizingly changed" (7-ft).

So what of the twenty-nine objects Messier saw as "nebulae without stars", that Herschel claimed — largely, if not completely — to have resolved into stars with the 'small' 20-ft in the winter of 1781/82 (see Table 1)? The last four of them were not in Messier's second catalogue and therefore could not possibly have been examined by Herschel at the date claimed. As to the telescopes he in fact used, he saw just thirteen of the twenty-nine with the 20-ft, all during the summer of 1783. Five he viewed only with the 7-ft, and ten with the 10-ft. The inclusion of the remaining nebula, M13, must be a slip, for he had twice seen it from Bath in August 1779 as "without stars" and did not see it again until he was sweeping with the 'large' 20-ft in 1787. The citation of M74 is also erroneous, for the object — whatever it was — is wrongly labelled in the observing notes.[31]

In his 1784 paper Herschel also listed nine Messier objects (M1, M3, M27, M33, M57, M79, M81, M82 and M101) that in one or other of his reflectors "shewed a mottled kind of nebulosity, which I shall call resolvable". He currently believed that some of the nebulae he was viewing were truly nebulous, continuous clouds of luminous fluid, while others were formed of 'discrete' stars. How was one to tell the difference? He sometimes saw in the sky a smooth or milky nebulosity, but sometimes the nebulosity was "mottled". Very plausibly, he took the milky nebulosity to indicate the presence of luminous fluid, and the mottled nebulosity to be star clusters on the verge of resolution into their component stars. But this would soon change.

TABLE 1. The Messier nebulae Herschel claimed to have resolved (wholly or partially) in the winter of 1781/82.

Messier no.	Type	Date Observed	Reflector	Herschel's Comments
2	glob. cl.	31 July 83	20-ft	"I can count 18 or 20 of the stars"
5	glob. cl.	21 May 83	10	"All stars"
9	glob. cl.	3 May 83	10	"connection between Nebulas in general & stars in clusters"
10	glob. cl.	21 May 83	10	"A cluster of very small stars"
12	glob. cl.	21 May 83	10	"A cluster of close stars of different sizes"
13	glob. cl.	22 Aug 79	7	"without stars"
14	glob. cl.	23 July 83	20	"I can distinguish a few stars & have not the least doubt it consists intirely of them"
15	glob. cl.	31 May 83	10	"all fairly resolved into stars"
16	gal. cl.	30 July 83	20	"Large stars with small ones among them"*
19	glob. cl.	28 May 83	10	" resolved into stars"
22	glob. cl.	4 July 83	20	"all resolved into stars"
24	gal. cl.	2 Aug 83	20	"Considerable stars in great number"*
28	glob. cl.	4 July 83	20	"if the night were clearer I doubt not of its being stars that might be seen very distinctly"
30	glob. cl.	31 Jul 83	20	"consists of very small stars"
31	sp. gal.	2 Aug 83	7	"227 [mag] A strong suspicion of stars. This speculum has not light enough. I doubt not but 20 feet with confirm it. 460, suspicion still stronger"
37	gal. cl.	24 Aug 83	7	"many small stars"*
51	sp. gal.	20 Sep 83	20	"Most difficult to resolve; yet I no longer doubt"
52	gal. cl.	29 Aug 83	7	"all resolved"*
53	glob. cl.	30 May 83	10	"More than a suspicion of stars"
55	glob. cl.	30 July 83	20	"fairly resolved into very small stars"
56	glob. cl.	31 May 83	10	"All resolved into stars"
62	glob. cl.	28 May 83	10	"A strong suspicion amounting to almost a certainty of its consisting of stars tho' I can distinguish none"
65	sp. gal.	31 May 83	20	"almost a certainty of its being stars. There is however in both the nebulas [65 and 66] a certain whitishness left which may be nebulosity"
66	sp. gal.	31 May 83	20	"A strong suspicion of stars"
67	gal. cl.	26 Mar 83	7	"A cluster of stars"*
71	glob. cl.	30 May 83	10	"resolved into stars. I can count between 20 & 30 of them"
72	glob. cl.	28 Sep 83	10	"fairly resolved into very small stars"
[74	sp. gal.	20 Sep 83	20	misidentification]
92	glob. cl.	25 Aug 83	20	"A most beautiful sight. I can count 50 or 60 stars besides numberless that only distinguish themselves by twinkling...."

*Comment quoted *in extenso* in J. L. E. Dreyer (ed.), *The scientific papers of Sir William Herschel* (London, 1912), ii, 651–60.

1783– 84: Herschel in Quandary

Herschel had long understood that there were two main tests for whether or not a nebula was in fact a star cluster disguised by distance. If the nebula altered shape, as (it seemed) had the Orion Nebula, it could not be a vast star cluster: there was therefore at least one undisputed example of true nebulosity. If on the other hand the nebula was resolved into stars when examined with a telescope of larger aperture than hitherto, then clearly it was a star cluster.

But to resolve one nebula, or even many, could never prove that *all* nebulae without exception were star clusters, for there seemed no limit to the number of nebulae in the sky. However, this logical point does not make due allowance for human nature: thus in 1845, when Lord Rosse's 'Leviathan of Parsonstown' seemed to show that the Orion Nebula was a star cluster after all, many astronomers would take this single 'resolution' to be demonstration that all nebulae were star clusters.[32] Herschel's 20-ft was currently resolving numbers of Messier objects into stars (even if the resolution was often incomplete); and many more seemed on the verge of resolution, or would surely be resolved on a finer night. One could cite innumerable examples of this from his notes. For example:

> I see several stars in it & make no doubt, a higher power and more light would resolve it into stars. This seems to be a good Nebula for the purpose of establishing the connection between nebulas in general & stars in clusters [commenting on the globular cluster M9, 3 May 1783].
>
> ... resolved into stars i.e. I can count 5 or 6; & all the rest of the light appears mottled like other nebulas when not sufficiently magnified and illuminated to shew the stars [on the globular cluster M19, 28 May 1783].
>
> Plainly resolved into very small stars. It is a difficult step i.e. if we divide the transition from the Pleiades down to the Nebula in Orion into six steps this is perhaps the 4th towards the real nebulas. The stars in this seem to be of two different sizes for I perceive 3 or 4 very visible ones branching out towards the north and several more exceedingly small at the sides. Towards the south in one place the light is very intense, but has all the appearance of crowded stars; so that there remains no doubt of the whole being stars [on the globular cluster M30, 21 August 1783].
>
> This & the 51st are both so far removed from the appearance of stars that it is the next step to not being able to resolve them. My new 20ft will probably render it easy [on the spiral nebulae M101 and M51, 20 September 1783].

Herschel several times imagines these six 'steps', with a simple cluster as Step 1 and the Orion and other "real" nebulae as Step 6. But it is difficult to resist the impression that he sees Step 1 as corresponding to the resolving power of the unaided human eye; Step 2, to that of a small telescope such as Messier's; Steps 3 and 4, to that of his present equipment; and Step 5, perhaps to that of the 'large' 20-ft soon to

be commissioned. And what of Step 6? Would the giant reflector the King might fund show the objects in Step 6 also to be clusters of stars? Revealingly, in a manuscript setting out ideas that would mature in his 1784 and 1785 papers on the construction of the heavens and which must date to 1783 or early 1784, he writes: "... the Nebulae are not any sort of vapours extended before the vacant spaces but are a collected body either of luminous matter or *most probably of stars* [italics supplied]".[33] But surely the Orion Nebula had altered shape, and so this at least must be a nearby cloud of true nebulosity.

1784: The Quandary Resolved

When Herschel sent his first paper on the construction of the heavens to the Royal Society in the spring of 1784,[34] he was still contrasting "nebulosity of the milky kind, like that wonderful, inexplicable phaenomenon about θ Orionis", with the nebulae that "shine with a fainter, mottled kind of light, which denotes their being resolvable into stars".[35] Then, on 22 June, just five days after the paper had been formally read, his sweeping brought him to M17, known to us as the Omega Nebula. He had viewed it twice with the 'small' 20-ft, on 31 July 1783 seeing it as "not without the possibility of being stars", and three days later as "A curious train of light. I can not resolve it". Now the 'large' 20-ft showed it as having "one or more places, where the milky nebulosity seems to degenerate into the resolvable kind".

> Should this be confirmed on a very fine night, it would bring on the step between these two nebulosities which is at present wanting, and would lead us to surmize that this nebula is a stupendous Stratum of immensely distant fixed stars some of whose branches are near enough to us to be visible as resolvable nebulosity, while the rest runs on to so great a distance as only to appear under the milky form.[36]

By this time Herschel was convinced that the Milky Way is the optical effect of our immersion in a layer or 'stratum' of stars (the Galaxy), and in his sweeps he was encountering what we regard as clusters of galaxies, but which he saw as the remnants of other strata of stars that had already fragmented under the destructive power of gravity. M17, it seemed, contained both resolvable and milky nebulosity; and he now decided it was a stratum of stars, some parts of which were near enough to us to be seen as resolvable, while others were so far away as to appear "under the milky form". If so, milky or 'true' nebulosity might be an illusion, the (imagined?) changes in the Orion Nebula notwithstanding.

A month later his sweeps brought him to a second and even more striking instance of the same phenomenon: M27, our Dumbbell Nebula. Its appearance led him to conceive of it as

> a double stratum of stars of a very great extent. The ends next to us are not only resolvable nebulosity but I really do see many of the stars mixt with the resolvable nebulosity. Farther on the nebulosity is but rarely resolvable & ends at last in milky whiteness of the same appearance as that in Orion.

These two examples persuaded him to reverse his earlier opinions. Milky and mottled (that is, resolvable) nebulosity were not contrasting physical substances, nearby luminous fluid and distant star clusters respectively. Rather, they were the same substance — collections of stars — at different distances. This greatly simplified the cosmos he would describe in his 1785 and 1789 papers on the construction of the heavens.[37] The universe was (he now believed) populated with star clusters, some scattered, others condensed. These clusters could have come about only through the action of gravity (or some other attractive force) as a result of which stars pulled each other and so moved closer together. A scattered cluster would *in time* become more and more condensed: scattered clusters were young, condensed clusters old. And thus Herschel tolled the death-knell of the Newtonian clockwork universe.

APPENDIX 1: THE 40-FT REFLECTOR

The nebulae that had formed Step 6 — most notably that of Orion — were now revealed, not as nearby clouds of true nebulosity, but as star systems at distances so great that their light was milky rather than mottled. If the Orion Nebula appeared so extensive despite its remoteness, its scale (in miles) must be enormous. It was, Herschel concluded, what we today would term a galaxy, one that was perhaps even more extensive than our own Galaxy: it "may well outvie our milky-way in grandeur".[38]

But what of the observed changes in the Orion Nebula? Fortunately Herschel had said nothing about them in public, and so he could close his mind to them without embarrassment — but not without a certain unease. He would be content only when he had examined the nebulae with a reflector of much greater light-gathering power than the 'large' 20-ft with its mirrors of a modest 18-inches. And so it was that in 1785 Herschel formally applied to King George for funds to build a giant reflector of 40-ft focal length and mirrors 4-ft in diameter, a telescope on a scale the world had never before seen, calling for patronage on a scale rarely equalled.[39] Its purpose was clear, as a French visitor back in August 1784 had recorded:

> The nebulae of M. Messier are nebulae with the 7-ft telescope, and when one observes them with the telescope of 20-ft, one sees clearly that the nebulae are star clusters. The mirror of the 40-ft telescope will weigh 700 *livres*.... The intention of M. Herschel in making this great telescope is not to magnify the object but to give, with the help of these larger mirrors, the greatest quantity of light possible.[40]

Herschel was perhaps the first astronomer to apply for funds on an unrealistically modest scale, confident that the fund-giving body would provide additional funds rather than see those already provided go to waste. When the overspend became evident, the outraged King, after a flaming row with Herschel, reluctantly doubled his original grant. At long last, in the summer of 1789, the monster neared completion. Herschel then found himself under intense pressure to use it to work miracles. After all, by his own account he was a miracle worker of proven ability: his 12-inch

mirror had — almost overnight — resolved into stars dozens of nebulae previously thought to be "nebuleuses sans étoiles".

Saturn came to his aid.[41] Its ring was currently edge-on, the ideal time to look for undiscovered moons. He had suspected the presence of a sixth moon back in 1787, when observing with the 'large' 20-ft, but had been distracted from pursuing the matter. On 28 August 1789 the 40-ft confirmed that there was indeed a sixth moon, and Herschel prepared to seize the opportunity: the monster reflector would thereby announce its arrival on the international stage in dramatic style. But then it occurred to him that he might not be the only observer using the favourable attitude of Saturn's ring to look for moons; and if not, a priority dispute might be in the offing. And so he wrote to Banks a letter to put on record his earlier observations with the 20-ft. They privately agreed that if there was indeed a priority dispute, the discovery of the moon would be credited to the 20-ft; if not, it would be presented as a triumph for the newly-completed 40-ft.

There proved to be no such dispute. The 40-ft, it seemed to the astronomical world, had immmediately revealed a sixth Saturnian moon — and then, only a few days later, a seventh. Banks, who had put his own reputation on the line when pressing the King to fund the great reflector, was ecstatic: "We expect daily to partake of new wonders from the effects of the 40 feet not to be content with 2 satellites, in truth if nothing else appears we shall be happy in the possession of them and gratefull to the discoverer but you will not wonder if our hopes are at the period a little elevated."[42]

Herschel had made a rod for his own back, for the astronomical world — and King George — sat back expecting a constant stream of such wonders. None came; and worse still, within months the reflector lost its primary purpose, to shed light on the riddle of the nebulae. In November 1790, within months of the completion of the 40-ft, Herschel's regular sweeps with the 20-ft brought him to what we know as the planetary nebula NGC 1514. To Herschel a planetary nebula had the outline of a planet but the ghostly light of a nebula, but this object was so near that he could actually see the central star that such nebulae in fact have. It was, he decided, "a star of about the 8th magnitude, with a faint luminous atmosphere ... a star which is involved in a shining fluid, of a nature totally known to us".

True nebulosity therefore existed after all, the changes in the Orion Nebula had been genuine all along,[43] and the great question that the 40-ft had been designed to answer had been resolved without its help.[44] So far it had never once been so much as pointed towards a nebula — unless one counted the bizarre episode enacted on 19 February 1887, when Herschel had progressed with grinding and polishing the first mirror of the 40-ft to the stage where he needed to know the focal length it currently had. The Orion Nebula set that night at 1 a.m., and an hour or two earlier Herschel put the mirror into place. He then climbed bodily into the mouth of the great tube, eyepiece in hand and no doubt with that evening's guest, Dr Charles Blagden, holding his ankles to stop him sliding down the tube, and he moved back and forth until he was able to glimpse the nebula.[45]

With the discovery of true nebulosity in November 1790, the 40-ft became a

millstone around Herschel's neck: the product of the greatest patronage of astronomy the world had seen, but now an unwieldy, cumbersome monster with little purpose beyond impressing guests to Windsor Castle after they had been wined and dined.[46]

APPENDIX 2: HERSCHELIAN ('FRONT-VIEW') REFLECTORS

In a Newtonian reflector, a substantial fraction of the light collected by the primary mirror is lost in the reflection in the secondary mirror. Herschel pioneered an alternative configuration whereby the observer looks directly down the tube through an eyepiece located near the edge of the rim. He experimented briefly with such a configuration with a 10-ft reflector on 28 May 1776, and again with his newly-commissioned 'large' 20-ft reflector on 20 November 1783; but it was only when he tried a second time with the 20-ft, on 22 September 1786, that he became convinced of the great advantage of 'front-view' reflectors. Thereafter the 20-ft was invariably used in this configuration, as was the 40-ft then under construction, and the 25-ft he built for the King of Spain and the 20-ft for the Empress of Russia. The obvious disadvantage — that the observer's head is an obstacle to the incoming light — proves on examination to be of little consequence with large reflectors.[47]

Herschel at first 'swept' for nebulae with the 20-ft by standing on a gallery, because he had to manhandle the tube from side to side; but when he quickly converted the 20-ft into a transit instrument he used a simple and convenient observing chair. However, from September 1786, the 'front-view' configuration required him always to use the gallery.

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2. William Herschel, "Astronomical observations relating to the construction of the heavens", *Philosophical transactions*, ci (1811), 269–336, p. 269.
3. For more on Herschel's time in Bath, see Michael Hoskin, "Vocations in conflict: William Herschel in Bath, 1766–1782", *History of science*, xli (2003), 315–33.
4. Robert Smith, *A compleat system of opticks* (Cambridge, 1738).
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6. Smith, *Opticks* (ref. 4), ii, 447.
7. *Ibid*., 447–8.
8. Ferguson, *Astronomy* (ref. 5), para. 364.
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10. Royal Astronomical Society Herschel Archive (hereafter: RAS) W.2/1.1, 1.
11. Herschel's rough notes are in RAS W.2/1 under the relevant date, and the fair copy in RAS W.4/1.
12. The definitive article on Herschel's telescopes is J. A. Bennett, "'On the power of penetrating into space: The telescopes of William Herschel", *Journal for the history of astronomy*, vii (1976), 75–108.
13. RAS W.2/1.1, 43.
14. H. C. King, *The history of the telescope* (London, 1955), chap. 5.

15. His paper, "An enquiry into the probable parallax, and magnitude of the fixed stars", *Philosophical transactions*, lvii (1767), 234–64, is filled with insights. John Smeaton, the great engineer, wrote to Michell after Smeaton had visited Herschel in 1785 when the 40-ft was under construction, and urged him: "From what I have said, instead of looking at the Satellites of Jupiter, and expecting them to form one Lucid point, or round surface, I would wish you to turn your great Telescope to some of the *Nebulae*, for, as the Surface of your Speculum, is more than double any M^r^ Herschell *yet* has, it is possible you may make some discoveries as yet unlooked for" (copy of letter dated 4 November 1785, RAS MS Radcliffe Hornsby 78). Michell's inactivity was probably the result of the poor quality of his mirror. After Michell's death Herschel bought the mirror (then in pieces) and examined it, concluding: "Its construction is what I cannot approve ...", see his "Remarks on M^r^ Michell's Telescope", RAS W.7/14.
16. Unfortunately the relevant CD Rom of Herschel's incoming correspondence is defective and does not include Priestley's reply, but see "William Herschel's lunatick friends" by Andrew Lound, *The speculum: The journal of the William Herschel Society*, ix/2 (2010), 11–26, p. 13. For Michell's letter to Watson, see RAS W./13.M.99.
17. For an account of this episode, see Michael Hoskin, *Discoverers of the universe: William and Caroline Herschel* (Princeton, 2011), 53–8.
18. "In a former paper I mentioned, that a more powerful instrument was preparing for continuing my reviews of the heavens. [My new reflector of 18-inches aperture] is far inferior to the one I had undertaken to construct when that paper was written...." William Herschel, "Account of some observations tending to investigate the construction of the heavens", *Philosophical transactions*, lxxiv (1784), 437–51, p. 437.
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20. RAS W.2/1.4.
21. Hoskin, *Discoverers of the universe* (ref. 17), chap. 6.
22. William Watson, Jr, to Herschel, 25 August 1784, RAS W.1/13.W.32.
23. William Watson, Jr, to Herschel, 7 December 1781, RAS W.1/13.W.11. Charles Messier, "Catalogue des nébuleuses et des amas d'étoiles", *Connoissance des temps pour 1783* (Paris, 1780), 225–49, 408.
24. Herschel, *op. cit.* (ref. 18), 439–40.
25. See ref. 11.
26. RAS W.4/33.1.
27. Michael Hoskin, "Caroline Herschel as observer", *Journal for the history of astronomy*, xxxvi (2005), 373–406, pp. 376–8.
28. Charles Messier, "Catalogue des nébuleuses et des amas d'étoiles", *Connoissance des temps pour 1784* (Paris, 1781), 227–69. Herschel first observed a nebula (M71) present in this catalogue but not in its predecessor on 30 May 1783; the summer months were far from ideal for delicate observations, and the next such nebula (M92) had to wait until 2 August.
29. His examination of Messier objects culminated on the nights of 30 and 31 July and 2 August, when he observed over twenty of them, most with the 20-ft but some with the 7-ft.
30. An exhaustive analysis of the nebulae and clusters discovered by Herschel is to be found in Wolfgang Steinicke, *Observing and cataloguing nebulae and star clusters: From Herschel to Dreyer's New General Catalogue* (Cambridge, 2010).
31. On the night in question, 20 September 1783, Herschel observed M74 and of this there is no doubt as he defines its position exactly; he saw it with some difficulty and says nothing about its appearance. The previous object he observed that night was M27, and the object previous to that is described as "All resolved into exceedingly small stars" in the 7-ft; it too is said to be M74, but this cannot be as M74 is a spiral galaxy. Wolfgang Steinicke offers the plausible suggestion that it was M71, which is not far from M27.
32. David W. Dewhirst and Michael Hoskin "The Rosse spirals", *Journal for the history of astronomy*,

xxii (1991), 257–66.

33. RAS W.4/33.1, facing inside cover.
34. The paper (*op. cit.* (ref. 18)) is dated April 1784 and was read on 17 June.
35. *Ibid.*, 443.
36. The topics that follow were discussed by me at length long ago in "William Herschel's early investigations of nebulae: A reassessment", *Journal for the history of astronomy*, x (1979), 165–76, and so the details are not repeated here.
37. William Herschel, "On the construction of the heavens", *Philosophical transactions*, lxxv (1785), 213–66, and "Remarks on the construction of the heavens", *ibid.*, lxxix (1789), 212–26, both reprinted with astrophysical notes by D. W. Dewhirst in my *William Herschel and the construction of the heavens* (London, 1963).
38. *Ibid.*, 260.
39. For an account of the negotiations and of the fate of the great reflector, see Michael Hoskin, "Herschel's 40ft reflector: Funding and functions", *Journal for the history of astronomy*, xxxiv (2003), 1–32.
40. "Les nébuleuses de M. Messier sont nébuleuses avec le télescope de 7 pieds et lorsqu'on les observe avec le télescope de 20 pieds, l'on voit clairement que les nébuleuses sont un amas d'étoiles. Le miroir du télescope de 40 pieds pèsera sept cent livres.... L'intention de M. Herschel, en faisant ce si grand télescope, n'a pas pour but l'agrandissement de l'objet, mais de se donner, à l'aide des plus grands miroirs, la plus grande quantité de lumières possibles", Audouin Dollfus, "Une visite chez William Herschel [par Barthélemy Faujas de Saint-Fond]", *L'astronomie*, ci (1987), 135–43, p. 141. The visit can be shown to have taken place on 15/16 August 1784.
41. Hoskin, *Discoverers of the universe* (ref. 17), 125–8.
42. J. Banks to Herschel, 7 November 1789, RAS W.1/13.B.24.
43. "The changes I have observed in the great milky nebulosity of Orion, 23 years ago, ... cannot permit us to look upon this phenomenon as arising from immensely distant regions of fixed stars", William Herschel, "Catalogue ... with remarks on the construction of the heavens", *Philosophical transactions*, xcii (1802), 477–528, p. 499.
44. William Herschel, "On nebulous stars, properly so called", *Philosophical transactions*, lxxxi (1791), 71–88.
45. RAS W.5/12.1, 74, and W.2/3.6.
46. Hoskin, *op. cit.* (ref. 39).
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