JHA, xlii (2011)

WILLIAM HERSCHEL AND THE NEBULAE, PART 2: 1785–1818

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True Nebulosity Rejected

When William Herschel sent to the Royal Society his 1784 paper on the construction of the heavens, he was still of the opinion that there were true nebulae to be found alongside those that were simply distant "star clusters in disguise" (as he later put it[1]), and he had persuaded himself that observers could tell the difference: true nebulae shone with a milky appearance, while star clusters disguised by distance appeared mottled, 'resolvable'. But, as we saw in Part 1,[2] he soon after came across M17, which we know as the Omega Nebula, and then M27, the Dumbbell Nebula; and to his surprise each contained both nebulosities, milky and 'resolvable'. Already convinced that the Milky Way is the optical effect of our immersion in a layer or 'stratum' of stars (the Galaxy), and that he had encountered the remnants of other strata that had already fragmented into nebulae and clusters as a result of gravitational attraction,[3] he interpreted these two objects as entire strata of stars, their stars in the middle distance appearing to us as resolvable nebulosity and those in the far distance appearing as milky. He concluded that, contrary to what he had hitherto believed, *all nebulae, whether milky or resolvable, were formed of stars.*

With the puzzle concerning nebulosity apparently solved, Herschel prepared a second paper on the construction of the heavens, dated New Year's Day 1785 and one of the greatest in the history of astronomy.[4] He begins in dramatic fashion with an imagined model of a stellar universe in its infancy: "Let us then suppose numberless stars of various sizes, scattered over an indefinite [but not infinite?] portion of space in such a manner as to be almost equally distributed throughout the whole." Gravity is the agent that will bring about change in this distribution: "The laws of attraction, which no doubt extend to the remotest regions of the fixed stars, will operate in such a manner as most probably to produce the following remarkable effects." And he goes on to describe the "Formation of Nebulae" — that is, star systems — likely to result from irregularities in the hypothetical distribution, places where the gravitational pull is greater than normal.

He instances the presence in a particular region of either one large star, or unusually many ordinary ones. The large star will attract those stars immediately around it, and this will result in a regular (spherical, or near-spherical) cluster of stars — Form I. The unusually numerous ordinary stars will also draw in those around, and this will result in an irregular cluster, its shape depending on the layout of these ordinary stars — Form II. Combinations of these situations will result in more complex configurations, Forms III and IV, as well as in Form V, "great cavities or vacancies by the retreat of the stars towards the various centers which attract them".

Does this mean, he asks himself, that clusters will one day end in what we today

0021-8286/11/4203-0321/$10.00

would term 'gravitational collapse'? "At first sight then it will seem as if a system, such as it has been displayed in the foregoing paragraphs, would evidently tend to a general destruction, by the shock of one star's falling upon another."[5] A century before, Isaac Newton too had worried about the role of gravity in the universe — which for him was strictly infinite — and he was puzzled as to why the stars still occupied the positions listed for them in Antiquity (as the evidence then suggested); for forces cause movements, and if each star was being pulled by the gravitational attraction of every other star it should surely respond by moving.[6] Newton's conclusion had been that Providence had established stars throughout the universe with a high degree of symmetry, so that each star would be pulled (more or less) equally in all directions and therefore in the short term would remain at rest. But since the symmetry was not perfect, sooner or later stars would begin to move. However, all was not lost, for God the Clockmaker had a servicing contract with his universe and would intervene at intervals, and by Divine fiat restore the original distribution of the starry universe.

Unknowingly following in Newton's footsteps, Herschel indulges in some reflections concerning his own "theoretical view". He comments that in large measure "the indefinite extent of the sidereal heavens ... must produce a balance that will effectually secure all the great parts of the whole from approaching to each other".[7] And, again like Newton, "there is no doubt that the great Author of [the system of the universe] has amply provided for the preservation of the whole, though it should not appear to us in what manner this is effected".[8] Herschel then proposes a third consideration, one not available to Newton: if the stars of a cluster are in rotation, then the projectile forces "will prove such a barrier against the seeming destructive power of attraction as to secure from it all the stars belonging to a cluster, if not for ever, at least for millions of ages".[9]

But what then?

> Besides, we ought perhaps to look upon such clusters, and the destruction of now and then a star, in some thousands of ages, as perhaps the very means by which the whole is preserved. These clusters may be the *Laboratories* of the universe, if I may so express myself, wherein the most salutary remedies for the decay of the whole are prepared.[10]

Planetary Nebulae

He explains what he has in mind in the concluding section of the paper,[11] where he lists half-a-dozen examples of what he calls "planetary nebulae", the term we still use today. Herschel had come across the first of these mysterious objects within weeks of taking up his duties at Windsor. On 7 September 1782 he found near ν Aquarii:

> A curious Nebula, or what else to call it I do not know. it is of a shape somewhat oval, nearly circular, and with this power [460] appears to be 10 or 15″ diameter. It is of the same shape with 278, but much less in appearance. with 932 it is still the same shape but much larger. So that its appearance seems to follow the law

> of magnifying, from whence it is clear that it is of some real magnitude in the heavens and not a glare of light. The brightness in all the powers does not differ so much as if it were of a planetary nature, but seems to be of the starry kind, tho' no star is visible with any power. It is all over of the same brightness. The compound eyepiece will not distinguish it from a fixt star, at least not sensibly....[12]

This momentous discovery of what we know as the Saturn Nebula was to have far-reaching consequences for Herschel's theorizing. The object appeared to have the disk of a planet but the pale light of a nebula; but whether it was a true nebula he was by no means sure. He returned to the object repeatedly to check whether it had changed its position (if so, it would be a planet of sorts);[13] he vacillated, but finally concluded it had not.

In his 1785 paper Herschel carefully considers the various possible explanations of these objects "that from their singular appearance leave me almost in doubt where to class them", and concludes that they are most likely nebulae that "consist of stars that are compressed and accumulated in the highest degree" — in other words, the terminal stage of a globular ('spherical') star system that has been condensing more and more as gravity works its magic.

> If it were not perhaps too hazardous to pursue a former surmise of a renewal in what I figuratively called the Laboratories of the universe, the stars forming these extraordinary nebulae, by some decay or waste of nature, being no longer fit for their former purposes, and having their projectile forces, if any such they had, retarded in each other's atmosphere, may rush at last together, and either in succession, or by one general tremendous shock, unite into a new body.[14]

The star that flared up in 1572 ('Tycho's nova') might, he thinks, have been an example of such a gravitational collapse.

This was Herschel's best guess as to the nature of planetary nebulae, but they continued to worry him. Soon after the paper was published we find him writing to the French astronomer Lalande describing planetaries as "heavenly bodies of which as yet we have no clear idea and which are perhaps of a type quite different from those that we are familiar with in the heavens".[15] And astronomers who visited Slough would be shown a planetary nebula and asked what they thought of it.[16]

The Galaxy

The readers of Herschel's 1785 paper must have been puzzled as to what to make of his near-uniform, indefinite — does he mean 'infinite'? — distribution of stars, for his commitment to the 'stratum' that is our Galaxy was unwavering (and much of the rest of the paper is devoted to an analysis of it). Clearly, there is no way in which gravity can derive strata from a near-uniform *infinite* distribution of stars. We probably have to understand Herschel as, for the sake of simplicity, talking about a purely hypothetical distribution of stars over "an indefinite portion of space", although in fact for him the local reality is a distribution that can be thought of as sandwiched

between two parallel (albeit widely separated) planes.[17]

The observations he has so far had time to make lead him to think that the Galaxy is "everywhere terminated",[18] finite. But he hesitates to be dogmatic on this. Persevering in his campaign to persuade the King to fund a large reflector, he comments:

> I ought to add, that a telescope with a much larger aperture than my present one, grasping together a greater quantity of light, and thereby enabling us to see farther into space, will be the surest means of compleating and establishing the arguments that have been used: for if our nebula is not absolutely a detached one, I am firmly persuaded, that an instrument may be made large enough to discover the places where the stars continue onwards.[19]

Prophetic words.

Not only is the Galaxy seemingly finite, but it has "a certain air of youth and vigour",[20] and it displays "fewer marks of profound antiquity"[21] than other systems; even though "Some parts of our system indeed seem already to have sustained greater ravages of time than others",[22] gravity has not yet disturbed the primeval uniformity of distribution of the stars of our Galaxy sufficiently to invalidate the investigation in which Herschel has been involved for some time.

In his 1784 paper Herschel had introduced his readers to 'star-gages', the first example in history of stellar statistics. He was occupied, he told them, in counting the number of stars in his field of view in various directions, "to come to a full knowledge of the sun's place in the sidereal stratum".[23] He develops the method in his 1785 paper. Granted that his 20-ft reflector can reach the borders of the Galaxy in every direction (as he thinks), and if within these borders the stars are still distributed with fair uniformity, then the number of stars in any field of view is related (by a simple arithmetical formula) to the distance to the border of the Galaxy in that direction. He has been, he says, unable to spare the time to count stars in *every* region of the sky visible from Windsor, a mammoth undertaking, but he has been able to count them around a great circle of the heavens. He has then used the resulting 'star-gages' to derive a diagram representing a cross-section of the Galaxy.[24] So famous would the diagram become that it was being reproduced long after his death, and longer still after he abandoned the two assumptions on which the diagram was based; for writers on astronomy, like Nature, abhor a vacuum, and when the diagram was discredited there was nothing equivalent to take its place.

But discredited it was. After Herschel commissioned his giant 40-ft reflector in 1789, he found he was able to see many galactic stars invisible in the 20-ft, so the first assumption was incorrect, and there was no reason to suppose that the 40-ft had succeeded where the 20-ft had failed.[25] As to the assumption of near-uniformity, long nights of searching for star clusters would (as we shall see) eventually convince him that a high star-count was an indication of clustering, rather than of an exceptional distance to the border of the Galaxy in that direction.

But this was for the future. For the present it seemed that the compound nebula[26] we know as the Galaxy was finite, indeed compact. The other nebulae (he believed)

were likewise star systems, of varying extent; and if the Orion Nebula, for example, or the Andromeda Nebula stretched across the sky and yet was so distant that its individual stars could not be detected, it "cannot be otherwise than of a wonderful magnitude, and may well outvie our milky-way in grandeur".[27] In other words, such nebulae were galaxies fully comparable with our own.

Our Galaxy was destined eventually to fragment, as time passed and gravity undermined the initial uniformity of distribution: "our system, after numbers of ages, may very possibly become divided so as to give rise to a stratum of two or three hundred nebulae."[28] The future, then, was clear; but the past was not: as to how the initial near-uniformity had come about, Herschel had no suggestions to offer, and never would have.

"Rise, Progress, and Decay"

The third of his cosmological papers of the 1780s takes the modest form of "a few introductory remarks on the construction of the heavens" as preface to his second catalogue of one thousand new nebulae and clusters, and is dated 1 May 1789.[29] By now the 40-ft was funded, indeed nearing completion, so there was no longer any need to argue the case for 'more light'; and his own unrivalled familiarity with the large-scale universe was beyond dispute. He begins "*analyzing* the heavens" by making the obvious point that in the solar system it is only the Sun, "a refulgent fountain of light", that would be visible from a distance; and so it is only the stars, or "suns, every one of which is probably of as much consequence to a system of planets, satellites, and comets, as our own sun", that the student of the large-scale universe can see and study. But he has a dramatic new way of looking at the specimens of 'systems' — star clusters — that he, the natural historian of the heavens, is collecting.

> ... the heavens consist of regions where suns are gathered into separate systems; but may we not hope that our knowledge will not stop short at the bare enumeration of phaenomena capable of giving us so much instruction? Why should we be less inquisitive than the natural philosopher, who sometimes, even from an inconsiderable number of specimens of a plant, or an animal, is enabled to present us with a history of its rise, progress, and decay?[30]

Most of the paper is devoted to the many systems he has encountered that have the form of "lucid spots, of equal lustre, scattered over a circular space, in such a manner as to appear gradually more compressed towards the middle".[31] He has no trouble in arguing that these are globular clusters, as indeed they are. They vary in size, in distance, and in the extent to which they are currently condensed, but he sees them all as members of the same species.[32] As a good astronomer Herschel preferred a simple theory to a more complex, and his thinking about celestial objects was invariably guided — for better or worse — by the image of the life-cycle of a *single* living organism with its unique trajectory through time.[33]

The structure of globular clusters demonstrates that they "are thus formed by the

action of central powers".[34] Gravity is the obvious candidate; Herschel cannot prove that it is the one and only attractive power at work, but in his heart he has no doubt that this is the case, and in later papers he will take this for granted.[35]

A globular cluster (his Form I) will become more and more compressed as time passes, culminating in a planetary nebula. But what of the clusters that are irregular? "I shall now extend the weight of my argument, by taking in likewise every cluster of stars or nebula that shows a gradual condensation, or encreasing brightness, towards a center or certain point."[36] But he has the problem that gravity alone will hardly suffice to make an irregular cluster spherical. However, he is determined to make his theory as simple as possible, and so he is driven to speculate.

> Although the form of [irregular clusters] be not globular, it is plainly to be seen that there is a tendence towards sphericity, by the swell of the dimensions the nearer we draw towards the most luminous place, denoting as it were a course, or tide of stars, setting towards a center. And — if allegoral [*sic*] expressions may be allowed — it should seem as if the stars thus flocking towards the seat of power were stemmed by the crowd of those already assembled, and that while some of them are successful in forcing their predecessors sideways out of their places, others are themselves obliged to take up lateral situations, while all of them seem equally to strive for a place in the central swelling, and generating spherical figure.[37]

Even his best friend found this unconvincing. Within days of the paper's being read to the Royal Society, William Watson wrote to him with detailed criticisms, among them:

> May not other collections of Stars have been equally exposed to the central powers as the round ones, & yet not arrived to that figure from the previous more unfavorable position of its stars? — If not, show the improbability of the latter hypothesis.

In his covering letter Watson emphasizes the point:

> For tho' a reason is required by you to shew why any oblong or irregular clusters have not become round; it should seem you ought to shew that the previous [*or* primaeval] arrangement in such clusters was similar to that of the globular ones & that therefore time only was required for the effect of making them globular likewise.[38]

We might think that Watson's objections were well founded. But Herschel was rarely persuaded into changing his mind, and although some of the clusters he encountered in the heavens were globular and others irregular, his instinct was against accepting that they formed two different species (as indeed they do). To make them a single species as far as possible, he insisted that even an irregular cluster would eventually develop into a globular; then it would be "in the perfection of its growth", eventually to condense to become a tightly packed planetary nebula, "very aged, and drawing on towards a period of change, or dissolution".[39]

Herschel's concluding paragraph in the 1789 paper epitomizes the revolution in

astronomical thinking that he is pioneering:

> This method of viewing the heavens seems to throw them into a new kind of light. They now are seen to resemble a luxuriant garden, which contains the greatest variety of productions, in different flourishing beds; and one advantage we may at least reap from it is, that we can, as it were, extend the range of our experience to an immense duration. For, to continue the simile I have borrowed from the vegetable kingdom, is it not almost the same thing, whether we live successively to witness the germination, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which a plant passes in the course of its existence, be brought at once to our view?[40]

True Nebulosity Once More

With the publication of Herschel's 1789 "Remarks", it seemed as though the essentials of his theory of the construction of the heavens were established. But there were problems. One concerned the Orion Nebula. On the supposition that it was a star system so far away that not even he could resolve it into its component stars, Herschel in 1785 had declared that it "may well outvie our milky-way in grandeur",[41] that it was a galaxy. But this was to close his eyes to the changes in the nebula that he believed he had observed in his early years as an astronomer. As he was eventually to write, in 1802, "The changes I have observed in the great milky nebulosity of Orion, 23 years ago, and which have also been noticed by other astronomers, cannot permit us to look upon this phaenomenon as arising from immensely distant regions of fixed stars".[42]

Then there were the planetary nebulae, "heavenly bodies, that from their singular appearance leave me almost in doubt where to class them".[43] His best guess was that they were compressed globular clusters on the verge of gravitational collapse; but what happened then?[44]

A planetary nebula is in fact a cloud of gas that has been ejected from a dying star, but in the examples Herschel had so far encountered, the star — if visible at all in his reflectors — had not been bright enough to force itself on his attention. This was about to change. At 3.51 a.m. on 13 November 1790, he was at the eyepiece of the 20-ft engaged in a routine sweep, number 980 in the series, with Caroline at her desk at a nearby window. There was no reason to expect that something dramatic was about to happen. But, as the sky slowly rotated overhead, a bizarre and ghostly object came into his field of view: a star with an atmosphere. Caroline copied down the description at her brother's shouted dictation:

> A most singular phenomenon! A star about 8m, with a faint luminous atmosphere of a circular form, of about 3′ dia[mete]r. The star is perfectly in the center, and the atmosphere is so diluted, faint, and equal throughout, that there can be no surmise of its consisting of stars; nor can there be a doubt of the evident connection between the atmosphere and the star.[45]

Here, surely, was an indisputable example of true nebulosity.

As he went back over his records, Herschel could scarcely believe the number of occasions when — with a mind closed to the possibility — he had come across other examples of what he now recognized to be nebulosity. For example, on 16 October 1784 he had encountered "A star of about the 9th magnitude, surrounded by a milky nebulosity, or chevelure, of about 3 minutes in diameter" (our NGC 2170). As he now admitted,

> My present judgement concerning this remarkable object is, that the nebulosity belongs to the star which is situated in its center.... It must appear singular, that such an object should not have immediately suggested all the remarks contained in this Paper...[46]

and he is hard put to it to find excuses.

Hitherto Herschel's best guess at the nature of planetary nebulae had been that they represented the final stage in the evolution of stellar systems, globular clusters about to collapse and thereby become one of the "laboratories of the universe". Now, in a dramatic change of heart, he would see a planetary as pre-stellar, as "a much condensed, luminous fluid",[47] soon to develop under gravity into a nebulous star, and thence into a true star.[48] "If, therefore, this matter is self-luminous, it seems more fit to produce a star by its condensation than to depend on the star for its existence."[49]

It is ironic that while to modern astronomers the object in question is a planetary nebula (NGC 1514), to Herschel it was not a planetary nebula at all but a 'nebulous star' — by definition, Herschel's planetary nebulae had uniform brightness, and this object was by no means uniform.

Herschel hints at the possible physical origins of the luminous fluid:

> How far the light that is perpetually emitted from millions of suns may be concerned in this shining fluid, it might be presumptuous to determine; but, notwithstanding the unconceivable subtilty of the particles of light, when the number of emitting bodies is almost infinitely great, and the time of continual emission indefinitely long, the quantity of emitted particles may well become adequate to the constitution of a shining fluid, or luminous matter, provided a cause can be found that may retain them from flying off, or reunite them.[50]

The individual particles of light will be travelling at immense speed in all directions, but as they "pass through innumerable systems" they will meet obstacles that will impede their flight, "Not to mention the great counteraction of the united attractive force of whole sidereal systems, which must be continually exerting their power upon the particles while they are endeavouring to fly off".[51] As a result, he seems to think, they will slow down, and so be able to attract surrounding particles and form luminous fluid.

The Final Cosmogony

Herschel's recognition of true nebulosity called for a major rethink of his cosmogony. Whereas his 1785 theoretical model of the universe had begun with a nearly uniform distribution of fully formed stars on which gravity went to work, his new picture of the real universe envisaged pre-stellar stages during which the clouds of nebulosity condensed into nebulae. These eventually gave birth to stars, which fed on any remaining nebulosity and then went on (as before) to develop into clusters. This revised cosmogony, which he was to accept for the rest of his days, he first expounded in the "Remarks on the construction of the heavens" prefaced to his final catalogue of nebulae, published in 1802.[52]

In 1784 Herschel had invoked what we today term the Copernican Principle, that the Earth's position in the universe is in no way special, to justify his belief that the Sun is a typical star of the Galaxy.[53] But in 1802, at the very time that Caroline was assembling the nebulae for their final catalogue, he was in process of re-examining his double stars after an interval of some two decades, and he had found that some were in fact not line-of-sight doubles occurring by chance, but 'binaries', formed of two stars that were companions in space and orbiting together about their common centre of gravity.[54] Were either of the two stars of a binary to have had in the past its own planetary system, the gravitational pull of the other star would long since have disrupted the orbits of these planets. Herschel concluded that only truly isolated stars — such as the Sun and the bright stars near to us — had the untroubled gravitational conditions that allowed for planets, and that the innumerable stars in multiple systems or clusters would therefore be unable to have satellites in orbit about them.[55]

In 1785, early in his long campaign of sweeps for nebulae and clusters, Herschel had seen the stars within the Galaxy as distributed with fair uniformity, but by 1802, at the end of sweeps during which he had discovered many hundreds of clusters, he had rejected this view: the stars of the Galaxy, he says, are in fact "very unequally scattered".[56] Perhaps his diagram of a cross-section of the Galaxy was becoming an embarrassment, for in later life he repeatedly disowns the assumption of equal scattering on which it was based.[57] To the contrary,

> ... the stars we consider as insulated [including the Sun] are also surrounded by a magnificent collection of innumerable stars, called the milky-way, which must occasion a very powerful balance of opposite attractions, to hold the intermediate stars in a state of rest. For, though our sun, and all the stars we see, may truly be said to be in the plane of the milky-way, yet I am now convinced, by a long inspection and continued examination of it, that the milky-way itself consists of stars very differently scattered from those which are immediately about us. But of this, more will be said on another occasion.[58]

This sounds almost like a ring theory of the Galaxy, but this is not his meaning, for as he was to explain in 1818, the Galaxy extends without visible limits: "... when our gages will no longer resolve the milky way into stars, it is not because its nature is

ambiguous, but because it is fathomless."[59] This had implications. The Andromeda Nebula, for example, may be another stellar system (although this is by no means certain[60]), but if so it is evidently of finite extent. Our Galaxy, being by contrast fathomless, is unique, "the most brilliant, and beyond all comparison the most extensive sidereal system";[61] and so again the Copernican Principle does not apply.

In the 1802 "Remarks" he goes on to discuss "groups of stars", formerly referred to as "irregular clusters" and "perhaps, of all the objects in the heavens, the most difficult to explain".[62] However, for once he is agnostic about what the future holds for them and makes no attempt to argue that they develop under gravity into globular clusters (which he esteems as "certainly the most magnificent objects that can be seen in the heavens"[63]).

The paper ends with an account of milky nebulosity, nebulous stars, planetary nebulae, and planetary nebulae with centres. Milky nebulosity, he says, may sometimes simply be a star system disguised by distance, "like the collections that construct our milky-way", or it may be "real, and possibly at no great distance from us". In the latter case, "To attempt even a guess at what this light may be, would be presumptuous". We know (he argues) that the Orion Nebula is formed of real nebulosity because it has been observed to change, although these changes are in fact "minute". As to the nebulous stars, their nature "is enveloped in much obscurity", but Herschel's best guess is that planetary nebulae develop into planetary nebulae with centres, and these in turn in nebulous stars.

And there the matter rested for nearly a decade, during which Herschel — to the dismay of his friends — became obsessed with explaining the colour effects we know as Newton's rings. But when he was in his seventies, and had long since given up serious observing, Herschel prepared two lengthy papers in which he assembled specimens from his great catalogues of nebulae and clusters, to allow us in effect to 'observe' the life-cycle of these objects to which he had devoted so much effort. In the first, published in 1811, he illustrates the gradual development under gravity of nebulosity and nebulae; in the second, published in 1814, he does the same for nebulae intermingled with stars, and then for the purely "sidereal part of the heavens".[64] There is, he says, less difference between the objects grouped in the successive 'articles' than "there would be in an annual description of the human figure, were it given from the birth of a child till he comes to be a man in his prime".[65]

He believes he has been able to show in the 1811 paper that "every succeeding state of the nebulous matter is the result of the action of gravitation upon it while in a foregoing one".[66] The 1814 paper demonstrates what then follows, the "very gradual conversion of the nebulous matter into the sidereal appearance"[67] and "the *growth* of stars".[68] It then goes on to show how star systems develop under gravity, ultimately to become "the most magnificently constructed sidereal systems",[69] the globular clusters in which "the exertion of a clustering power has brought the accumulation and artificial construction of these wonderful celestial objects to the highest degree of mysterious perfection".[70] The 1811 and 1814 papers together, he says, reveal

> the intimate connection between the two opposite extremes, one of which is the immensity of the widely diffused and seemingly chaotic nebulous matter, and the other, the highly complicated and most artificially constructed globular clusters of compressed stars.[71]

Problems that Remain

(i) *The universe in the large.* The limitations of these later papers are significant. In them, Herschel deals with the life-stories only of individual astronomical objects — clouds of nebulosity, stars, star clusters — or of groups of closely related objects; and while he has a few remarks to make about the Galaxy, he has nothing to say about the cosmos as a whole. Given Herschel's astonishing boldness and inventiveness as a theorist, this is surprising.

(ii) *The origins and nature of nebulosity.* The 1811 paper begins with examples of "extensive diffused Nebulosity",[72] but as to how this nebulosity originated he is silent (the paper, so to speak, begins with "the birth of a child" but does not explain its conception). The only clue we have been given was in the 1791 paper that first announced the existence of true nebulosity, where he spoke of "the light that is perpetually emitted from millions of suns" and suggested ways in which the light particles might be slowed down to the point where they would attract other particles and coalesce to form nebulosity. In 1802 he was agnostic.[73] In 1811 he does no more than hint that we may learn something from the "small telescopic comets as often visit our neighbourhood",[74] for these may be composed of nebulosity, if indeed they are not condensed nebulae; otherwise he is again agnostic: "By nebulous matter I mean to denote that substance, or rather those substances that give out light, whatsoever may be their nature, or of whatsoever different powers they may be possessed."[75]

Nebulosity, whatever its nature may be, gives out only a pale light, and therefore the only nebulosity within sight is that close to us. But what little we can see is surprisingly extensive, and therefore the total quantity of nebulosity in the universe must be immense. "A nebulous matter", he says in the 1811 paper, "diffused in such exuberance throughout the regions of space, must surely draw our attention to the purpose for which it may probably exist",[76] and later in the paper he confirms that this purpose is to provide the material that will in time develop into nebulae and thence into stars:

> ... the present state of the heavens presents us with several extensive collections of scattered nebulae, plainly indicating by their very remarkable arrangement, that they owe their origin to some former stock of nebulous matter.[77]

(iii) *The fate of globular clusters.* The 1814 paper ends with globular clusters ("a man in his prime"), but on what then happens to a cluster as it ages and declines past its current perfection he has nothing to say: he makes no attempt to shed light on the celestial counterpart to old age and death. Back in 1785, when he thought all nebulae were star clusters, he had imagined gravity as bringing about the development of a

globular cluster into an even more compact planetary nebula, the final stage before gravitational collapse; but of this we have now no hint. Yet in his later writings there is no suggestion that globular clusters are eternal, and surely gravitational collapse is the fate that must await them, even if orbital motions postpone the evil day. One might have expected Herschel to argue that the explosion of such gravitational collapses will result in light flung out into space in all directions, to form nebulosity and so begin the cycle over again. If this was his opinion — as seems very possible — he does not say.

(iv) *How do irregular clusters become globular?* Herschel simply assumes that celestial objects that have been subject to the action of gravity for long enough become spherical. If a cluster is presently irregular in shape, then give it time and eventually it will become a globular cluster: "... the still remaining irregularity of their arrangement additionally proves that the action of the clustering power has not been exerted long enough to produce a more artificial construction."[78]

(v) *How does the spinning motion of stars originate?* Here Herschel does have some hints to offer, for he sees the nebula out of which the star will be born as already rotating as a result of irregularities in the nebulosity that formed the nebula, notably the opposite appendages to its nucleus, or 'branches':

> Will not the matter of these branches in their gradual fall towards the nucleus, when discharging their substance into the chevelure, produce a kind of vortex or rotatory motion? ... do we not see some natural cause which may give a rotatory motion to a celestial body in its very formation?[79]

He later enlarges on this:

> ... it appears that every figure which is not already globular must have eccentric nebulous matter, which in its endeavour to come to the center, will either dislodge some of the nebulosity which is already deposited, or slide upon it sideways, and in both cases produce a circular motion; so that we can hardly suppose a possibility of the production of a globular form without a consequent revolution of the nebulous matter, which in the end may settle in a regular rotation about a fixed axis.[80]

Time Past and Time Future

In his private notes on the geological formation of the Earth itself, Herschel had no hesitation in envisaging "thousands of centuries";[81] and he was still bolder in his thinking about the universe. To look at distant objects was, he said, to look into time past, and he believed he had seen light that had taken two million years on its journey to Earth;[82] even if its source had ceased to exist two million years ago, it would still be visible to him. In the development of nebulae, "millions of years, perhaps are but moments".[83] Once he even remarks that "we have an eternity of past duration to

resort to",[84] although it is not clear whether he intends 'eternity' in the literal sense or as shorthand for "immense periods of time".

He ends his 1814 paper with some thoughts about the Galaxy. As gravity continues its work, in the Galaxy clusters will be created which will eventually reach "the ripening period of the globular form", so that the Galaxy "must finally be broken up, and cease to be a stratum of scattered stars".[85] And he concludes with a remark that is at once enigmatic and profound:

> We may also draw a very important additional conclusion from the gradual dissolution of the milky way; for the state into which the incessant action of the clustering power has brought it at present, is a kind of chronometer that may be used to measure the time of its past and future existence; and although we do not know the rate of going of this mysterious chronometer, it is nevertheless certain, that since the breaking up of the parts of the milky way affords a proof that it cannot last for ever, it equally bears witness that its past duration cannot be admitted to be infinite.[86]

Herschel and the Construction of the Heavens

William Herschel's investigations into 'the construction of the heavens' were triggered by his interest in two questions: Are all nebulae simply clusters of stars disguised by distance?, and How can we explain the appearance of the Milky Way? And his answers depended on two pivotal concepts: in space, that stars are arranged in strata; and in time, that gravity is the agent of change.

He displays a mature grasp of the problem of the nature of the nebulae already in 1774, on the very first page of his first observing book: nebulae that change shape cannot be distant star systems but must be formed of a luminous fluid, true nebulosity. He believed that he had detected changes in the Orion Nebula while still in Bath, and this was still his position in 1784 when he wrote his first paper on the construction of the heavens.

In this paper he gave an enduring answer to the puzzle of the Milky Way: the Sun is immersed in a stratum of stars and this is why we see a milky effect as we look around us within the Galaxy. In 1784 and 1785 he believed that the stratum was of finite extent and that the stars within it were distributed with fair uniformity. This allowed him to use stellar statistics ('star-gages') to plot the outline of a cross-section. But when he commissioned the 40-reflector in 1789 he found that the Galaxy extended further than he had imagined — indeed, as far as his instruments could tell, it was without limits. In 1802 he focused on the contrast between the isolated stars of which the Sun is one and the groups and clusters found elsewhere in the Galaxy, but his concept of the Galaxy as a stratum of stars never wavered. But how such a stratum might have originated was a mystery to which Herschel could offer no solution.

In 1784 he was already familiar with regions where many nebulae and clusters were to be found, and these collections he interpreted as strata analogous to the Galaxy, but fragmented. One might almost "already fragmented" — as a result of the destructive

effects of gravitational attraction — but it was only after he decided in the summer of 1784 that true nebulosity was an illusion and that all nebulae were simply clusters of stars, that his cosmos acquired the simplicity that forced gravity on his attention.

Gravity is a force, and forces cause movements, changes. His 1785 paper is shot through with this insight. Strata of stars will fragment under gravity, and our now-youthful Galaxy may one day become a stratum of two or three hundred isolated clusters. Because the Orion Nebula and the Andromeda Nebula appear large and yet are too distant for us to detect the stars of which they are composed, they are examples of comparable galaxies.

In his 1789 paper Herschel expresses his vision of the globular cluster as the culmination of a star system's development under gravity. He sees all star systems as forming a single species, and so even irregular clusters must somehow join the mainstream of development and become globular. But what happens next? He suspects that a planetary nebula may be a highly-compressed globular cluster, about to undergo gravitational collapse.

Herschel's recognition in 1790 of the existence of true nebulosity requires his cosmogony to be extended back in time, to the stages before stars have formed, and planetary nebulae are now given an entirely different role: that of the luminous fluid out of which stars will be born. In his 1791 paper Herschel hints that nebulosity — which itself develops into the luminous fluid of which nebulae are composed— might originate in the light emitted by the stars of the universe; but this is the only occasion on which he addresses the issue.

His final papers on the construction of the heavens re-present his two great insights, but leave them enveloped in mystery. Nebulae, stars and star clusters are successive stages in the life-cycle of a single species as gravity works its effects, and the stages set out for us begin with diffuse nebulosity and end with the perfection of globular clusters; but how the nebulosity arose, and what eventually happens to the globular clusters, we are not told. The Galaxy meanwhile is a stratum of nebulae and stars, and the stratum is of unknown origins and indefinite extent. It is unique, for its one-time rivals (such as the Orion Nebula and the Andromeda Nebula) are clearly finite, and may be nebulous, and not stellar at all.

All this is a far cry from the clockwork universe of Newton and Leibnitz, but Herschel left too many questions unanswered, and astronomers were uncomfortable with theories supported by evidence available to one man alone. And so when the future Royal Astronomical Society published in 1820 an "Address ... explanatory of their views and objects", potential members read:

> Beyond the limits however of our own system, all at present is obscurity. Some vast and general views of the construction of the heavens, and the laws which may regulate the formation and motions of sidereal systems, have, it is true, been struck out; but, like the theories of the earth which have so long occupied the speculations of geologists, they remain to be supported or refuted by the slow accumulation of a mass of facts....[87]

REFERENCES

1. "We may also have surmised nebulae to be no other than clusters of stars disguised by their very great distance", William Herschel, "Astronomical observations relating to the construction of the heavens ...", *Philosophical transactions*, ci (1811) [hereafter: 1811 paper], 269–336, p. 270; "... clusters of stars in disguise, on account of their being so deeply immersed in space", William Herschel, "Astronomical observations and experiments, selected for the purpose of ascertaining the relative distances of clusters of stars ...", *Philosophical transactions*, cviii (1818) [hereafter: 1818 paper], 429–70, p. 466.
2. Michael Hoskin, "William Herschel and the nebulae, Part 1: 1774–1784", *Journal for the history of astronomy*, xlii (2011), 177–92, p. 186.
3. "A very remarkable circumstance attending the nebulae and clusters of stars is, that they are arranged into strata.... It is probable enough, that they may surround the whole apparent sphere of the heavens, not unlike the milky way, which undoubtedly is nothing but a stratum of fixed stars", William Herschel, "Account of some observations tending to investigate the construction of the heavens", *Philosophical transactions,* lxxiv (1784) [hereafter: 1784 paper], 437–51, p. 442. Much of the rest of the paper is concerned with these strata.
4. William Herschel, "On the construction of the heavens", *Philosophical transactions*, lxxv (1785) [hereafter: 1785 paper], 213–66.
5. *Ibid*., 216.
6. Michael Hoskin, "Newton, Providence and the universe of stars", *Journal for the history of astronomy*, viii (1977), 77–101.
7. Herschel, 1785 paper, 217. *Cf.* William Herschel, "Catalogue of 55 new nebulae ... with remarks on the construction of the heavens", *Philosophical transactions*, xcii (1802) [hereafter: 1802 paper], 477–528, p. 479: "... the stars we consider as insulated are also surrounded by a magnificent collection of innumerable stars, called the milky-way, which must occasion a very powerful balance of opposite attractions, to hold the intermediate stars in a state of rest."
8. Herschel, 1785 paper, 216.
9. *Ibid*., 217.
10. *Ibid*., 217.
11. *Ibid.*, 263–6.
12. Royal Astronomical Society Herschel Archive (hereafter: RAS) W.2/1.2, f. 231.
13. For example, in 1783 on 30 July, 25 August, 20 September, 17 and 23 October and 14 November, and in 1784 on 16 and 28 June, 15 July and 12 November. RAS W.4/1.5, W.4/1.7, W.2/3.2, W.2/3.3.
14. Herschel, 1785 paper, 265–6.
15. RAS W.1/1, 129, letter to Lalande, 17 March 1785: "... des corps celèstes dont nous n'avons pas encore d'idée bien claire & qui sont peut-être d'un genre tout à fait different de ce que nous connoissons dans les cieux."
16. For example, on 27 November 1787, Herschel showed his visitors the planetary nebula H.IV.18: "Mess^{rs} Cassini, Mechain Le Seure & Carochet saw this nebula, and the moon being absent, it appeared in its usual planetary view; these Gentlemen saw it very well and admired it as a great curiosity. Mr Cassini observed that a very small fixt star nf the nebula appeared not unlike a sattelite to it" (RAS W.2/3.7). Planetary nebulae were also shown to William Watson and a Mr Marsden on 11 March 1788, to Lord Palmerston on 3 August 1788, to Lalande on 5 August 1788, he "having never before seen a planetary one", to Edward Pigott on 6 August 1788, and to the Abbé Ximenes on 13 April 1789, *ibid.*
17. As he had explained at length in the 1784 paper, 443–5. There is a minor complication. Because we see the Milky Way as bifurcated, our Galaxy, "the stupendous sidereal system we inhabit", consists of an "extensive stratum and its secondary branch", Herschel, 1785 paper, 244.
18. Herschel, 1785 paper, 244.
19. Herschel, 1785 paper, 248.

20. Herschel, 1785 paper, 255.
21. Herschel, 1785 paper, 255.
22. Herschel, 1785 paper, 256.
23. Herschel, 1784 paper, 445.
24. Herschel, 1785 paper, 250–4.
25. "By these observations it appears that the utmost stretch of the space-penetrating power of the 20 feet telescope could not fathom the Profundity of the milky way ... [the 40 feet] would then leave us again in the same uncertainty as the 20 feet telescope", Herschel, 1817 paper, 327.
26. Herschel, 1785 paper, 244: "We inhabit the planet of a star belonging to a compound nebula of the third form." *Cf.* ref. 17 above.
27. Herschel, 1785 paper, 260. He supposes the Andromeda Nebula to be "the united lustre of millions of stars", *ibid.*, 249.
28. Herschel, 1785 paper, 255.
29. William Herschel, "Catalogue of a second thousand of new nebulae and clusters of stars; with a few introductory remarks on the construction of the heavens", *Philosophical transactions*, lxxix (1789) [hereafter: 1789 paper], 212–55.
30. Herschel, 1789 paper, 213, 214.
31. Herschel, 1789 paper, 214.
32. "... the component clustering stars [of a globular cluster] do not, perhaps, exceed each other in magnitude more than in some such proportion as one full-grown plant of a certain species may exceed another full-grown plant of the same species", Herschel, 1789 paper, 216; "This variety of size [that we encounter among] different spherical clusters, I am however inclined to believe, may not go farther than the difference in size, found among the individuals belonging to the same species of plants, or animals ...", *ibid.*, 224.
33. As we shall see, in 1811 and 1814 he would arrange innumerable nebulae and clusters from his catalogues in sequence, to imitate "the annual description of the human figure, were it given from the birth of a child till he comes to be a man in his prime", Herschel, 1811 paper, 271. In 1817 Herschel assumes that "one with another the stars are of a certain physical generic size and brightness, still allowing that all such deviations may exist, as generally take place among the individuals belonging to the same species", 1817 paper, 309.
34. Herschel, 1789 paper, 219.
35. Herschel, 1811 paper, 284: "Instead of inquiring after the nature of the cause of the condensation of nebulous matter, it would indeed be sufficient for the present purpose to call it merely a condensing principle; but ... why should we not look up to the universal gravitation of matter as the cause of every condensation, accumulation, compression, and concentration of the nebulous matter?"
36. Herschel, 1789 paper, 221.
37. Herschel, 1789 paper, 222.
38. William Watson to Herschel, 12 May 1789, W.1/13.W.55. From the covering letter I quote the words Watson originally wrote, as better representing his opinion.
39. Herschel, 1789 paper, 225.
40. Herschel, 1789 paper, 226.
41. See ref. 27 above.
42. Herschel, 1802 paper, 499; *cf.* Herschel, 1811 paper, Article 31.
43. Herschel, 1785 paper, 263.
44. Herschel, 1789 paper, 225.
45. RAS W.2/3.8, sweep 980.
46. William Herschel, "On nebulous stars, properly so called", *Philosophical transactions*, lxxxi (1791) [hereafter: 1791 paper], 71–88, p. 78. Wolfgang Steinicke (private communication) comments that Herschel might well have said the same of two 'planetary nebulae' in which the central star is prominent and which he encountered long before the object that provoked his change of

mind: NGC 2170 (IV.19, but not a planetary nebula in the modern sense), which he viewed on 16 October 1784 and which he cites in the 1791 paper, and NGC 2392 (IV.45), which he viewed on 17 January 1787. *Cf.* Wolfgang Steinicke, *Observing and cataloguing nebulae and clusters* (Cambridge, 2010), 40.

47. Herschel, 1791 paper, 86.
48. *Cf.* Herschel, 1811 paper, 318: "... perhaps in progress of time these nebulae which are already in such a state of compression, may be still farther condensed so as actually to become stars."
49. Herschel, 1791 paper, 85.
50. Herschel, 1791 paper, 87.
51. Herschel, 1791 paper, 87.
52. Herschel, 1802 paper.
53. "Now, should we imagine [the Galaxy] to be an irregular ring of stars, in the center nearly of which we must then suppose the sun to be placed, it will appear not a little extraordinary, that the sun, being a fixed star like those which compose this imagined ring, should just be in the center of such a multitude of celestial bodies, without any apparent reason for this singular distinction ...", Herschel, 1784 paper, 445.
54. William Herschel, "An account of the changes that have happened, during the last twenty-five years, in the relative situation of double stars ...", *Philosophical transactions*, xciii (1803), 339–82, and "Continuation of an account ...", *Philosophical transactions*, xciv (1804), 353–84.
55. "... probably, we can only look for solar systems among isolated stars", 1802 paper, 480.
56. Herschel, 1802 paper, 495.
57. "when we examine the milky way ... this supposed equality of scattering must be given up" (Herschel, 1811 paper, 270); "it is, however, evident that, if ever it consisted of equally scattered stars, it does so no longer" (William Herschel, "Astronomical observations relating to the sidereal part of the heavens", *Philosophical transactions*, civ (1814) [hereafter: 1814 paper], 248–84, p. 282); his gages of the 1780s, he says in 1817, "relate more immediately to the scattering of stars" than to distance (William Herschel, "Astronomical observations and experiments tending to investigate the local arrangement of the celestial bodies in space", *Philosophical transactions*, cvii (1817) [hereafter: 1817 paper], 302–31, p. 25.
58. Herschel, 1802 paper, 479–80.
59. Herschel, 1818 paper, 463; *cf.* Herschel, 1817 paper, 326–7.
60. "... its nature remains mysterious", Herschel, 1814 paper, 260.
61. Herschel, 1818 paper, 453.
62. Herschel, 1802 paper, 496.
63. Herschel, 1802 paper, 497.
64. Herschel, 1811 paper and 1814 paper.
65. Herschel, 1811 paper, 271.
66. Herschel, 1811 paper, 331.
67. Herschel, 1814 paper, 248.
68. Herschel, 1814 paper, 253. *Cf.* p. 259, where he writes: "We can only hint, that every nebulosity which is carried into the region of a small patch of stars will probably be gradually arrested and absorbed by them, and that thus the *growth* of stars may be continued."
69. Herschel, 1814 paper, 280.
70. Herschel, 1814 paper, 278.
71. Herschel, 1814 paper, 248.
72. Herschel, 1811 paper, 272–3.
73. Herschel, 1802 paper, section IX.
74. Herschel, 1811 paper, 306.
75. Herschel, 1811 paper, 277.
76. Herschel, 1811 paper, 280.

77. Herschel, 1811 paper, 291–2.
78. Herschel, 1814 paper, 267.
79. Herschel, 1811 paper, 312.
80. Herschel, 1811 paper, 319.
81. RAS W.7/15, 1798 tour.
82. Herschel, 1802 paper, 498–9. In September 1813 Herschel met the poet Thomas Campbell and told him the same. Campbell wrote to a friend, "I really and unfeignedly felt at the moment as if I had been conversing with a supernatural intelligence" (Constance A. Lubbock, *The Herschel chronicle* (Cambridge, 1933), 336, citing *Life and letters of Th. Campbell*, ed. by William Beattie (London, 1849)).
83. Herschel, 1811 paper, 302.
84. Herschel, 1811 paper, 287.
85. Herschel, 1814 paper, 283.
86. Herschel, 1814 paper, 283–4.
87. "Address ...", *Memoirs of the Astronomical Society of London*, i (1822–25), 4.