PART I

HISTORY OF GALACTIC RESEARCH

Tuesday 31 May, 2045 - 2215

Public lecture by M.A. Hoskin
Chairman: H. van Woerden

Monday 30 May, 1450 - 1545

Lecture by E.R. Paul
Chairman: M.A. Hoskin

Thursday 2 June, 1130 - 1220

Lecture by R.W. Smith
Chairman: M.A. Hoskin

Tuesday 31 May, 1430 - 1505

Lecture by O. Gingerich
Chairman: B.E. Westerlund

At the exhibition about Kapteyn and Van Rhijn, in front of Kapteyn's portrait (page 1): Kapteyn's grandson, with A. Blaauw (left) and Dr. W.H. Koops, Director of University Museum. Blaauw was Professor of Astronomy at Groningen in 1957-1970.

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THE MILKY WAY FROM ANTIQUITY TO MODERN TIMES

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ABSTRACT: The paper outlines the history of attempts to explain the Milky Way, from Antiquity to the early-twentieth century, with special reference to the eighteenth and nineteenth centuries. Also discussed is the relationship of the Galaxy to other star systems, and particularly the question of whether there are other galaxies in the visible universe.

1. INTRODUCTION

The other historical papers in this volume discuss the late-nineteenth-century and early-twentieth-century background to contemporary scientific debates concerning the Galaxy. In this paper our task is to outline the broader historical context. We shall concentrate on the eighteenth and nineteenth centuries, because whereas earlier attempts to make sense of the motions of the planets led to the creation of Newtonian dynamics, early discussions of the Milky Way proved largely sterile and are of concern to the historian rather than to the practising astronomer interested in the genesis of his science.

The late medieval picture of the world was dominated by the teaching of Aristotle, according to whom the spherical Earth is at the centre of a spherical heavens. On and near the Earth is constant change and decay, coming-to-be and passing-away. By contrast, the heavens are changeless except for the eternal cycling of the stars and planets. Comets, since they change, belong to the terrestrial world, and are discussed by Aristotle under 'meteorology' rather than 'astronomy': they are exhalations from the Earth that ascend to the sphere of fire. The Milky Way, partly because of the similarity of its appearance to an extended comet, is also part of meteorology rather than astronomy.

Aristotle's was by no means the only theory of the Milky Way proposed in Antiquity. Among the others was that of Democritus, preserved for us most completely in the words of Macrobius: "Democritus's explanation was that countless stars, all of them small, had been compressed into a mass by their narrow confines, so that the scanty spaces lying between them

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were concealed; being thus close-set, they scattered light in all directions and consequently gave the appearance of a continuous beam of light." By the sixteenth century there was considerable support for this view that the Milky Way was celestial rather than terrestrial, so much so that when Galileo published in 1610 an account of his first discoveries with the newly-invented telescope, his resolution of the Milky Way into "nothing but a congeries of innumerable stars grouped together in clusters" aroused little interest: the Milky Way was accepted as the optical effect of great numbers of small stars.

This being so, one might have supposed that in the century of Descartes and Newton, the century when the stars were recognised as distant suns and the Sun as merely our local star, and when the closed cosmos of Aristotle was replaced by the infinite space of the geometers, there would be attempts to discover the three-dimensional distribution of stars that would bring about the optical effect we see as the Milky Way. But this would be to underestimate the legacy of the many centuries in which the 'fixed' stars had been nothing more than a backcloth, a reference frame, for the challenging motions of the planets. Until towards the end of Newton's life, no single star had been known to alter its position in the sky relative to the other stars since records began in Antiquity, and the stars -- including those of the Milky Way -- continued to be of minimal interest. Newton's Principia almost totally ignores the stars, and he addressed himself to the question of whether the stars are finite or infinite in number only when challenged on the matter by a theologian. At no time did Newton give more than passing consideration to the Milky Way.

2. WRIGHT, KANT AND LAMBERT

In the middle decades of the eighteenth century, three speculative thinkers who lay outside the mainstream of astronomy turned their minds to the phenomenon of the Milky Way. The oldest of these, and the first to go into print on the subject, was Thomas Wright (1711-86) of Durham in the north of England. Wright came from a modest home and was largely self-taught. He earned a living giving popular lectures on science, and assisting aristocratic families with the care of their estates and the construction of new buildings. His interest in the Milky Way stemmed from his life-long desire to produce a unified cosmology, a vision of the universe that began close at home with the astronomer's account of the visible universe, and then extended this limited picture by the use of symmetry and of the principles of Wright's theology. A manuscript from 1734, apparently for a public lecture with elaborate illustration, describes a universe in which, at the centre, is heaven, the abode of God and of the blessed. Far away, in all directions, is the outer darkness, "the shades of Darkness & Dispare supposed to be The Desolate Regions of ye Damnd". In between these is "the Gulfe of Time or Region of Mortality", a spherical shell of space within which all the stars (including the Sun) move in orbit in different directions, each circling around heaven, which is at the centre of the spherical shell (see Figure 1). This led Wright

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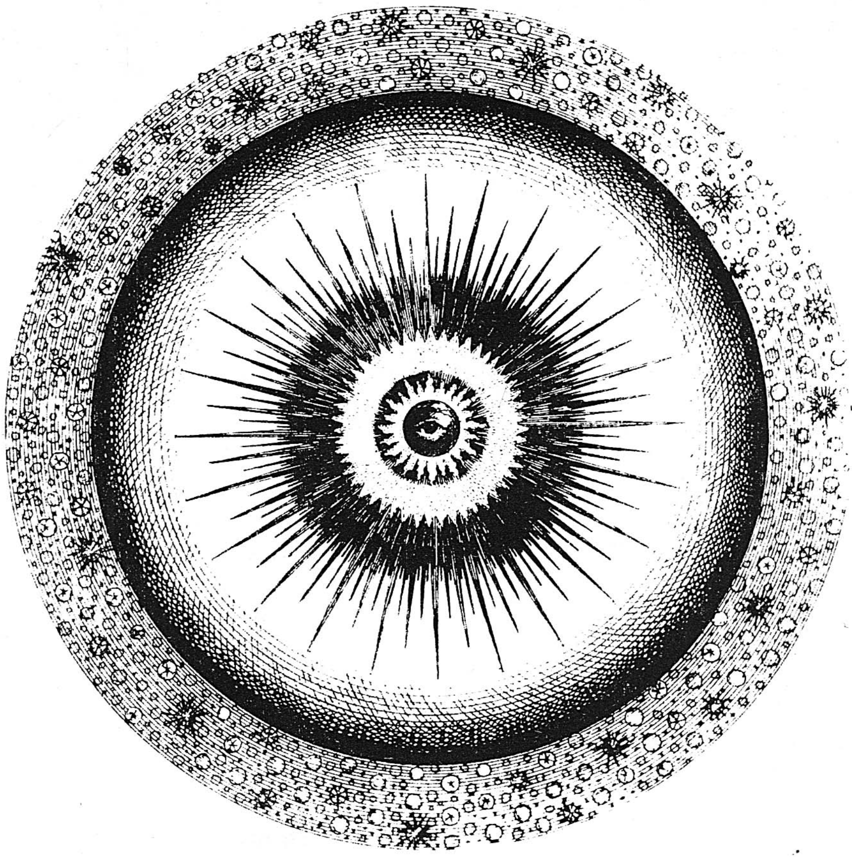

Fig. 1. Thomas Wright's basic conception of the universe. At the centre is heaven, denoted by the Eye of Providence. All the stars, including the Sun, occupy a shell of space surrounding heaven (and here represented in cross-section), and they orbit within this shell. (Plate XXV of An Original Theory.)

to postulate the motion of the Sun and of every star, and he was later gratified to discover in Philosophical Transactions for 1718 the paper by Halley giving news of the discovery of the first proper motions.

In order to bring home to his audience their personal involvement in Wright's cosmos, he allowed himself artistic license when picturing our immediate corner of the universe. The immense drawing he displayed to his audience showed a cross-section of the universe, in which the sphere of the stars was of course represented by a ring of stars surrounding heaven. But in portraying the Sun and the planets, he drew them as they are seen by us, rather than as seen by a distant observer. He took the same license in drawing the visible stars, first the nearest

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and brightest, then the fainter, until "at a certain distance from ye Sun equal to a vissual ray of ye smallest visible star is a faint circle of light terminating the utmost extent of ye visible creation, in a finite view from ye Earth...".

Wright believed that in this way he had succeeded in explaining the Milky Way, the "faint circle of light"; though in fact his drawing showed an arbitrary cross-section of the creation, whereas the plane of the Milky Way is unique. Sometime in the 1740s he realised this, and considered what modifications of his world-picture were required. His conclusions form the centre-piece of his handsome quarto volume, An Original Theory or New Hypothesis of the Universe (London, 1750), on which his fame chiefly rests. Although the explanation of the Milky Way is a source of great pride to Wright, the book is in fact a stage in Wright's life-long attempt to reconcile his theological world-picture with the observations of astronomers. Specifically, our Sun and the other stars of our system -- now one among many -- are in orbit around our (local) Divine Centre. These stars of our system may, as before, move within a spherical shell of space, but if so -- and this is the difference from 1734 -- the shell is very thin. When we look inwards or outwards, we quickly see past the individual stars that are our neighbours, and then we look into empty space; but when we look tangentially to the spherical shell, which has a radius so large that it curves almost imperceptibly, then we see so many distant stars that together they have a milky appearance. The plane of the Milky Way, in other words, is the tangent plane to the spherical shell occupied by the Sun and the other stars of our system, at the point occupied by the observer.

As an experienced teacher, Wright introduces his readers gently to this concept of a spherical shell of space with radius so great that the curvature is almost imperceptible to astronomical observers. He does so by discussing first the (hypothetical) situation where the radius of curvature is infinite -- where, that is, the stars would be located within two parallel planes. The inclusion of the related illustration in An Original Theory (see Figure 2) has misled many subsequent writers into believing that this was Wright's picture of the actual universe, and he has been credited with being the first to teach that the Galaxy has a disk-like structure. As we have seen, Wright's fundamental belief that the stars of our system orbit a Divine Centre made a disk-like Galaxy entirely in the natural order unthinkable for him.

Wright offered an alternative picture of the Galaxy that was to be misunderstood -- creatively -- by the philosopher Immanuel Kant (1724-1804). In this alternative picture, the space occupied by the Sun and the other stars of our system was not spherical but planar and shaped like a hollow disk. The stars would orbit about the Divine Centre within the plane of the disk, and the star-system would therefore look rather like the rings of Saturn, with Saturn itself replaced by the Divine Centre. (Indeed Wright speculated that Saturn's rings were "no other than an infinite Number of lesser Planets".) The visible stars would then occupy a (continuous) disk of space which was a small fragment to one side of the complete and hollow disk.

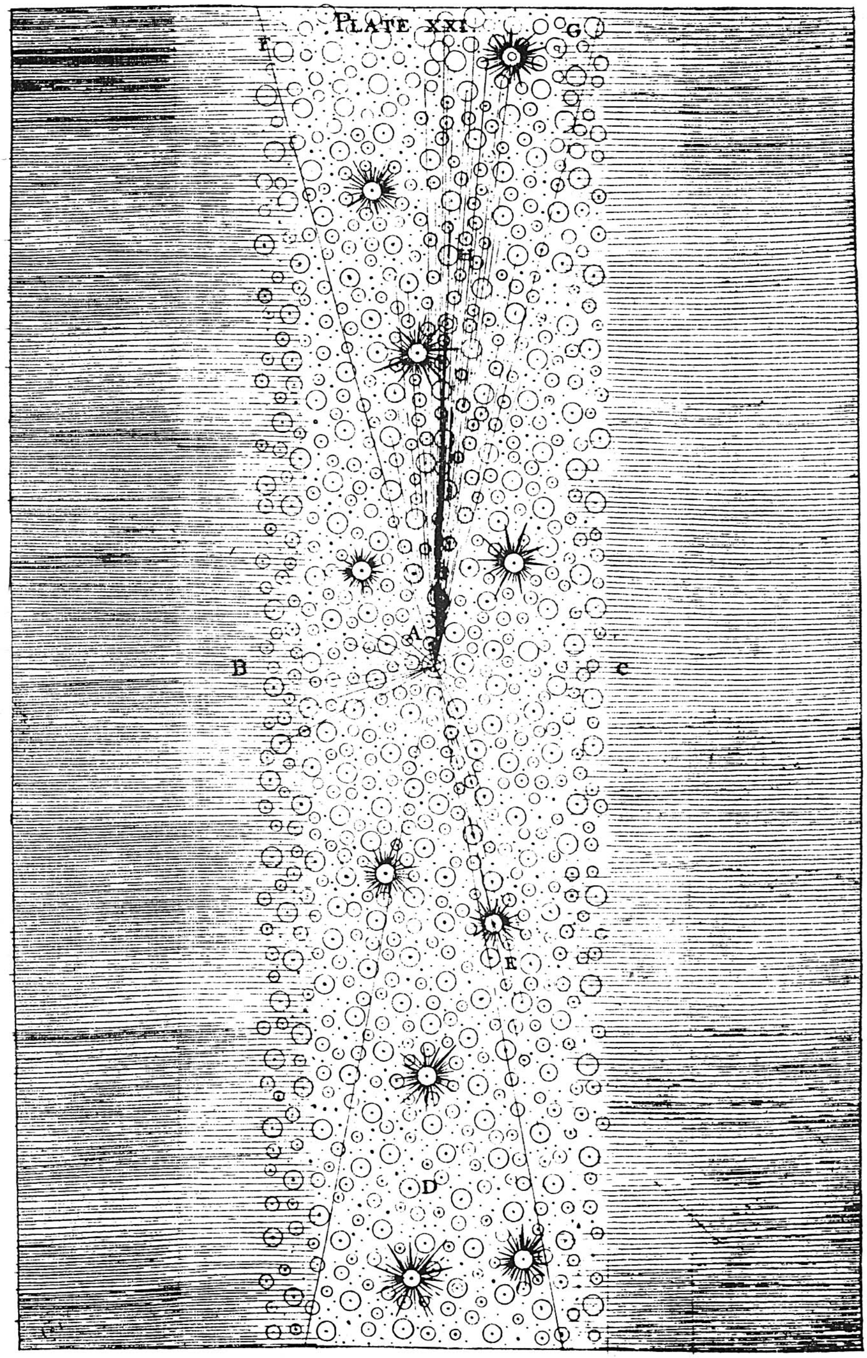

Fig. 2. Plate XXIII (misnumbered XXI) of Wright's An Original Theory, explaining the appearance of the sky as seen by an observer within a (hypothetical) star system bounded by parallel planes.

We can be sure that this second alternative picture was not that preferred by Wright, since the spherical symmetry is lost. But when a summary of Wright's book appeared (without illustrations) in a Hamburg periodical in 1751 and came to the eyes of Kant, it was not clear to Kant that every single star system was arranged about its own Divine Centre. He therefore saw no reason why, in the 'Saturn's rings' alternative, the stars should not extend from the outer edge on one side of the disk right across, without interruption, to the other. Such a system, viewed from a distance, would appear either circular or elliptical in outline; Wright's spherical shells, however, would always appear circular. As Kant believed that Maupertuis had observed nebulae that were elliptical in outline, and as Kant thought these nebulae were analogous star systems, he rejected Wright's spherical shells but gladly accepted a disk-model of the Galaxy (but without the hollow centre and therefore entirely in the natural order). This, the first genuine disk-model of the Galaxy, in which the Milky Way is seen as the 'ecliptic' plane of the stars, was included by Kant in his Allgemeine Naturgeschichte und Theorie des Himmels (Königsberg, 1755). Kant envisaged -- as had Wright -- moons, planets, stars, star systems as forming steps in an hierarchy. But for Wright the hierarchy ended there, as it moved from the natural to the supernatural. Kant, being free of such limitations, allowed the hierarchy to extend upwards infinitely, so that just as the Milky Way is the visible appearance of the disk-shaped Galaxy or star system to which the Sun belongs, so the Galaxy is but one component of a larger system, and so on.

Simultaneously, but independently, the Alsatian physicist Johann Heinrich Lambert (1728-77) was also reflecting on the phenomenon of the Milky Way. In 1749, as he later told Kant, "I went into my room after the evening meal, and looked through the window at the stellar sky, and especially at the Milky Way. The insight, which I had then, to see it as an ecliptic of the fixed stars, I wrote down on a quarto page". Lambert was so struck by this analogy that he became convinced that the stars of our system, just like the planets, lie close to a given plane and are all in orbit about the centre of the system. He outlined his conception in his Photometria (Augsburg, 1760), and elaborated it the following year in his Cosmologische Briefe (Augsburg, 1761). Greatly influenced by Leibniz and therefore committed to a universe with all the stability and permanence of the Sun and the solar system, he too believed in a hierarchy of systems, but a hierarchy of finite extent. The Sun and the other stars that we see as remote from the plane of the Milky Way, together with the brighter (and nearer) stars in the plane of the Milky Way, form one of several clusters that together make up the Galaxy and orbit about its centre. Whereas Kant believed that at each stage of his hierarchy a luminous body lay at the centre of the system (Sirius being perhaps the body at the centre of the Galaxy), Lambert thought that the stars gave all the light necessary and the central bodies in the higher orders might well be dark: the variable light seen in Orion (actually the Orion Nebula) might be the central body of our cluster, variably illuminated by nearby stars as they orbited around it. From the details of the appearance of the

Milky Way he infers that our cluster lies "not only somewhat outside the plane of the Milky Way but also closer to its periphery than to its centre". Only when the Briefe were drafted did Lambert learn that some stars were known to have proper motions; until then he relied solely on his theory for proof that the stars are in orbit, reasoning (as Newton had failed to do) that it was because the stars are very distant that their proper motions had not yet been detected.

3. WILLIAM HERSCHEL

Wright, Kant and Lambert had been led to theorise about the Milky Way because of their unorthodox interests in astronomy, and it was partly for this very reason that their speculations had little impact. William Herschel (1738-1822), who was to make cosmology part of the science of astronomy, owned a copy of An Original Theory but probably obtained it late in his career. Kant's work he seems not to have known -- not surprisingly, as its publication was blighted by the bankruptcy of the publisher. Lambert's Briefe he encountered for the first time only in 1799, when he was asked for an opinion concerning a proposed English translation. Therefore, while we cannot exclude the possibility that some hint deriving from one or other of these works (and especially that of Wright, who was living near Durham when Herschel was an organist in the north of England) reached him and later resurfaced in his mind, it is likely that Herschel owed nothing to his speculative predecessors. Herschel himself saw no harm in speculation -- indeed he gave public notice of his own intention to speculate too much rather than too little -- but his speculations were based on heroic campaigns of observational astronomy, using monster telescopes that he had designed and built with his own hands and which were unavailable to any other astronomer. In his unorthodox commitment to discovering "the construction of the heavens" Herschel distanced himself from the professional astronomers of his day, as he did by embarking on a natural history of the heavens, collecting huge numbers of specimens of nebulae, double stars and so forth; and because he alone had access to the evidence, other astronomers did not see how to confirm or refute his novel theories. But whatever the ambiguities surrounding his impact on his contemporaries, he was given most generous use of the pages of Philosophical Transactions for the publication of his observations and theories, and this ensured that his work was available world-wide, both then and in the future. Herschel's attack on the problem of the Milky Way was therefore decisive in making the question a regular part of the science of astronomy.

The attack came in two major papers on the construction of the heavens, published in Philosophical Transactions in 1784 and 1785. In 1781, in the course of a systematic examination of all the brighter stars, Herschel had come across an object that he had recognised at once as an unknown member of the solar system. It proved to be a major planet, now known as Uranus, and the fame of the discovery enabled his allies in the English court to lobby successfully on his behalf for financial support. By 1782 the refugee musician from Hanover with an amateur enthusiasm for

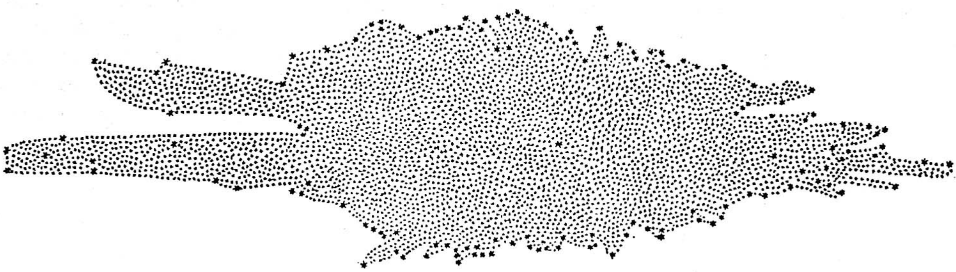

Fig. 3. William Herschel's cross-section of the Galaxy (from Phil. Trans. for 1785).

astronomy found himself installed near Windsor Castle, a professional astronomer whose duties were confined to showing the heavens on occasion to the royal family. The following year he completed his most successful reflector, with mirrors of 18 inches diameter and of 20ft focal length and -- most importantly -- with a stable and convenient mounting. His 1784 and 1785 papers presented the first major results from this instrument with its unrivalled capacity to reach distant and faint objects. Herschel almost takes it for granted that the Milky Way is the optical effect of our immersion in a layer of stars -- indeed, this virtually follows from his working principle that the apparent brightness of a star is an excellent index of its distance. By no means content with a merely qualitative result, however, Herschel asks himself how he can actually map the outline of the Galaxy. He concludes that this can be done with the help of two assumptions. First, that his telescope can indeed penetrate to the borders of the Galaxy in all directions -- for otherwise the task is hopeless. Second, that within the borders of the Galaxy the space is uniformly stocked with stars -- in other words, that the number of stars visible in his telescope at any one time is a reliable guide to the length of the axis of the cone whose vertex is the eye of the observer and whose base is the border of the Galaxy within the observer's field of view.

In what was the first major exercise in stellar statistics -- a technique which he virtually created for the purpose -- Herschel began to count stars. Time would not permit him to examine the whole of the sky that was accessible to him, so he chose a great circle on which to concentrate his efforts. In most directions he counted the stars in ten neighbouring fields of view and took the average. The resulting map of this cross-section of the Galaxy (see Figure 3) confirmed his visual impression that in the directions of the Milky Way there are indeed more stars than usual, and it incorporated quantitative evidence that our system extends further in the galactic plane.

Meanwhile Herschel was devoting his major effort to a systematic search for nebulae. To 'sweep' the whole of the sky visible from Windsor would take him years, and as he collected hundreds of specimens of nebulae so the problems of their classification, and of their physical nature, grew more acute. In his first modest exercises as an observer in the late 1770's, Herschel had become convinced that he had observed changes in the Orion Nebula and that this therefore could not be a distant star system. Some nebulae were therefore truly nebulous and not formed of the familiar stars, but others were undoubtedly star systems in disguise, appearing nebulous only because the telescope used to examine them was insufficiently powerful to 'resolve' them into stars. In his 1784 paper he took the view that 'true' nebulosity presented a smooth, milky appearance to the observer, whereas the 'resolvable' nebulosity of distant star systems appeared uneven and mottled. Soon after the paper had been sent for publication, he came across two nebulae in which both kinds of nebulosity were present, the one merging into the other. This convinced him that he had been on the wrong track. Ignoring the 'changes' he had himself observed in the Orion Nebula, he now took the view that the difference between 'milky' and 'resolvable' nebulosity was simply one of distance; both were star systems, and a star system that appeared 'resolvable' would appear 'milky' if removed to a greater distance. This being so, the Orion Nebula and other nebulae that appeared 'milky' must be very distant star systems; and if they nevertheless appeared extended across a wide area of sky, they must be of enormous extent and may well "outvie our Milky Way in grandeur" -- in other words, be galaxies larger than our own Galaxy.

In 1790 Herschel came across a 'nebulous star' (actually the planetary nebula NGC 1514, which has a prominent central star), and he was forced to admit that the star appeared to be condensing out of the surrounding nebula (by gravitational accretion). This implied that 'true' nebulosity existed after all. The Orion Nebula was now demoted to being a nearby (and changeable) cloud of nebulosity, and Herschel could no longer point to any nebula and declare it to be a galaxy to rank with our own -- for any such galaxy would be indistinguishable from a cloud of nebulosity. Worse still, his continued searches for nebulae had introduced him to many star clusters which were evidence of how non-uniform is the distribution of stars within our Galaxy. This undermined one of the two assumptions on which his map of the Galaxy was based, and he now accepted that a high star-count was a sign of clustering rather than of greater distance to the border of the Galaxy. His other assumption had been put into question by the recent completion of his monster reflector of 40ft focal length, which had brought into view many stars invisible in the 20ft. He had therefore been mistaken in assuming that the 20ft could reach the borders of the Galaxy in all directions, and there were no grounds for arguing that the 40ft could do so either.

The upshot of all this was that Herschel had to withdraw his map of a cross-section of the Galaxy (though this did not prevent it from being reproduced in textbooks long after his death), and he could not with confidence point to any nebula and declare it to be a galaxy independent of and comparable to our own vast system with its unknown extent. He might consider it unreasonable for anyone to argue that our Galaxy is unique in an infinite universe; but the confident theorizing of the late 1780s,

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with our Galaxy mapped in outline and compared to other galaxies, had had to be abandoned.

4. THE NINETEENTH CENTURY

The boldness of William Herschel's theorizing, and the sudden reversals of opinion that were forced upon him by new evidence, produced an inevitable reaction. The next generation of astronomers, his son John (1782-1871) among them, were much more cautious, and indeed the infant (Royal) Astronomical Society of London, of which William was nominally the first president in his extreme old age, was careful to distance itself from the recent spate of speculations. Part of the problem lay in the growing evidence that the stars differ greatly from one another in their physical characteristics. William had adopted as a working hypothesis the assumption that the stars are highly uniform, so that apparent brightness is a reliable guide to distance: since faint stars were more distant than bright ones, the very faint stars in the Milky Way were proof that the Galaxy extends very far in those directions. But now it appeared that some stars were intrinsically small and faint in comparison with others; and if so, then the Milky Way might be a true ring of small stars surrounding a central cluster containing the Sun and other large stars. Between 1834 and 1838 John Herschel took his father's refurbished 20ft reflector to the Cape of Good Hope, to extend his father's surveys to the southern skies that William had never seen. This gave John the opportunity for a leisurely examination of the Milky Way. He noted dark regions devoid of stars, and it seemed to him more reasonable to assume that these were gaps in a ring or other structure of limited extent, than that they were extended cylinders of empty space whose axes changed to be pointed directly towards the observer. He found many places where the stars were projected against a perfectly black background, which indicated that the system was of finite extent in those directions; and other places where bright stars were projected against a background of small ones. All this resulted in a view of the structure of the Galaxy that was more firmly grounded in dispassionate observation than the theories of William, but it was necessarily vague: "...our situation as spectators is separated on all sides by a considerable interval from the dense body of stars composing the Galaxy, which in this view of the subject would come to be considered as a flat ring of immense and irregular breadth and thickness, within which we are excentrically situated, nearer to the southern than to the northern part of its circuit" (Outlines of Astronomy (London, 1849), art. 788).

In 1845 the third Earl of Rosse (1800-67) at Birr Castle in Ireland completed a monster reflector with mirrors 6ft in diameter. Within a month the new telescope had made what was to be its most significant discovery, that of the spiral structure of the nebula M51. In the years to come observers at Birr found spiral structure in several more nebulae (and claimed to find it in still more); and at the very end of the century, at Lick Observatory in California, long-exposure photographs showed that spiral nebulae exist in enormous numbers. Some astronomers suggested that our Galaxy has a spiral structure, and they had little difficulty in devising suitable spiral arms to reproduce the observed meanderings of the Milky Way. Especially influential were the drawings published by the Dutch astronomer Cornelis Easton (1864-1929) around the turn of the century.

Whether the spiral nebulae were galaxies was a matter of much controversy. Lord Rosse and his colleagues were convinced they had 'resolved' into stars the brighter nebulae they had examined, and some astronomers saw this as grounds for rejecting the existence of 'true' nebulosity in any form. But in 1864 William Huggins (1824-1910) used the infant science of spectroscopy to prove that some nebulae are indeed gaseous.

In the long debate over the status of the nebulae, two observational tests had been of central importance. The first was, whether nebulae had altered shape over the years, for rapid changes of shape would not be possible in galaxies of enormous extent. William Herschel, as we have seen, believed he had seen changes in the Orion Nebula; but later observers, notably his son John, were more sensitive to the danger of spurious changes ascribed to nebulae but in fact occasioned by changes in seeing conditions, in the power of the telescopes, in the skills of the artists in sketching the nebulae, and so on. The second was, whether particular nebulae had been 'resolved' into stars -- and here a danger not fully appreciated at the time was that condensations of light that were of star-like appearance might be taken for stars. One of the few to recognise this danger was Otto Struve (1819-1905), who with his colleagues at Pulkova in Russia believed (erroneously) that changes had been observed in the Orion Nebula that prevented it from being a huge star system. Writing in 1869 to Birr, where the nebula had supposedly been resolved into stars, he urged them to be more cautious and to say "there is a tendency of the nebulous matter to form itself in separate knots sometimes in this, sometimes in an other direction".

In addition to these ongoing observational questions, in the late nineteenth century two new observational facts encouraged the belief that our Galaxy is unique in the observable universe. The first was the clear recognition that those nebulae that were candidates for the status of galaxies (or "island universes") were mostly found well away from the Milky Way, which became known as the "zone of avoidance". Why, it was asked, should independent island universes arrange themselves in space so as to avoid the plane of the Galaxy? The second was the new star that flared up in the Andromeda Nebula in 1885 (S Andromedae). It was estimated that this one star had rapidly increased to become equal in brightness to one-tenth of the entire nebula -- easily explained if the nebula was a cloud that had encountered the star, but physically incomprehensible if the nebula was a vast galaxy of millions of stars.

5. THE EARLY TWENTIETH CENTURY

As our story reaches the twentieth century, we begin to trespass on the subject matter of the other historical papers in this volume. Nevertheless, an outline of the events leading to the final recognition of our Galaxy as one vast system among many may be of help.

The force of the arguments based on the zone of avoidance and the 1885 nova in the Andromeda Nebula was greatly weakened in the 1910s, when Heber D. Curtis (1872-1942) resumed the programme of nebular photography at Lick Observatory that had been cut short in 1900 by the untimely death of the then-director. Curtis found many examples of edge-on nebulae with dark bands of obscuring matter in their central planes, and he realised that similar obscuring matter in our own galactic plane would account for the zone of avoidance: spiral nebulae (in particular) are not seen near the galactic plane simply because they are hidden from us. Further, in 1917 Curtis found in past photographs of spiral nebulae additional examples of new stars, though his investigations were somewhat overtaken by events when G.W. Ritchey (1864-1945) of Mount Wilson announced that a nova was currently visible in the nebula NGC 6946. These novae were all much fainter than the 1885 star, which began to be recognised as wholly exceptional, and therefore an unsafe basis for theorising on the nature of nebulae.

Meanwhile, dramatic developments were taking place in the theory of the Galaxy. As related in the paper by R.W. Smith, Harlow Shapley (1885-1972) at Mount Wilson was using the powerful new technique of Cepheid variable stars to measure great distances, in particular the distances to the globular clusters, of which he was making a detailed study. These clusters, which other astronomers had already noted were concentrated to one half of the sky, he took to be grouped around the true centre of the Galaxy, whose position and distance he could now establish. On this dramatic new theory, the Galaxy was many times bigger than previously thought, and the Sun was far from the centre: earlier investigations, supposedly of the Galaxy, had in fact been studies of the stars in our immediate neighbourhood. Furthermore, on Shapley's view, since our Galaxy was so enormous, it was all the more unlikely that the spiral nebulae were independent island universes.

By no means all astronomers were convinced by Shapley's arguments, especially because earlier sizes for the Galaxy seemed perfectly satisfactory. Furthermore, believers in the island-universe theory of spiral nebulae (such as Curtis) had recently been much encouraged by the careful studies of radial velocities of spirals carried out at Lowell Observatory by V.M. Slipher (1875-1969), which had revealed speeds much larger than that of any known star. These studies, like the discovery of novae in spirals and the evidence in favour of obscuration in the galactic plane, fitted well with the theory that the spirals are independent star systems.

But unexpected opposing evidence now appeared. We have seen that in the debate over the status of the nebulae, the question of whether nebulae have changed shape was long recognised as fundamental, but that prudent observers had accepted that pencil sketches were not to be relied upon. However, this criticism did not apply to photographs of nebulae. It chanced that at Mount Wilson one of Shapley's friends was the Dutch astronomer Adriaan van Maanen (1884-1946), who was noted for his meticulous measurement of photographic plates. In 1916 van Maanen used a stereocomparator to (in effect) superimpose two plates of the spiral M101, and he concluded that the spiral had changed (by rotation) in the interval between the two photographs. Early in the 1920s van Maanen came to similar conclusions about several more spirals. It was common ground among astronomers that if van Maanen's results were reliable, then the spirals could not be island universes, for that would require their outlying parts to move with more than the speed of light; and it is hard to imagine an investigation that could stay closer to the basic evidence than these stereocomparator measurements. Shapley believed his friend; Curtis did not. The two men met in a famous encounter in Washington in April 1920, and agreed to differ.

In 1923, Edwin P. Hubble (1889-1953) began a photographic study of the Andromeda Nebula with the 100-inch telescope at Mount Wilson. He quickly found what at first he took to be a nova, but which proved to be a variable star. Plotting its light curve by examining plates going back to 1909, he found it was a Cepheid variable star. This proved that it was a true star, and not a star-like condensation. And because it was one of the stars that Shapley and others were using for measurement of great distances, Hubble could use Shapley's own theory to derive a distance for the nebula of around one million light years -- far outside our Galaxy even on Shapley's reckoning. Hubble waited until in February 1924 he had photographed the nebula on successive nights and confirmed that his plates showed the characteristic upward leap of the light of a Cepheid variable, and then he began to share his discovery with other astronomers with whom he was in correspondence. But he hesitated to publish his result in print because it implied that the Andromeda Nebula, and presumably other spirals, were independent island universes, in contradiction to the measurements of his colleague (but no friend!) van Maanen.

At the end of 1924 Hubble was persuaded to break silence, and as a result the existence of island universes (whether or not comparable with our Galaxy) was accepted by almost all astronomers. There remained however the problem of van Maanen's measures. At last, around 1930, Hubble determined to remove the anomaly once and for all. With the aid of colleagues he remeasured some of van Maanen's plates, and more besides, and he and his allies could find none of van Maanen's changes. This meant that either van Maanen was in error, or that Hubble was in error and in every case by exactly the amount needed to get a null result. Obviously the fault must lie with van Maanen, and Hubble prepared for publication long papers making this abundantly clear. His director, however, would not tolerate a public squabble between members of his staff, and imposed a compromise. Each man wrote a mild and brief paper for the 1935 volume of Astrophysical Journal, but it was clear that the last obstacle to the acceptance of island universes -- galaxies -- had been removed.

FURTHER READING

As this is a survey article, I have not given the references appropriate to a research paper, but the reader who wishes to pursue the subject further will find detailed discussion in my "Stellar Astronomy: Historical Studies" (Science History Publications, Halfpenny Furze, Mill Lane, Chalfont St Giles, Bucks, U.K., 1982). The most complete study of the history of theories of the Milky Way is Jaki, S.L., "The Milky Way: An Elusive Road for Science" (Neale Watson Academic Publications, New York, 1972), of which the earlier chapters are conveniently summarised by Jaki in J. Hist. Astron. (1971, 2, 161-7, and 1972, 3, 199-204). The best available account of the modern period is in Smith, Robert W., "The Expanding Universe: Astronomy's 'Great Debate' 1900-1931" (Cambridge University Press, 1982).

EDITOR'S NOTE

The extensive discussion following this Public Lecture was not recorded.

Michael Hoskin telling tales to Ria van Woerden at conference dinner. Further around table: Hugo van Woerden, Victor Clube, Gerry Gilmore; at right: Bernard Burke LZ

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