The Harmony of the Sphere

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Edited by

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To the memory of Gary Banham
(1965-2013)

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Silvia De Bianchi

Abbreviations

All references to Kant's works are in accordance with the *Akademie-Edition* Vol. 1-29 of *Kant's Gesammelte Schriften*, Berlin/Leipzig, 1902-. References to the *Critique of Pure Reason* follow the customary pagination of the first (A) and second (B) edition. Unless otherwise indicated, the English translations are from the *Cambridge Edition of the Works of Immanuel Kant* (New York: Cambridge University Press, 1992-). The following abbreviations are used throughout the book:

Ak	*Immanuel Kants Schriften*. Ausgabe der Königlich Preussischen (Deutschen) Akademie der Wissenschaften (Berlin: W. De Gruyter, 1902–)
Br	*Briefwechsel*, Ak 10, 11, 12 *Correspondence*
DS	*Von dem ersten Grunde des Unterschiedes der Gegenden im Raume* (1768), Ak 2 *Concerning the Ultimate Ground of the Differentiation of Directions in Space*
ID	*De mundi sensibilis atque intelligibilis forma et principiis* (1770), Ak 2 *On the Form and Principles of the Sensible and the Intelligible World*
KrV	*Kritik der reinen Vernunft* (1781, 1787). Cited by A/B pagination. *Critique of Pure Reason*
KpV	*Kritik der praktischen Vernunft* (1788), Ak 5. *Critique of Practical Reason*
KU	*Kritik der Urteilskraft* (1790), Ak 5. *Critique of the Power of Judgment*
LF	*Gedanken von der wahren Schätzung der lebendigen Kräfte und Beurtheilung der Beweise, deren sich Herr von Leibniz und andere Mechaniker in dieser Streitsache bedient haben, nebst einigen vorhergehenden Betrachtungen, welche die Kraft der Körper überhaupt betreffen* (1747), Ak 1. *Thoughts on the True Estimation of Living Forces*
MAN	*Metaphysische Anfangsgründe der Naturwissenschaft* (1786), Ak 4. *Metaphysical Foundations of Natural Science*
ND	*Principiorum primorum cognitionis metaphysicae nova dilucidatio* (1755), Ak 1. *A New Elucidation of the First Principles of Metaphysical Cognition*

P *Prolegomena zu einer jeden künftigen Metaphysik die als Wissenschaft wird auftreten können* (1783), Ak 4. *Prolegomena to Any Future Metaphysics*

PM *Metaphysicae cum geometria iunctae usus in philosophia naturali, cuius specimen I. continet monadologiam physicam* (1756), Ak 1. *The Employment in Natural Philosophy of Metaphysics Combined with Geometry, of which Sample I Contains the Physical Monadology*

RM *Reflexionen Kants über Metaphysik*, Ak 17. *Kant's Reflections on Metaphysics*

TH *Allgemeine Naturgeschichte und Theorie des Himmels oder Versuch von der Verfassung und dem mechanischen Ursprunge des ganzen Weltgebäudes, nach Newtonischen Grundsätzen abgehandelt* (1755), Ak 1. *Universal Natural History and Theory of the Heavens, or Essay on the Constitution and Mechanical Origin of the Entire Universe, Treated in Accordance with Newtonian Principles*

UD *Untersuchung über die Deutlichkeit der Grundsätze der natürlichen Theologie und der Moral* (1764), Ak 2. *Inquiry concerning the Distinctness of the Principles of Natural Theology and Morality [Prize Essay]*

VL *Logik. Ein Handbuch zu Vorlesungen* (1800), Ak 9. *Lectures on Logic*

OP *Opus postumum* (1796-1801), Ak 21, 22. *Opus postumum*

PART III:

KANT AND HERSCHEL IN CONTEXT

REFLECTIONS ON KANT AND HERSCHEL: THE INTERACTION OF THEORY AND OBSERVATION?

MICHAEL ROWAN-ROBINSON

In the work of Kant and Herschel, these great contemporaries, we see the time-honoured interaction of theory—as embodied by Kant's application of Newton's theory of gravitation to the formation of the Milky Way and the solar system—and observation—consisting in Herschel's pioneering surveys of our own and other galaxies. We shall see that the problems they were interested in were not really solved, nor even realistically addressed, for another two centuries. And the person who really paved the way for these modern developments was another contemporary of theirs, Pierre-Simon de Laplace. I first review Kant's cosmogony and its impact, and then turn to Herschel's observational programme and speculations. I then consider the role of Laplace's *Systeme du Monde* and his relationship with his two contemporaries. Finally, I briefly review modern developments and comment on to what extent they have been influenced by Kant, Herschel, and Laplace.

Immanuel Kant's *Universal Natural History and Theory of the Heavens* (1755) was his sole contribution to astronomy and cosmology, and it was a work of his youth. In this treatise he notes that Thomas Wright (1750) explains the Milky Way as due to a planar distribution of stars confined between two planes. Kant asks why the stars are distributed relative to a fixed plane. He argues that it is the effect of gravitational attraction between the stars, since the force of gravity extends to infinity:

> "[…] thus all the solar systems are in the situation that, by unceasing and unhindered reciprocal approaching, they would sooner or later collapse into one lump were it not that this destruction was prevented, just as the spheres in our planetary system are, by forces fleeing the centre point, because they divert the heavenly bodies from a straight fall and, together with the forces of attraction, create the eternal orbits, as a result of which the edifice of creation is protected from destruction and made appropriate to an unending duration". (TH, Ak 1:250)

Kant suggests, by analogy with the solar system, that the orbits of the stars are confined to a plane. The Milky Way is like a vast solar system, in circular motion:

> "The width of this illuminated zone, which represents a kind of zodiac, will be caused by the different degrees of deviation of the aforementioned planets from their plane of reference and by the inclination of their orbits towards the same surface, and because most of them are close to this plane, their number will appear more dispersed according to the degree of their distance from this plane". (TH, Ak 1:251)

In line with his claim that all the stars are in motion, Kant then estimates what the orbital period of the nearest star about the sun would be. He uses Huygens's (1698) estimate of the distance of Sirius as 21,000 AU, along with Kepler's law, to estimate that it would take 1.5 million years to orbit the sun. So the proper motions of the nearest stars would be small. Kant suggested that observers try to detect these motions. If he had used the correct distance to the nearest star (4.2 ly), he would have estimated the orbital period as 160 million years, close to the actual orbital period of stars near the sun around the galaxy. Kant develops his argument as follows:

> "I now come to that part of the doctrine advanced that makes it most attractive because of the sublime view it presents of the plan of creation". (TH, Ak 1:253)

Kant asks what a system like our Milky Way would look like from a great distance, and concludes that

> "[it] will appear under a small angle as a minute space illuminated by a weak light, the shape of which will be round as a circle when its plane presents itself straight to the eye and elliptical when it is seen from the side. The weakness of the light, the figure and the perceptible magnitude of its diameter will clearly distinguish such a phenomenon, if it is present, from all other stars that can be observed individually". (TH, Ak 1:254)

This phenomenon had indeed been perceived by different astronomers. These are what were referred to as the "nebulous" stars, or rather a species of them, which M. de Maupertuis described in his *Discours sur la Figure des Astres* (1742). Kant refers to this work when claims:

> "That they are small places illuminated a little bit more than the darkness of the empty space of the heavens, which all have in common that they represent more or less open ellipses but whose light is much weaker than any other that we perceive in the heavens". (TH, Ak 1:254)

Kant was not the first to make this observation. Christopher Wren had also speculated that nebulae like that in Andromeda might by distant systems like the Milky Way. In his "Inaugural Address as 9th Professor of Astronomy at Gresham College, London 1657", he stated:

> "[Men should] find the Galaxy to be Myriads of them [stars]; and every nebulous Star appearing as if it were the Firmament of some other World, at an incomprehensible Distance, bury'd in the vast Abyss of intermundious Vacuum".

It is worth noticing that Kant also speculates on how such systems might have formed, and advances the idea that if a region of the universe has a slightly higher density than the average, then nearby matter would tend to fall towards this region. His picture is that the galaxies represent regions where the development of order has proceeded strongly, while outside them the primordial chaos still persists. This represents a very modern picture of how structure forms in the universe. Kant's idea of a rotating Milky Way system was not demonstrated conclusively until radio astronomers mapped the Milky Way in the 1950s and 1960s. The fact, discovered in the 1980s, that the rotation speed falls off with distance more slowly than Kepler's law would predict, demonstrated that there must be a dark matter halo around the Milky Way. Kant's idea of the growth of structure from density perturbations became firmly established through computer simulations, matched to large-scale galaxy surveys, in the 1980s and 1990s. Kant's treatise is thus not just armchair speculation. However, there is no mathematical detail at all, and so Kant's musings are merely a stepping-stone to the work of the great Laplace (1749–1827), "the French Newton", who laid the foundations of gravitational astrophysics. Kant is aware of the observations of his time and speculates about future discoveries. However, when compared with Euler, Lagrange, or Laplace, it seems too much to call him a theoretician. Kant's work does not seem to have been discussed by Herschel or Laplace, and it was not until the 1840s that Arago and von Humboldt drew attention to Kant's astronomical speculations.[1] In Part 2 of the *Universal Natural History and*

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[1] In my view, the only philosopher after Kant to make a significant contribution to astronomy and cosmology was Ernst Mach (1838–1916), who influenced Einstein

Theory of the Heavens, Kant goes on to discuss the origin of the solar system from a diffuse cloud of gas, contracting under the influence of gravity. He proposes that condensation would then occur at the centre, with centrifugal force determining the orbits of material.

> "This body at the centre point of attraction, which according to the above has become the main piece of the planetary structure through the quantity of its collected matter, is the Sun, even though at that time it does not yet have the flaming heat that breaks out upon its surface after its formation is entirely complete". (TH, Ak 1:266)

> "The planets are formed out of particles that have precise motions as circular orbits at the height at which they hover: thus the masses that are constituted by them will continue exactly the same motions in exactly the same degree in exactly the same direction. This is sufficient to have insight into why the motion of the planets is approximately circular in form and their orbits are on one plane". (TH, Ak 1:268)

This picture is known today as the *Kant-Laplace nebular hypothesis*. The picture of a diffuse cloud contracting under gravity and flattening to a disk as angular momentum is conserved remains broadly correct, although the key element in the formation of planets is the growth of planetesimals through aggregation of dust grains.

It is worth considering that the lives of Kant, Herschel, and Laplace overlapped for fifty-five years; yet they did not interact directly. William Herschel's work on cosmogony has been very fully described by Hoskin (1963). Stimulated by Messier's 1783 list of nebulae, Herschel embarked on a series of surveys for nebulae, which became the basis for modern catalogues of bright nebulae such as the New General Catalogue (NGC). In 1785 he discussed the formation of star clusters through the effects of gravity, but there is no mathematical detail, so this does not represent a real advance on the speculations of Kant. One interesting remark which Herschel makes is that the orbits of stars in a forming cluster could become almost radial, and this is likely to be true for a globular cluster. In 1789 he introduced the revolutionary concept of the evolution of nebulae and star clusters, albeit as pure speculation. It took the infrared and submillimetre astronomy of the 1970s and 1980s to make real progress in understanding star formation within the molecular gas clouds.

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and other relativists, although Mach's Principle has probably dropped out of fashion today. Poe's *Eureka* (1848), written in a similar discursive style to Kant's treatise, contains a profound analysis of why the sky is dark at night and has hints of big bang cosmology.

More practically, Herschel also set out to map the structure of the Milky Way using star counts, and his results were published in 1784 and 1785. There were two problems with this work. The first was how to estimate the distances of stars. Even if all stars had the same luminosity, the conversion from stellar magnitude to apparent flux was not known at the time. Herschel tended to assume that stars of magnitude

1 2 3 4 5 6 7 8 9 10

were at relative distance

1 2 3 4 5 6 7 8 9 10

whereas the correct value (for a star of fixed luminosity) is

1 1.6 2.5 4.0 6.3 10 16 25 40 63

That is, his assumption was sufficiently accurate for magnitudes 2 to 5, but did not hold for the fainter stars. The assumptions underlying Herschel's gages ran into contemporary criticism, and he returns to a discussion and justification of these assumptions in his 1817 paper. But his son, John Herschel, was forced to conclude in 1833 that because stars are of very different luminosities, not much could be learnt from star counts. The second problem is that interstellar dust plays a major role in determining the surface density of stars in different directions. Therefore, Herschel could not in fact determine the structure of our galaxy from star counts at that time. However, the problem of distances in the Milky Way was not solved till the 1920s, using Cepheid variable stars. Edwin Hubble's 1929 application of this distance method to other galaxies was off by a factor of eight, however. The problem was resolved by Allan Sandage in 1958, to an accuracy of 20%. An accuracy of 2% in the distance scale of the universe, as measured by the Hubble constant, was reached in 2006 using data from the WMAP satellite. The role of dust in affecting the apparent brightness of stars and so determining the appearance of the Milky Way was not appreciated until Trumpler's work (1936). Star counts have in fact been used to determine the structure of our galaxy in modern times, especially at infrared wavelengths (Bahcall, 1986; Rowan-Robinson and Chester, 1987). The advantage of infrared wavelengths is the greatly reduced effect of interstellar dust. The issue of the wide range of luminosities of stars is dealt with by modelling. In his discussion of nebulae, and of the Milky Way and its structure, Herschel seems to be unaware of Wright and Kant, and certainly makes no reference to them, although he is known to have possessed a copy of Wright's 1750 book. However, to be fair, Laplace also does not refer to Kant in his discussion of the nebular hypothesis for the origin of the solar system (whereas he refers to Herschel at least twice in *Systeme du Monde*). Herschel actually refers very rarely to other scientists in his papers—perhaps a relic of his amateur beginnings.[2]

In the concluding chapter of his classic study, Michael Hoskin sees Herschel as "a somewhat tragic figure" (Hoskin, 1963). Herschel was a driven man, yet "his achievements measured in terms of his contribution to established knowledge of [the construction of the heavens] bore little relation to his Herculean efforts". On the contrary, Pierre-Simon de Laplace was one of the giants of modern mathematical physics. His nebular hypothesis appears as Note VII at the very end of his *Exposition du système du monde* (1796):

> "On a, par le Chapitre précédent, pour remonter à la cause des movements primitifs du système planétaire, les cinq phénomènes suivants: les mouvements des planètes dans le même sens et à peu près dans un même plan; les movements des satellites dans le même sens que ceux des planètes; les mouvements de rotation de ces différents corps et du Soleil, dans le même sens que leurs mouvements de projection et dans des plans peu différents; le peu d'excentricité des orbes des planètes et des satellites; enfin, la grande excentricité des orbes de comètes, quoique leurs inclinaisons aient été abandonnées au hasard".

Laplace refers in this note to Buffon, Mayer, Olbers, Bouvard, Nicollet; but does not mention Kant. Laplace was not always scrupulous in referencing earlier works, especially if they were by his contemporaries, but he does manifest a more professional approach than Kant or Herschel. The loss of the Laplace family papers makes it hard to establish whether he was aware of Kant's work. He certainly knew of Herschel's work, as we have already had cause to note. Laplace's Note VII, however, does not contain any mathematical details, and so it does not represent a huge advance on the speculations of Kant. Credible models of the origin of the solar system and of the Milky Way were not developed until the twentieth century, but the modern work was built on the gravitational physics and equations of Laplace. Laplace's equation for the gravitational field *in vacuo* was modified in 1812 by Poisson (1781–1827), and this modified

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[2] In my opinion, Herschel's most significant discovery was infrared radiation (1800), opening the way to the astronomy of the whole electromagnetic spectrum, but that is another story. See Rowan-Robinson (2013).

equation forms the basis for gravitational astrophysics. Some of Laplace's other achievements include: the Laplace transform, stability of solar system, conservation of eccentricity and inclination, spherical harmonics, potential theory, proof of method of least squares, probability theory, and the speed of sound. In 1802 Herschel travelled to Paris and had several meetings with Laplace. Herschel also had an audience with Napoleon, at which Laplace was present. On that occasion Herschel gave an outline of his findings on the structure of the heavens. Napoleon then invited Laplace to explain how this could have been possible. Laplace attempted to show that all the structure in the universe, including the solar system, could be explained as formed through natural laws. Napoleon is said to have responded: "Who is the author of all this?"

Should we consider this meeting as an interaction between observation and theory? Laplace knew about and was interested in Herschel's observational work, but it is not very clear that Herschel understood or was interested in Laplace's mathematical programme. Nevertheless, Laplace was to mention William Herschel's sister, Caroline, as one of the few women who understood his work, along with Mary Somerville, who in 1831 would translate his *Mechanique Celeste* into English. Ironically, Caroline did not accompany William on his trip to Paris. Presumably Caroline Herschel and Laplace corresponded, and this correspondence might provide an interesting addition to her image as comet-hunter and crucial assistant to William's surveys for nebulae. The survey of nebulae by William, Caroline, and John Herschel (1864, 5,079 objects) was updated by J. L. E. Dreyer in 1880 in the New General Catalogue of Nebulae and Clusters of Stars (7,840 objects). A famous modern version of this galaxy catalogue, with the galactic nebulae and star clusters stripped out, is de Vaucouleurs's 1976 Second Reference Catalogue of Bright Galaxies (4,364 galaxies). De Vaucouleur's catalogue is only slightly deeper than the Herschels'. The deeper IRAS (Infrared Astronomical Satellite) all-sky infrared galaxy survey (Rowan-Robinson et al., 1991, 17,664 galaxies) was used to map the three-dimensional galaxy distribution (using the redshift to get the distance, see Fig. 2), to demonstrate the origin of our galaxy's motion through the cosmic frame (a process analogous to Herschel's 1783 estimate of solar motion), and to estimate of density of the universe in the form of normal and dark matter. Today, much larger surveys are planned from the ground (e.g. LSST) and from space (e.g. EUCLID) in order to study the details of 'dark energy'.

It is beyond the scope of this article to give a review of modern ideas on cosmogony, but I would like to mention some of the milestones in reaching the modern picture of star and galaxy formation:

— Jeans (1902): studied the condition for the collapse of a uniform gas cloud, derived from a Newtonian stability analysis of Laplace's equation (as extended by Poisson). The Jeans criterion was later extended to include the effects of General Relativity and the expanding universe, and is still relevant today.

— Hoyle (1953): on the fragmentation of gas clouds into stars and galaxies. In this paper Hoyle tries to explain why galaxies are found in clusters and why galaxies and stars have their observed mass ranges.

— Lin and Shu (1964): on the spiral structure of disk galaxies, showing that spiral structure is due to an instability, a wave that rotates through the disk of gas causing star formation, triggered by interaction with a companion galaxy.

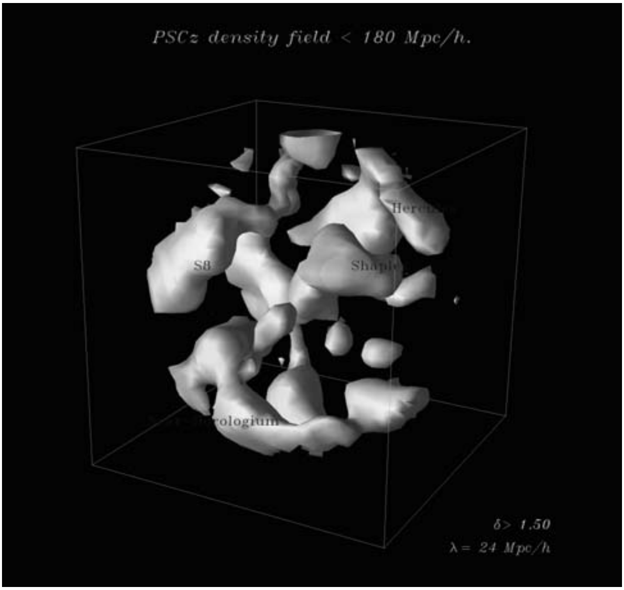
— White and Rees (1978): core condensation in dark matter halos. The idea is that dark matter aggregates into halos, then gas condenses in the gravitational potential well of these halos and forms a disk of stars. This picture was confirmed by computer *n*-body simulations during the 1980s and 1990s, calculated using Laplace's equation (see Davis et al., 1985).

As we read at the very beginning of Jeans (1902):

> "The object of the present paper can be best explained by referring to a sentence which occurs in a paper by Professor G. H. Darwin. This is as follows: 'The principal question involved in the nebular hypothesis seems to be the stability of a rotating mass of gas; but, unfortunately, this has remained up to now an untouched field of mathematical research. We can only judge of probable results from the investigations which have been made concerning the stability of a rotating mass of liquid.'"

We can see that the Kant-Laplace nebular hypothesis was still in the minds of researchers at the end of the nineteenth and the beginning of the twentieth century. However, Jeans's work took ideas of structure formation in a new direction, that of fragmentation and dynamical instability. Therefore it appears that the speculations of Kant and Herschel had little influence on the work on structure formation of the second half of the twentieth century. Astronomy advances through the interaction of theory and observation. This is certainly how scientists proceed today. Does the case of Kant, Herschel, and Laplace reveal this methodological character? Kant's speculations on the origin of cosmic structure were prescient, but they do not seem to have influenced Herschel (or Laplace). Herschel and Laplace met, but was it a meeting of minds? The names of Kant and Laplace are linked in the nebular hypothesis for the formation of the solar system, and this remained an influential idea through the nineteenth century. Herschel's surveys are at the heart of and profoundly influenced modern astronomy. Laplace's equation is the starting point for modern gravitational physics. In a way, the main surprise is that these three great contemporaries, whose lives overlapped by over five decades, interacted so little.

(Fig. 1) William Herschel (1738–1822) with kind permission of John Herschel-Shorland.



(Fig. 2) Three-dimensional map of the galaxy distribution derived from the IRAS survey.