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THE AFTERMATH OF NEWTON

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At the heart of Newton's Principia lies a profound paradox. Gravity is a force, and universal gravity is a universal force; and a universal force is -- or ought to be -- a cause of universal motion. Yet in the Principia the term Newton uses for a star is fixa, for fixa stella, 'fixed star'; and by his time the observations of nearly two thousand years had fully justified this name. Not one star was known to have altered its position in any way: the universe of stars was a motionless universe.

It is remarkable that in the Principia Newton has nothing to say about the paradox whereby a universal cause of motion results in a universe of stars in which there is no motion whatsoever. But then, in the Principia, Newton has almost nothing to say about the stars. His attention was directed to questions of cosmology only in 1692 when Richard Bentley the theologian wrote to him and asked him, in particular, whether the universe of stars was finite or infinite.

Newton and Bentley easily agreed that the universe of stars could not be finite, because the stars were 'fixed', at rest, and a finite system of stars in which the stars were at rest would quickly suffer gravitational collapse: the stars near the outside of the system would be pulled towards the centre of the system and so would immediately begin to move. In time the whole system would be in chaos. But God was the great clockmaker and his universe was clockwork, and therefore the only changes were cyclic motions. Just as in a clock the various parts turn and return to their original positions so that no true changes occur, so in the universe of God the clockmaker there must be stability and this we see in the cyclic movements of the planets and in the motionlessness of the stars. A universe in which there was gravitational collapse would be a universe unworthy of God the clockmaker.

Of course God might have chosen to create a system of stars analogous to the system of the planets: that is, stars finite in number that were in orbit around the centre of the system as are the planets in orbit around the centre of their system. But observations seemed to show that in fact the planets moved but the stars were fixed. Therefore the stars must be infinite in number.

It is remarkable that Newton accepted the 'fixity' of the stars at face value, because he was the first person in history who should have realised that the evidence that the stars were at rest was inconclusive. James Gregory had published in 1668 a little-read work on geometry that contained in a brief appendix a brilliant method of determining the approximate distances of the stars. The method depended upon the principle, that was then becoming increasingly accepted, that the Sun is merely the star that happens to be closest to us -- stella fixa vicina, as Gregory terms it in a memorable phrase -- and that the Sun and the other stars are all physically similar. It follows that the Sun and a star, Sirius for example, differ in apparent brightness because they are at different distances from us; and if the Sun were at the distance of Sirius it would look like Sirius. Now if space is perfectly transparent, light diminishes with the square of the distance; this means that if we compare the apparent brightness of the Sun with the apparent brightness of Sirius and take the square root of this ratio, we have the distance of Sirius in astronomical units, one astronomical unit being the distance of the Sun from the Earth. The difficulty in this method is, how in practice to compare the apparent brightness of the Sun with the apparent brightness of Sirius, using the technology available in the seventeenth century. Gregory had an ingenious way round this practical difficulty; and when the Gregory method was applied by Newton in his System of the world, Newton concluded that Sirius lies at the astonishing distance of about one million astronomical units. This result happens to be correct to within a small factor, and thus Newton became the first man in history to have an appreciation of the scale of the distances between one star and another.

Newton was then uniquely well-placed to appreciate that even after two thousand years, the evidence that the stars were at rest was inconclusive: the stars are very distant, so distant that although they do move these movements are to us almost imperceptible; in fact few of them appear to move more than one minute per century. This inference was indeed made in 1761 by Johann Heinrich Lambert, who also believed that the universe is a great clock and who therefore concluded that the stars must form a finite system in rotation, just like the system of the planets. Newton failed to make the inference; perhaps he was mesmerised by his own constant use of the Latin abbreviation fixa for fixa stella, for how can one think of a fixa that is not fixed? Believing that the stars were indeed at rest, Newton was forced to conclude that their system was infinite rather than finite. But even if the system was infinite, why did the stars in it remain at rest?

Newton´s answer, embodied in draft theorems for a planned second edition of the Principia, was, first, that the system of the stars is almost symmetric, and each star remains at rest because it is balanced in every direction between equal and opposite forces. He engages in a pioneer investigation of stellar statistics to show that the star catalogues do indeed support his claim that the universe of stars is symmetric. But it is not perfectly symmetric, and here Newton plays the theologian. Newton believes that the true God is not the God of Descartes, who creates the world and sustains it in existence but otherwise leaves it to care for itself. Newton´s God is a providential and caring God, who reveals his Providence through the book of Scripture, but also through the book of Nature. Thus the astronomer who considers the solar system is impressed at the planning and forethought which have ensured for the solar system long-term stability; but the astronomer realises that in the very long term the solar system must become unstable, and then God the clockmaker will intervene and reform the system and restore stability. Leibniz will criticise this view of God, arguing that since God is perfect, he is a perfect clockmaker and his universe is perfect and does not need repair through miracles; but Newton believes that God´s interventions are not miracles since they have been planned from the beginning -- they are God´s way of convincing man that he is a caring God. And as in the solar system, so in the system of the stars: because the system of the stars is not perfectly symmetric, after a long period of time it too will be in danger of gravitational collapse, and again God will intervene to restore the original order.

Newton recognises what is obvious, that the system of the stars is not perfectly symmetric. But he seems to close his eyes to the obvious proof that the system is, on the contrary, highly unsymmetric: the Milky Way. In fact, the lack of interest in the Milky Way in the seventeenth and early eighteenth centuries is remarkable. It is symptomatic of how in this period astronomy concentrated almost exclusively on the solar system; problems of the large-scale structure of the universe were the concern of philosophers and theologians, such as Richard Bentley, or of scientists like Newton when they were thinking theologically. And so it was that the next stage in this story of the Newtonian universe centres round a most unlikely figure: the physician and antiquarian William Stukeley, who knew next to nothing about science. He tells us that in conversation with Newton around 1720, he proposed to Newton a theory of the stellar universe. According to Stukeley, the bright stars that are individually visible all over the sky form a spherical system, what a modern astronomer would call a globular cluster. Then there is an interval of empty space, after which we come to the stars of the Milky Way. These stars all lie in or close to a plane, so that they form a flat ring surrounding the globular cluster. This is indeed the model of the universe proposed over a century later by one of the great observers of all time, John Herschel; and Stukeley suggests that the Milky Way is the stellar analogue to the ecliptic in the planetary system -- an astonishing insight.

Stukeley does not develope a gravitational theory of his star system; he could hardly do so, because he claims the star system is growing all the time as God continually creates new stars to add to those of the Milky Way. Newton commented that it might instead be preferable to consider the stars as distributed uniformly in every direction -- as we know was to be the case in his own unpublished model of the universe. But Stukeley replied that in that case the whole sky would "have had the appearance of that luminous gloom of the Milky Way". In this way Stukeley identified the Milky Way as the decisive proof that the universe of stars is not uniform: a model of the universe developed by Newton to deal with gravity and the problem of gravitational collapse is challenged by Stukeley on grounds of appearances -- of light.

One morning in 1721 Stukeley had breakfast with Newton and Edmond Halley, and they talked of matters astronomical. What Stukeley contributed to the conversation we are not told, but it must surely have included his thoughts on the Milky Way, because a few days later Halley read to the Royal Society the first of his two famous papers on light in an infinite universe of stars. In this paper Halley reports an argument he has heard put forward -- he does not say by whom -- according to which, if the number of stars was infinite, the whole heavens would appear "luminous" -- the very word used by Stukeley. Halley advances arguments to answer Stukeley´s difficulty and rescue the infinite Newtonian universe of stars; but his arguments are misconceived. His papers were however published in Philosophical Transactions, and even in the famous abridgement of Phil. Trans., and so the private theorizing of Newton and his closest friends moved into the public domain. In 1744 the question was taken up again, this time with greater mathematical competence, by the Swiss astronomer Cheseaux, and in 1823 by the German Olbers; and in modern times this question, so crucial to contemporary cosmology, has been named ´Olbers´s Paradox´. It would more accurately be known as ´Stukeley´s Paradox´, and it is part of the aftermath of Newton´s attempt to reconcile the supposed fixity of the stars with gravity as a universal force.

These problems arose from Newton´s conviction that the fixed stars were indeed fixed and at rest. We have seen that Newton was already in possession of information which could, and should, have led him to question the observational evidence. In Newton´s own lifetime, in 1718, Halley found that in fact three stars had moved from the positions they occupied in Antiquity. We do not know what Newton made of this, but Halley seems to have thought that an infinite universe of stars was highly stable under gravity, and that the individual or ´proper´ motions that he had observed were nothing more than oscillations about mean positions. Lambert, whom I have already mentioned as questioning the fixity of the stars, was unaware of Halley´s results when around 1760 he first drafted his book, Cosmological Letters. But before completing the work he learned of these proper motions, and in the published text he welcomes them as examples of the movements he had predicted. Lambert is a late example of a resolute believer in the clockwork universe, which for him is hierarchical: the moons of a planet form a stable system in orbit about the parent body; the planets form a stable system in orbit about their star; stars form a stable system or ´cluster´ in orbit about a massive central body; clusters of stars similarly form a stable system in orbit, and one such system of clusters includes all the visible stars including those of the Milky Way; and so on for perhaps a thousand steps. In Lambert´s hierarchical universe, there is at every stage the clockwork stability we ourselves can observe in the system of the moons of Jupiter or the system of the planets.

Another writer who saw in Halley´s proper motions evidence for the orbits of stars in a stable and finite system was an idiosyncratic English speculator, a self-taught astronomer with a very personal theology, Thomas Wright of Durham. Wright, who was born in 1711, earned his living as a young man by giving public lectures on scientific and quasi-scientific subjects. In one of the lectures he was giving in 1734 Wright set out to integrate the scientific knowledge that astronomers have of the limited region of the universe that is accessible to their telescopes, into the cosmological picture of the total universe that came from Wright´s personal theology. Wright believed that God, together with the angels and the blessed, is in a heaven that is located somewhere in the physical universe. Heaven is both the moral and the gravitational centre of this universe. The Sun and the other stars together form a system that surrounds heaven; that is, the stars occupy a spherical space at the centre of which is heaven. Outside the spherical space of the stars is an infinite emptiness, the outer darkness of hell. After death we shall either move inwards to the centre to join God and the angels in heaven, or we shall move outwards to the darkness of hell. Now because for Wright this universe is permanent and stable, the system of stars must not be allowed to collapse under gravity and fall into heaven. The stars therefore are not motionless but in orbit as are the moons in orbit about their planet and the planets in orbit about the Sun; and Wright saw in the three proper motions announced by Halley, observational evidence of the orbital motions of the stars.

In his major publication, An original theory or new hypothesis of the universe, which appeared in 1750, Wright gave an explanation of the Milky Way in the context of this cosmology. The stars that we can see with astronomical telescopes naturally lie in the spherical region that contains all the stars, whether visible to us or not; that is, they lie between the spherical inner surface of this region and the spherical outer surface. If the spherical region has a very large radius, the stars that astronomers can see lie between surfaces that are very nearly flat. When we as astronomers look either inwards, towards the inside of the spherical region, or in the opposite direction, towards the outside, then we see a few stars, near to us and therefore bright, before we find ourselves looking into empty space. But when we look tangentially, along the nearly flat region, then we see first a few near and bright stars, and then many stars that are more distant and therefore fainter, and then very many more stars that are very distant and faint and whose light therefore merges to create a milky appearance. And this is how Wright explains the Milky Way: it is the optical effect of our immersion in a huge spherical shell of stars that surround heaven, and the Milky Way defines the tangent plane to this sphere at the place where we in the solar system are located.

Wright has to admit there is another possible explanation of the Milky Way, if we are prepared to abandon spherical symmetry. We can explain the Milky Way if our stars all lie in or near a plane, forming a flattened circle or ring within this plane. The centre of the circle will be empty of stars, because it is divine. The stars near enough to us for us to observe them with telescopes will all be in the same region of the flattened circle as ourselves. That is, the Sun and the other visible stars lie all around us in or near this plane; when we look away from the plane, then we see only a few stars, but when we look around us in the plane itself then we see great numbers of stars whose light merges to give the Milky Way.

Wright´s book has many fine illustrations, but his words are confused and hard to understand. In 1751, the year after Wright´s book was published, a summary -- but without illustrations -- appeared in a Hamburg periodical, where it was read but only partially understood by the young philosopher Immanuel Kant. Kant knew he was being offered two alternative models of our star system, one spherical and the other circular. But he did not understand that in either case the centre of the our system was divine, and so he saw no reason why in the second model the circle of stars should not be continuous, extending without interruption from one edge of the circle, across the middle, to the opposite edge. As we have seen, Wright could not allow this, because the centre of the system was not natural but supernatural. Now Kant believed, as indeed did Wright, that there are other systems of stars in the universe besides our own; and the nearer of these systems are visible to us as milky patches of light in the sky, or nebulae. Kant further believed that the French astronomer Maupertuis had observed some of these nebulae and that they were elliptical rather than circular in shape. Now if one observes a spherical star system from a distance, that system must always appear circular in outline; but if one observes a circular star system, then from most directions it will appear elliptical in outline, as do the nebulae of Maupertuis. Kant therefore concluded that of the two alternative models he believed were proposed by Wright, the spherical one was disproved by observation; the other, the circular model which for Kant was continuous from one side across to the other, was therefore correct. And of course it is correct: the Milky Way _is_ the optical effect of our immersion in a Galaxy of stars that form a flattened and roughly circular system.

Kant, like Lambert, made the limited hierarchy envisaged by Wright -- moons, planets, stars -- the first steps in an extended hierarchy of systems of stars and systems of systems of stars, and indeed for Kant the hierarchy extended infinitely upwards. But in his book _A general natural history and theory of the heavens_, which received a limited publication in 1755, Kant also developed a cosmogony, one based on the aspect of gravity with which we began: gravity as the agent of change. Newton´s universe, Lambert´s universe, were clockwork universes in which stars were either motionless or orbited eternally, and similarly no fundamental change could take place in the universe of Wright. But these were all universes in which the natural consequences of gravity -- fundamental change -- were frustrated, so to speak, by the artificially stable star arrangements devised by God. Kant, as a speculative cosmologist, and William Herschel, as an observational astronomer, conceived of universes in which the changes brought about by gravity were dramatic.

Kant invites us to consider at the creation of the world an infinite chaos of matter, in which gravity begins to operate. We imagine one region where the density of matter is unusually high and the force of gravity therefore more powerful than elsewhere, and it is convenient to speak of this region as the centre of the infinite universe. With time, gravity works on the matter in this central region so as to bring structure and order out of the initial chaos, and we then have a universe in which there is a central spherical region of structure surrounded by a continuing chaos. As time goes on, the central sphere of structure gets larger and larger, expanding into the surrounding chaos and slowly bringing it to order. But gravity continues to work on the central structure, and since this structure cannot be eternally stable, it is slowly dissolved back into a state of chaos. At this stage in the history of the universe, we have a central spherical region of what was once structure but is now chaos again; surrounding it a spherical region of structure; and outside that, the region in which the original chaos continues to exist.

More time passes. Gravity works on the central chaos to give it structure for the second time. Gravity works on the surrounding structure to dissolve it back into chaos for the second time. Outside this is a region where structure has appeared for the first time. And outside this there is still the original chaos.

As time goes on, so the original sphere of structure extends further and further outwards into the infinite chaos. Inside this sphere is another sphere marking the boundary of a region in which recently formed structure has fallen back into chaos again. Inside this is a region where structure has formed for the second time; inside this a region where chaos exists for the third time; then a region of structure for the third time; and so on, until we come to the centre of the universe, which will already have experienced several changes from chaos into structure and back again into chaos.

Here we have a totally speculative model of the universe in which oscillations from chaos to structure and back again occur in combination with continuous change in which the advancing spherical region of the new structure moves further and further out into space. The book in which Kant expressed this conception had limited circulation and its influence is uncertain. But now the time had come for such speculations, which had begun with Newton´s disregard of the evidence of the Milky Way and had continued with minimum reference to observational fact, to give way to theories based on evidence.

William Herschel was born in Hanover in 1738, and came to England in 1757 as a refugee from the Seven Years War. Herschel was by profession a musician, and in 1766 he was appointed organist to a chapel in the fashionable city of Bath. There he was able to indulge his growing interests in astronomy, and unlike professional astronomers Herschel´s ambition was to understand, not the solar system, but the large-scale structure of the universe -- what he called "the construction of the heavens". For this he realised he needed the largest possible telescopes, for distant objects are necessarily faint and the larger the mirror of the telescope, the fainter the objects the observer can see and the more of the universe he can investigate. Such telescopes were not to be bought, so Herschel manufactured them for himself, becoming in the process one of the great telescope builders of all time. In 1781, through a combination of exceptional skill and good luck, he became the first man in recorded history to discover a new planet, and he was awarded a royal pension that allowed him to devote himself totally to astronomy. The following year he began systematically to search the whole of the visible sky for the mysterious milky patches termed ´nebulae´, of which about one hundred were known. In twenty years Herschel increased this figure to 2,500. Some nebulae were obviously, like the Milky Way itself, formed of great numbers of stars. Others might, or might not, be clouds of some kind of luminous fluid. In either case the concentration of matter -- whether in the form of stars or of fluid -- must result from the action of an attractive force, almost certainly the force of gravity. And unlike Newton, Herschel accepted that gravity is a force that leads to change.

Herschel twice altered his mind on the question of whether luminous fluid existed. The second change of mind occurred in 1790, when he came across a star surrounded by what was obviously a cloud of luminous fluid, and this he interpreted as a star condensing out of the cloud of fluid, under the action of gravity -- a star was being born. This led him to propose a vast cosmological synthesis, in which the luminous fluid was nothing other than light itself. We are to imagine a situation in which light is thinly-spread throughout a vast region of space. Here and there the light is more dense than elsewhere, and in these places the force of gravity is more powerful and pulls in the surrounding luminosity. In this way the initial vast cloud of light breaks up into smaller, more concentrated clouds which we see as nebulae. In these nebulae, under the continued action of gravity, individual stars begin to form here and there; and as gravity continues to work, these stars move together to form clusters. In the end each cluster will collapse in a vast cataclysmic explosion, and this will throw out light in all directions, to begin the process all over again.

Herschel´s universe, then, is one in which infant nebulous clouds of light pass through a life-cycle in which they develope under the action of gravity into tightly-packed clusters of stars, whose eventual death by gravitational collapse starts the whole process all over again. Herschel´s prestige gave him almost automatic right of publication in the Royal Society´s Philosophical Transactions, and so his bold ideas became available throughout the scientific world. Gravity for Newton himself was the force that held together a mechanical, clockwork universe; for Herschel it was the quasi-biological force that carried the infant nebulosity through life to maturity, and eventually to old age and death as a collapsing cluster of stars. Such was the diversity of Newton´s legacy.

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