Gravity and Light in the Newtonian Universe of Stars

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Abstract

Newton's claim that gravity is a universal force was contradicted by observations that seemed to show the stars were motionless. When challenged on this by Richard Bentley, he argued that the solution lay in the near-perfect symmetry of the stellar system. William Stukeley however suggested that in such a universe the sky would be filled with light similar to the Milky Way. Edmond Halley disputed this in print, but mistakenly, and later discussions of such a universe led to 'Olbers's Paradox'.

Key Words: Isaac Newton; William Stukeley; Edmond Halley; Olbers's Paradox; universe of stars; gravity

Resumen

La petición de principio de Newton que la gravedad es una fuerza universal se contradice con los resultados aparentes de las observaciones de las estrellas inmóviles. Al ser preguntado sobre esto por Richard Bentley, argumentó que la solución reside en la simetría casi perfecta del sistema estelar. Sin embargo, William Stukeley sugirió que, en tal universo, el cielo se llenaría de luz similares a la de la Vía Láctea. Edmond Halley tomó parte en la disputa, pero erróneamente, y posteriormente estos debates en torno a semejante universo han dado lugar a "la paradoja de Olbers".

Palabras clave: Isaac Newton; William Stukeley; Edmond Halley; paradoja de Olbers; universo de estrellas; gravedad.

When Isaac Newton published his *Principia* in 1687, it seemed that the stars were as 'fixed' as ever. In Antiquity the Greeks had given them this name, to contrast them with the 'wandering stars' or planets that moved with an individual motion across the sky. The fixed stars maintained their positions relative to each other, century after century, and it had been thought that this was because they were all attached to a single sphere.

When Newton entered Cambridge as an undergraduate in 1661, the university statutes still required students to study Aristotle. But in the colleges tutors were able to teach the new philosophy of Descartes, and Newton became a convinced Cartesian. As such he knew that the stars were independent bodies scattered throughout infinite space, and that the Sun is merely our nearest star. Nevertheless, he continued to speak in Latin of the stars as "fixae stellae", or simply "fixae", and this terminology may have disposed him to think of them as motionless, even though he knew they were free to move.

In the years before he completed the *Principia*, Newton became the first person to arrive at an understanding of the immense distances that separate the solar system from the nearest stars. He did this by adopting the plausible hypothesis that the stars are physically similar, and that a faint star appears faint simply because it lies at a great distance. He found a way of comparing the brightness of Sirius with the brightness of the Sun, and concluded that the Sun was around one million million times brighter than Sirius and therefore — since brightness diminishes with the square of the distance — Sirius is about one million times further from us than the Sun (Hoskin 1977, 96). Because he knew Sirius was so enormously far away, it should have occurred to him that Sirius might well be in motion, but that because of its great distance this motion would be imperceptible to us on Earth. But it seems he did not think of this. He continued to speak of Sirius as one of the *fixae*, and this term may have influenced his thinking.

Descartes's universe was a plenum, completely full of matter, and Newton spent a lot of effort trying to understand how planets might move in accordance with Kepler's laws in such a plenum. But in Gresham College, London, the magnetical philosophy held sway (Pumfrey 1989). Influenced by the book on the magnet published by William Gilbert in 1600, the Gresham circle — and Robert Hooke in particular — held that the universe, far from being completely full, was nearly empty; and that bodies continued to move in a straight line unless diverted by the forces of magnetic attraction exerted by other bodies across seemingly empty space (Bennett 1989). Many suspected that these forces diminished with the square of the distance, because that is what happens with light, but no one was mathematician enough to prove it. Hooke wrote to Newton about the problem, and eventually pressured Newton into investigating a universe that Newton as a Cartesian regarded as entirely fanciful. But Newton found to his amazement that in the universe imagined by Hooke, the planets would indeed move in accordance with Kepler's laws of planetary motion: Hooke must be right after all. And so Newton ceased to be a Cartesian and instead became a Newtonian. He accepted that, left to themselves, bodies move in a straight line with constant speed. But they are diverted from their straight-line motion by the inverse-square gravitational pulls of other bodies. This is the world picture of Newton's *Principia* (Wilson 1989)

But there is a curious gap in the *Principia.* Newton has a lot to say about falling bodies, and the tides in the seas, and the Moon, and the planets and comets, but hardly a word about the fixed stars. He claims the inverse-square law of gravity is universal, but in the large-scale universe the evidence was in fact against him. Forces cause motions, and if a star is being pulled by other stars, it must surely move. And so, if the stars are indeed motion*less*, *fixae*, then gravity surely cannot be universal as the *Principia* claims.

That he should fail to see this objection seems extraordinary. But in the winter of 1692/3 the problem was put to him by a young theologian, Richard Bentley (Newton 1961, 246). Bentley had recently given a series of sermons funded by the will of the late Robert Boyle, in which Bentley's duty had been to reconcile science and religion. He now planned to publish these sermons, but before doing so he wished to know what insights there were in Newton's *Principia*, which was far too mathematical for Bentley to understand. And so Bentley wrote to the author.

Both men believed that the stars were at rest, and Newton explains to Bentley that this shows that the system of stars must be infinite — for stars that are at rest in a finite system will immediately begin to move towards the centre of the system, and what we would call gravitational collapse will follow (Newton 1961, 234). Bentley then asks Newton how gravity would affect matter "eavenly scattered" throughout infinite space — evenly, that is, uniformly. Newton does not take Bentley literally, and tells him that where there are regions where the matter is more concentrated and the pulls are therefore stronger, gravity will cause the surrounding matter to move towards these regions.

Bentley then insists that he was asking about matter that is at rest and is distributed with strict and absolute uniformity, and of course Newton has to admit that such matter would remain at rest despite the pulls of gravity in every direction, for in such a universe there would be no reason for any particle to move one way rather than another. But, he says, perfect uniformity is almost inconceivable, it is like asking for infinitely many needles all to balance on their points on some vast mirror (Newton 1961, 238).

At this point Bentley poses the crucial question, replacing his imagined particles with the very real fixed stars: "... is it not as hard, yt infinite such Masses in an infinite space should maintain an equilibrium ...?" (Newton 1961, 251). In other words, how can all the stars be permanently at rest in a cosmos in which gravity is a universal force?

In the early 1690s, at the time of this correspondence, Newton was professor in Cambridge and he was at work on a second edition of the *Principia*. But in 1696 he left academic life. As a result, the second edition as planned by Newton never appeared. However, in Cambridge we still have Newton's chaotic drafts for this planned second edition, and it seemed to me that in them he might well have attempted to answer the challenge Bentley had put to him: how can the stars be at rest if gravity is universal?

I therefore went through the manuscripts and made a photocopy of any page where the word 'star', *fixa*, appeared. I then spread these photocopies across the floor of a large room, and gradually a succession of drafts of a theorem began to take shape (Hoskin 1977). According to this theorem, the stars are distributed throughout space with near-uniformity. The pulls on any given star in one direction are therefore almost matched by the pulls in the opposite direction, and this is why the star remains at rest.

The observational evidence in support of this theorem could come only from the star catalogues of Newton's day. These gave the position of a star on the heavenly sphere, that is to say, two of its coordinates in space, together with its apparent brightness. Apparent brightness therefore had to supply the third coordinate, the distance of the star from us. Newton was working with the assumption that the stars are all physically similar, and that therefore apparent brightness is indeed an excellent indicator of distance.

Ever since Ptolemy in Antiquity, stars had been classified as being from first magnitude, the brightest, to sixth magnitude, the faintest visible to the unaided eye. How did this classification relate to distance? Newton, without thinking seriously about the matter, assumed that sixth magnitude stars were six times further than those of first magnitude. The correct value is ten times, and so Newton would encounter a problem as he drafted his theorem.

The star catalogues record the heavens as seen from Earth, and to make predictions that can be tested against the star catalogues, Newton had to employ a geometrical model of the uniform distribution that had the Earth at the centre. He therefore imagines the solar system as surrounded by a succession of concentric spheres. The first sphere has radius one unit, which is the distance of the first magnitude stars. The second has radius two units, the third three units, and so on.

In the model, the first magnitude stars lie on the first sphere and so are one unit from Earth. But they must also be one unit or more from each other, and Newton asks himself what is the maximum number of such points that can be crammed onto a single sphere. The answer is 12 or 13 (he is not sure which), and he is pleased that this is indeed roughly the number of first magnitude stars in the sky. The model has successfully passed its first observational test.

On the sphere of radius 2 will lie the stars of second magnitude. Of course, because they are on the sphere of radius 2 they are the required minimum distance of one unit from all the stars on the previous sphere, but they must also be at least one unit of distance from each other. How many stars will there be room for on this sphere? It has four times the surface area of the first sphere, and therefore room for about four times 12 or 13, perhaps 50. On the next sphere, of radius 3, there will be room for about nine times 12 or 13, and on the next, sixteen times.

How did these predictions from the geometrical model compare with the actual numbers in the star catalogue? In writing his first draft Newton did not stop to find a star catalogue and count stars, he simply took it for granted that there would be a satisfactory correspondence between prediction and observation, and he left space that would allow him to fill in the actual numbers later. Such was his complete confidence in his model of the universe of stars!

However, when in writing a later draft he came to count the stars in a star catalogue, he found that the numbers did not in fact match the predictions. But he had an easy explanation: this problem was due to his over-hasty assumption that stars of magnitude *n* lie at *n* units of distance. He could instead allow himself some flexibility here, and with it he easily convinced himself that the numbers matched well enough.

Interestingly, Newton expressly says that the stars at distance 2 are four times as numerous and one-quarter as bright as those at distance 1; that those at distance 3 are nine times as numerous and one-ninth as bright; and so on. But he fails to draw the conclusion, so obvious to a modern cosmologist, that the *total* light in the sky due to the stars that are at distance 1, and to the stars that are at distance 2, and so on, is the same in each case, and therefore if we gradually take into account stars that are at greater and greater distances, we will find that the entire sky will fill with light. This of course is what we know as Olbers's Paradox: why is the sky in fact dark at night?

Newton's failure to notice the paradox when it was staring him in the face reflects the fact that he was preoccupied with gravity in his universe of stars, and not with light. And however satisfactory the counts of the brightest stars, a glance at the night sky shows that the symmetry of the distribution of the stars is not complete. This created a serious problem, but Newton had an answer.

God (according to Newton and many of his contemporaries) revealed himself to mankind through two books: the book of Scripture (the Bible) and the book of Nature. Newton viewed God as the Great Clockmaker, and his universe as a complex mechanism; and when Newton studied this universe, Newton learned to appreciate the role of God's Providence in caring for mankind. For example, in the solar system the planets all orbit the Sun in the same plane, rotating like the hands of a cosmic clock, and we see the care of Providence in locating the two massive and potentially disruptive planets Jupiter and Saturn at the outer edge of the system, where they can do least harm by their gravitational pulls. As a result, in the medium term the solar system is stable, as one would expect of the Great Clockmaker. But in the long term the system will eventually become unstable as a result of the gravitational pulls. The system will be threatened with collapse and, in Newton's words, "want a reformation" (Newton 1931, 402). But God has what we might term a servicing contract with his creation: he will regularly intervene and restore the original order.

The student of the solar system, therefore, learns to appreciate God's two-fold care for his creation. First God creates for the home of mankind a solar system that has stability over vast periods of time. But second, when nevertheless the system in the long term is threatened with collapse, God intervenes to restore the original order. Newton's contemporary Leibniz argued that a good clockmaker would not need to keep repairing his work in this way (Alexander 1956, 11), but Newton saw these regular interventions by God as one way in which God reveals to mankind his care for his creation.

Newton takes a similar view of the system of the stars. God creates a system whose near-symmetry gives it stability over long periods of time. But when in the very long term it is at last threatened with gravitational collapse, he intervenes and restores the stars to their original positions (Hoskin 1985, 89).

So much for gravity in the Newtonian universe. The problem of light was at last put to Newton, face to face, sometime around 1720, by William Stukeley (Hoskin 1985, 79). Stukeley was a medical man, but he had an amateur interest in questions of cosmology, and especially in the Milky Way. It is extraordinary that Newton should have argued that the stars are distributed uniformly throughout space, when the Milky Way is obvious proof that this is not so. Galileo's telescope had confirmed that the Milky Way is the optical effect of great numbers of faint stars, but Stukeley, a century later, is one of the first to ask himself, What is the structure of the Milky Way?

Stukeley noted that the brightest stars are scattered all over the sky, but that the faintest are concentrated in the plane of the Milky Way. He therefore proposed to Newton that the brightest stars form what we would term a globular cluster (of which the Sun is a member), and that the faint stars of the Milky Way form a flat ring that surrounds the cluster. The star system, seen from a distance, would therefore look rather like Saturn and Saturn's ring (Hoskin 1985, 83).

Knowing nothing of Newton's model of the universe, which was secret to all but a few of his intimates, Stukeley expressly put it to Newton that the Milky Way proved that the stars were not "filling infinite space *quaquaversum*" — on every side (Hoskin 1985, 82). And he added that if they had done so, the entire sky "would have that luminous gloom of the milky way", and so "we should have lost the present sight of the beauty and the glory of the starry firmament". Newton had at last been confronted with the contradiction between his model of a uniform universe of stars and the existence in the sky of the Milky Way.

On 23 February 1721 Stukeley took breakfast with Newton and Edmond Halley, the recently appointed Astronomer Royal. Stukeley lists for us the subjects raised by Newton and Halley (Hoskin 1985, 96), but says nothing about his own contribution to the conversation. It seems highly likely, however, that he talked again of how in an infinite universe of stars the entire sky "would have that luminous gloom of the milky way", for just two weeks later Halley read a paper to the Royal Society in which he discussed objections to an infinite universe of stars. "Another Argument I have heard urged [he says], that if the number of stars were more than finite, the whole superficies of the apparent Sphere would be luminous" (Halley 1720–21a).

In the paper Halley focuses on how the problem of gravity in the universe is solved if the stars are infinite. As the Royal Society's Journal Book says in its summary, Halley maintains that in an infinite system a star remains at rest "because it has not any tendency to move one way rather than another" (Hoskin 1982, 96). But he must make some response to Stukeley's objection that in such a universe, the light of the stars would combine to give the whole sky the luminous gloom of the Milky Way. However; his solution to the problem is based on an elementary mathematical error.

A week later Halley read a second paper to the Royal Society (Halley 1720–21b), asking himself "what might be the consequence of an Hypothesis, that the Sun being one of the Fixt Stars, all the rest were as distant from one another, as they are from us" — in other words, the Newtonian symmetric and infinite universe of stars. Halley believes this solves the problem of gravity, but does it solve the problem of light? Imitating Newton's analysis of the concentric spheres imagined as surrounding the solar system, he discussed the one-hundredth sphere, on which each star would have an apparent brightness equal to one-10,000th that of a first magnitude star. This, he argues, "is so small a pulse of Light" that the star will be imperceptible to our eyes. In other words, he claims that beyond a certain distance the stars are so faint that we cannot see them, and so it is as though they do not exist. Problem solved!

Halley's confused papers were published in *Philosophical Transactions*, and at last Newton's model of the stellar universe became publicly known, although Halley's was the name associated with it. It could not be long before someone realised that Halley's analysis was erroneous, and it was the young Swiss astronomer Jean-Philippe Loys de Chéseaux in 1744 who gave the first accurate statement of what we know as Olbers's Paradox (de Chéseaux 1744).

Chéseaux gives a clear analysis of the model of stars located on concentric spheres first investigated by Newton. The stars on the first sphere, he says, collectively occupy a certain extent of the sky, which they illuminate with a give intensity. The stars on the second sphere individually occupy only one-quarter of the sky as compared to the stars on the first sphere, but there are four times as many of them, so when their light is combined the extent of the sky that they illuminate is the same. And similarly with the third sphere, and the fourth, and so on. The stars of each sphere will in combination illuminate a fixed area of the sky, and as we take more and more spheres into account, so more and more of the sky will be illuminated. With an infinite number of such spheres — or even a very large number — the entire sky will be illuminated.

But this assumes that the light of distant stars diminishes exactly with the inverse-square of the distance, and no more. That is, this assumes that space is perfectly transparent. But we have no reason to believe that this is in fact the case. If even a small amount of light is lost in the journey from one sphere to the next, these losses will accumulate for the more distant stars, until these stars become virtually invisible. The darkness of the night sky, therefore, is fully compatible with the number of stars being infinite. A similar analysis was given in 1823 by H. W. M. Olbers (Olbers 1823), and it is his name that we wrongly associate with this model of the universe of stars.

The problem of the darkness of the night sky fascinated nineteenth-century astronomers, but they had many explanations to offer (Jaki 1969, chap. 8). Instead of stars evenly distributed throughout space, John Herschel proposed a hierarchy of star systems, and it was easy to construct the hierarchy so as to retain the infinity of the stars while explaining the darkness of the night sky. Others thought there were many dark stars that blocked off light. Others again thought that the stars had existed for only a finite time and that the light of the more distant stars had not yet had time to reach us; while others imagined, between one cluster of stars and another, an etherless vacuum through which light could not pass.

To conclude, then. Stars in a Newtonian universe influenced that universe in two ways: by their gravitational pulls, and by the light they transmitted. Newton, focusing his attention on the gravity, had argued that the fixed stars are infinite in number, because if they were finite they would be subject to gravitational collapse. Halley, Chéseaux, Olbers and many others had discussed whether the light in such an infinite system was compatible with the darkness of the night sky. For most of them, it was, and only in the later twentieth century did cosmologists find in the darkness of the night sky a paradox: the so-called Olbers's Paradox, which we now know goes back to Stukeley and even to Newton.

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