



# From Newton to Einstein<sup>1</sup>

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*Nature and Nature's laws lay hid in night:  
God said, Let Newton be! And all was light.*

This was Alexander Pope's epitaph for Sir Isaac Newton (1642–1727). While we might regard this as a bit of an overstatement, Newton's contribution to our understanding of the physical universe is outstanding. First, he established clearly the basic principles of mechanics through his three laws of motion:

1. In absence of any force a body moves with constant velocity (i.e. in a straight line)
2. Force is equal to rate of change of momentum (usually force = mass x acceleration)
3. Action and reaction are equal and opposite.

Now by themselves these laws were not immediately very useful, other than in simple idealised circumstances. For example, even supposing the force on a body like a planet was known – and, of course, it wasn't before Newton's time – then the second law of motion would allow the body's acceleration to be calculated. But to convert that into a meaningful planetary orbit required a new branch of mathematics to be invented, the differential and integral calculus. This Newton supplied, although that new branch of mathematics was also independently developed by his contemporary Gottfried Leibniz (1646–1716).

Newton's greatest and unique achievement was the formulation of his law of gravity. This can be formulated neatly by the comparatively simple equation that states that the gravitational force between two bodies of mass  $M$  and  $m$  is given by  $F$ , where

$$F = \frac{G \times M \times m}{r^2}$$

[Equation 1]

Here  $G$  is a universal constant and  $r$  is the distance between the two bodies.

All this and much more was stated in *Principia*, Newton's major work, first published in 1687 in Latin. It was not translated into English until 1729,<sup>2</sup> which was after Newton's death. Although much was totally original in Newton's work, his achievement was also a synthesis of many partial solutions offered by a number of great thinkers in the Copernican revolution. This was instigated by the work of Nicolaus Copernicus (1473–1543), who first challenged a geocentric picture of the universe. For the ancient Greeks, science, and in particular astronomy, was regarded as a branch of philosophy. A detailed model, centred on a stationary Earth, was developed with the Sun, Moon and planets, and indeed the whole sphere of the fixed stars revolving round it. This culminated in the work of Ptolemy,<sup>3</sup> who lived in the second century AD. Although the geometrical details of the Ptolemaic model seem rather cumbersome to us today, its success is shown in the fact that it was still making useful predictions of the planetary positions 1500 years later. Copernicus proposed an alternative theory centred on the Sun, with the Earth merely one of the planets in orbit round it. Moreover the diurnal movement of the Sun and stars was accounted for by the Earth spinning on its polar axis.

Copernicus' major work, *De revolutionibus orbium coelestium*, was published in the last year of his life. It did not produce much of a stir at the time.<sup>4</sup> It was regarded as an alternative way of calculating planetary positions but was not seriously taken as physical reality, some have suggested not even by Copernicus himself, although I think that is unlikely. In particular, the Roman Catholic church was not concerned with this new theory, and, if anything, there was a more critical response from Reformed churches. The new theory still contained the messy epicycles that were a feature of Ptolemy's theory. The traditional view, first established by Aristotle (384–322 BC), was that the heavens and the earth were separate realms, in

which different laws applied. On the earth bodies naturally fell downwards, while in the heavens circular motion was regarded as the natural law. To describe planetary motion around a stationary Earth required something more complicated than a circle, and the epicycle was introduced by Hipparchus (second century BC) and developed in Ptolemy's theory. Essentially this meant that the planet was regarded in moving in a circle about a point, which was itself moving in a circle about the Earth.

The resistance to accepting that the Earth could be in motion and spinning on its axis is shown in the theoretical work of Tycho Brahe (1546–1601). He devised a compromise theory in which the two interior planets were in orbit round the Sun, but the Sun and the rest of the solar system were still regarded as in orbit around the stationary, non-spinning, Earth. As a model of the solar system this was clearly a retrograde step, but the importance of Tycho lay in his observational work. He was, without doubt, the greatest of pre-telescopic observers and he provided a corpus of planetary observations which were accurate to about one minute of arc.<sup>5</sup> This body of work provided the observational basis for Tycho's student and successor, Johannes Kepler (1571–1630), to derive his empirical laws of planetary motion.

Unlike Tycho, Kepler was a convinced Copernican from the outset. From a study of Tycho's observations over many years, principally of Mars, he derived three laws of planetary motion round the Sun. They are:

1. A planet orbits the Sun in an ellipse with the Sun at one focus<sup>6</sup>
2. During a planet's orbit around the Sun, equal areas are swept out in equal times
3. The square of a planet's orbital period is proportional to the cube of its semimajor axis.

An ellipse is an oval curve, which can be described mathematically in a number of ways. Probably the simplest is to say that it is the locus of points, the sum of whose distances from two fixed points (the foci) is constant. The semimajor axis is just half of the longest axis which passes through the two foci. A circle is a special case of an ellipse where the two foci are coincident and the semimajor axis then reduces

to the radius of the circle. These laws give what is broadly a correct description of planetary motion, but it is no explanation. That had to await the introduction of Newton's law of gravitation.

Galileo Galilei (1564–1642) was a contemporary of Kepler and, like him, a convinced Copernican. He was less concerned with the details of predicting planetary positions in the sky, but enthusiastically promoted the principle of the heliocentric universe. This, of course, brought him seriously into conflict with the Roman Catholic church and he was accused of heresy and forced to recant. I do not wish to say much about that admittedly fascinating episode but rather to concentrate on Galileo's importance as a precursor of Newton. However, we should note in passing that this conflict between science and religion, unlike later ones, was not about the ultimate truth of religion. Both sides were essentially believers. It was about the church's authority and whether this extended to the realm of science or could science be allowed to establish a realm of its own.

Galileo is also important as the first person to make astronomical observations using a telescope. He did not invent the instrument but, on hearing of its invention, immediately recognised its potential for making astronomical observations. Consequently a number of discoveries, which were just beyond naked eye recognition, were made by Galileo. One such discovery was the four main satellites of Jupiter, which Galileo observed in 1609. He regarded this as a miniature solar system and evidence that the Copernican theory was correct. Another was the phases of Venus, whose nature conclusively proved that that planet at least was in orbit around the Sun rather than the Earth.

Galileo also made a number of terrestrial experiments going some way to establishing the laws of mechanics and terrestrial gravitation. The Roman Catholic church did not find these so troublesome but they are important in understanding Galileo's contribution to the eventual Newtonian synthesis of ideas. It is interesting to compare the statements dating from Aristotle, which were then currently accepted, with the new results of Galileo's experiments:

	<b>Aristotle</b>	<b>Galileo</b>
1	<i>Objects move only as long as we apply a force to them</i>	<i>Objects keep moving after we stop applying a force (if no friction)</i>
2	<i>Falling bodies fall at a constant rate</i>	<i>Falling bodies accelerate as they fall</i>
3	<i>Heavy bodies fall faster than light ones</i>	<i>Heavy bodies fall at the same rate as light ones</i>

Notice that the first of Galileo's conclusions is identical with Newton's statement of the first law of motion. René Descartes (1596–1650) independently came to the same conclusion. The third of Galileo's results is somewhat counterintuitive<sup>7</sup> and is an important property of Newton's theory of gravitation, and ultimately Einstein's as well.

Newton drew all this work (from Copernicus through to Galileo) together and the lynchpin was his theory of universal gravitation. He compared the acceleration of an apple falling in his garden with the acceleration of the Moon in its orbit round the Earth. Due to Galileo's third conclusion as stated above, these two accelerations are not dependent on the mass of the apple or the mass of the Moon. The two accelerations will differ only because of the difference between the apple's and the Moon's distance from the centre of the gravitating body, namely the Earth. Newton could directly observe the apple's acceleration by experiment and he could calculate the Moon's acceleration using his newly invented calculus. For, although the Moon's speed in its orbit might be approximately constant, its velocity was not as it was continually changing its direction. Moreover the calculus revealed that the Moon's acceleration was directed towards the Earth. Comparing the two accelerations Newton deduced the inverse square law that is stated in Equation 1.

Newton then turned his attention to the solar system where the dominant gravitating body is, of course, the Sun, which has a mass more than a thousand times greater than the total mass of all the planets. Here he was concerned to show that Kepler's empirical and highly successful laws deduced from observation were consequences of his single law of gravitation. In fact he was able slightly to extend and improve the laws of Kepler. Let us consider them individually.

1. Kepler's first law stated that a planet's orbit would be an ellipse. Newton's law of gravity predicts that the orbit should be either an ellipse or a hyperbola.<sup>8</sup> So Kepler's first law is correct but, in a sense, incomplete.
2. Kepler's second law was found by Newton to be totally correct. It represents the conservation of angular momentum.
3. Kepler's third law is neatly expressed by the equation  $a^3/T^2 = I$ , where  $a$  is the planet's semimajor axis expressed in astronomical units (AU), and  $T$  is its orbital period expressed in years. The AU is just the Earth's semimajor axis. Newton's law of gravity requires a slight modification of this formula, using the same units, to give

$$a^3/T^2 = M_{\text{sun}} + m_{\text{planet}}$$

[Equation 2]

where the masses on the right-hand side are expressed in units of the solar mass. Clearly the mass of the Sun dominates in each case, so Kepler's third law is seen to be approximately correct. Equation 2, however, opens up other applications in astronomy – for example, to the orbits of double stars.

For Newton the universe existed in absolute space, and time too was absolute. The second of these postulates is understandable; any other concept of time is counterintuitive. He was a Christian believer, although a crypto-Unitarian, as this was a time of religious intolerance. He thought that at a particular instant of time God had created the universe, but that time itself extended back indefinitely before the instant of creation. His belief in the absolute nature of space is scientifically a bit more puzzling, for it is not a necessary consequence of any of his theories. Even so, Newton believed that there was a fundamental frame of reference similar to the aether that came into vogue in the nineteenth century.

As already pointed out, Galileo had recognised Newton's first law of motion, which essentially implies that the imposition of a constant velocity on a whole system does not affect its mechanics. So a transformation to a new system of reference that is in constant

motion with respect to the original one is referred to as a *Galilean Transformation*. The formal statement can, therefore, be made that ‘*Newtonian Mechanics and Gravitation is invariant under a Galilean Transformation*’. The reason for this is that, although all velocities are altered through the transformation, accelerations are unaffected and Newton’s second law of motion is unchanged.

This means that there was already an element of relativity in Newtonian mechanics and gravitation; it is relativity of space but not of time. This is not too surprising. To consider a simple example: suppose we have a train passing through a station but not stopping and we have an observer *A* standing on the platform. This train has a buffet car at the front, where a second observer *B* buys a cup of coffee. He then carries this back to his seat at the rear of the train, where he drinks it. Let’s consider the two events, the purchase of the coffee and its consumption. The observer *B* would regard his consumption of the coffee as taking place behind its purchase as he would naturally refer these events to their position in the train. Whereas the observer *A* on the platform, allowing for the motion of the train, would think that the consumption of the coffee would occur ahead of its purchase. So in Newtonian theory observers could, in a sense, disagree about where events took place but they would be in total agreement about the times at which they happened. Einstein’s theory would alter even that.

Newton’s *Principia* completely changed how we could think about nature: the universe is governed by a few simple laws which can be understood using mathematics, and the first of these was his law of universal gravitation. This point of view was criticised by some of his contemporaries, particularly by Leibniz. He complained that there was a serious absence of explanation of any mechanism by which gravity worked. He referred to Newton’s gravity as an ‘occult’ force verging on the blasphemous, which left no room for God. This was rather unfair to Newton as he acknowledged that he had not explained where his gravity came from and how it could operate across empty space. Newton, however, recognised that God had created the universe at some time in the past and in doing so had set its initial conditions. From then on scientific theory, like gravitation, could determine how it would develop. But Newton was no deist; he did not think that God was unconcerned with how his universe developed. God had created

the law of gravity by which the universe ran, but Newton believed that God could suspend it or modify it if he chose.

Generally speaking I think it is true to say that Newton, unlike Leibniz, liked to keep his science and theology separate, at least in published work. This opened the possibility for the two disciplines to proceed separately. Whereas in the seventeenth century almost all astronomers would regard their study as searching out the hand of the creator of the universe, after the Newtonian synthesis a new detached approach became possible and ultimately standard. This is reflected in the assessment of Newton by the great eighteenth-century French mathematician Joseph-Louis Lagrange (1736–1813), who said ‘Newton was the greatest genius who ever lived, and the most fortunate, for we cannot find more than once a system of the world to establish’.

The main field of application of Newtonian gravitation was the study of planetary motions in the solar system. From ancient times six planets were known, namely – moving outwards – Mercury, Venus, Earth, Mars, Jupiter and Saturn. After the invention of the telescope in the seventeenth century a number of satellites had been discovered going round Jupiter and Saturn. Those going round Jupiter could periodically go into eclipse as they moved into the planet’s shadow. The observed timing of these eclipses provided a method for estimating the velocity of light,<sup>9</sup> for the eclipses were observed to occur early when the Earth was closer to Jupiter and late when further away. This distance could vary by up to 2 AU, equivalent to a light travel time of about 15 minutes.

No new planet was discovered until late in the eighteenth century when William Herschel (1738–1822) first observed the planet subsequently named Uranus. This object was about twice as far away from the Sun as Saturn and just too faint normally to be seen with the naked eye. The planet can however be observed with even the smallest of telescopes and had in fact been observed on many occasions before its true nature was recognised by Herschel. On each of these occasions Uranus had been mistaken for a faint star and in many cases this had been recorded as such on a star map. The principal ‘offender’ was the first Astronomer Royal, John Flamsteed (1646–1719), who observed it on no less than six occasions. Flamsteed produced a



catalogue of accurate positions of over 3000 stars and among these were six observations of the position of Uranus, with the date of each observation recorded. This meant that, once the planetary nature of Uranus had been established, it was possible by studying historical records to find observations of its position in the sky covering a period of nearly 100 years.

In the eighteenth century a new subject of celestial mechanics developed; this is the detailed application of Newton's law of gravitation to the whole solar system. According to this law a planet moves in an ellipse around the Sun; but this is only the first approximation, which allows for the Sun's influence but ignores the contributions of all the other bodies in the solar system. Each planet is acting gravitationally on every other planet and body within solar system. Within celestial mechanics all these effects need to be included, which makes that subject fraught with complications and difficulties.

The recognised master of this field was the great French mathematician, Pierre-Simon Laplace (1749–1827). His major work, *Mécanique céleste*, ran to five volumes. The story (probably apocryphal) is told that, on presenting one volume of this work to Napoleon, he was asked 'Where is God within your theory?' Laplace is said to have replied 'I have no need of that hypothesis.' On hearing this story, that other giant of eighteenth-century French mathematics, Joseph-Louis Lagrange, commented 'Ah, it is a fine hypothesis, it explains many things.' Today most scientists would regard Laplace's statement as a principled, if perhaps rather pompous one, while they would see Lagrange's comment as merely flippant. But I wonder if this does display a certain hubris on the part of the science community. It certainly shows how far science and theology have gone their separate ways.

The discovery of Uranus provided fresh grist for the mill of celestial mechanics. The corpus of pre-discovery observations meant that there was a sound basis to build a theory for the new planet and precise predictions for its future motion could be confidently made. It was soon found, however, that there were substantial discrepancies between the theoretically-predicted and observed positions of Uranus. Attempts to modify the theory to remove these discrepancies were only partially successful and involved downgrading the reliability

of historical observations. By the 1840s over 150 years of data was available and some astronomers suspected that there might be an unknown planet beyond Uranus that was perturbing its motion. Two highly skilled mathematicians, John Couch Adams (1819–92) in England and Urbain Jean Joseph Le Verrier (1811–77) in France, examined the discrepancies in Uranus’ positions in the sky and independently predicted the existence and location of an unknown planet that could be the cause of the problem. They each handed their predictions to observational astronomers in their respective countries so that the unknown planet could be searched for. However, either through inertia or scepticism, nothing significant happened. Le Verrier eventually lost patience and sent his predicted location to the Royal Observatory in Berlin. Here within the first night of searching, September 22–23, 1846, the planet Neptune was recognised.<sup>10</sup>

This discovery of Neptune was a fantastic result and could be regarded as the high-water mark of Newtonian gravitation on which the discovery was based. Le Verrier assumed the mantle of Laplace. He thoroughly checked the positions of all the planets and found satisfactory agreement between the predictions of celestial mechanics and observed positions with one tiny exception. There was an unexplained precession of perihelion<sup>11</sup> in Mercury’s orbit of just 38 seconds of arc per century. This means, instead of being a fixed ellipse, Mercury’s orbit was slewing round at this tiny rate amounting to only one degree in about ten thousand years.

Le Verrier naturally looked for a similar explanation to the one that led to the discovery of Neptune. He sought an unknown planet in an orbit inside that of Mercury. This hypothetical planet was even given a name, Vulcan, and for about twenty years in the middle of the nineteenth century it was actively looked for.<sup>12</sup> Vulcan would be very difficult to observe. There must be many an astronomer who has never managed to see Mercury because it is always close to the Sun in the sky. Vulcan would be even more difficult to observe. There were a number of claims to have seen it, all of them subsequently recognised as spurious. For example, on 26 March 1859, a French country doctor and keen amateur astronomer claimed to observe a black spot on the surface of the Sun. Normally this would be recognised as a sunspot, but this feature appeared to move at a regular rate across the surface

of the Sun before disappearing over the limb. For a while Le Verrier and the rest of the astronomical community were convinced. Later an international effort was made to find Vulcan at the total eclipse of the Sun on 29 July 1878, when the Moon would cut off the glare of the Sun and might allow the putative planet to be seen. There was one such claim at the time, but it was generally thought that this was merely a known star seen near the Sun.

After the failure of 1878, the astronomical community abandoned the idea of searching for this interior planet and accepted that Vulcan did not exist. Le Verrier's analysis of Mercury's orbit was checked and found to be essentially correct; in fact the discrepancy was found to be slightly larger at 43 arc seconds per century. Scientists, however, could not yet bring themselves to accept that Newton's theory of gravity could be wrong; the 43 arc seconds per century was just accepted as an *ad hoc* correction in celestial mechanics.

Meanwhile, during the late eighteenth to mid-nineteenth century new fundamental forces were being investigated. Laws in the theories of electricity and magnetism associated particularly with the names of Coulomb (1736–1806), Ampère (1775–1836) and Faraday (1791–1867) were being established. Clearly electricity and magnetism were just as fundamental as gravity, but they were more complicated and very clearly connected in some way. James Clerk Maxwell (1831–79) unified the two apparently separate theories as the theory of electromagnetism in 1873. This is usually stated in the modern form as four differential equations. Maxwell also showed that his equations predicted the existence of electromagnetic waves travelling at a fixed speed  $c$  which could be deduced from his equations. He identified this with the speed of light, a conclusion that was experimentally justified by the discovery of radio waves at the end of the nineteenth century.

The study of electromagnetism was at that time a more active field of scientific research than celestial mechanics. Astronomy was giving place to physics as astronomy's traditional area of interest, gravitation, seemed almost worked out – cosmology had not yet been invented. One important feature of Maxwell's equations is that they were **not** invariant under the Galilean transformation. It seemed necessary to dispense with this element of relativity. After all Newton himself had regarded it as superfluous, and, although his motives for

this may have been theological rather than scientific, perhaps he had been scientifically right as well. It was postulated that all space was filled with a luminiferous aether. This was the medium through which electromagnetic radiation moves at its constant speed  $c$ .

Since the Earth itself is moving round the Sun at a speed of about 30 km/s, which is about a ten-thousandth of the speed of light, it surely follows that the Earth is moving through the aether and this motion should be detectable. An attempt was made to measure this motion in the famous *Michelson-Morley Experiment*,<sup>13</sup> which was first performed in 1887. This sought evidence for variations in the speed of light in different directions and found there was none, leaving an awkward hiatus in the fundamental theory of electricity and magnetism.

With hindsight we can review the situation in quite a simple way, and hopefully with clarity. Clearly the velocity of light  $c$  is a fundamental physical constant, but constant relative to what? There are only three simple possibilities:

1	Constant relative to the source	Like projectiles	Seems reasonable
2	Constant relative to the medium	Like sound waves	Seems reasonable
3	Constant relative to the observer	Previously unknown	Seems totally absurd!

1. The clearest example of the first possibility is a fast bowler in cricket. By running in at speed the bowler adds about 15 mph to his speed of projection. This possibility had been ruled out in the theory of electromagnetism. Moreover there is very strong evidence in double stars that this possibility cannot be right.<sup>14</sup>
2. Despite the fact that this is what happens with sound waves, for light it requires the aether. The Michelson-Morley Experiment showed that the aether does not exist. Again this possibility is ruled out.
3. This possibility is utterly counterintuitive but is included as a logical possibility. So to quote Sherlock Holmes ‘Once *you* eliminate the *impossible*, whatever remains, no matter how improbable, must be the truth.’

So we are forced to the conclusion that the speed of light is constant with respect to *the observer*. This is one of the cornerstones of the *Special Theory of Relativity* (SR) which was formulated in 1905 by Albert Einstein (1879–1955). This theory introduces a more complex form of relativity; it is a relativity not just of space like Galileo’s but also of time. To illustrate the latter point, consider the following:

*Thought Experiment:* Suppose we have a station platform of length 100 m and that a train, which is 110 m long, passes through the station without stopping or even decelerating. At the moment the front end of the train reaches the front end of the platform a flash of light is sent out in a backward direction. Now at this moment the train is alongside the platform but with a 10% overlap at the rear. It will simplify the arithmetic if we assume that the train is moving at 10% of the speed of light – although this is absurd, it is not illogical. Then it is easy to see that the flash of light will reach the rear end of the platform at the same instant that the rear end of the train does. This flash of light will have travelled 100 m along the platform but 110 m along the train. Since the speed of light is the same for both systems, it follows that the time interval between the events of emission and reception of the flash must be 10% longer on the train than on the platform.

The argument that has just been given is not completely rigorous but is correct to first order. When made exact it is found that the transformation from one inertial system to another is not the *Galilean transformation* but its generalisation, which is called the *Lorentz transformation*. Under this transformation the equations of electromagnetism are invariant.

Within SR time is effectively a fourth dimension; it has the same algebraic status as the three space dimensions but appears in the equations with a different sign. This means that instead of talking about space we should talk of spacetime. In this 4D world a point specifies not just a location but also a time, consequently it represents an *event*. A body’s history is a continuous sequence of events, represented by a curve in 4D spacetime; this is called its *world line*. A free particle, that is one not subject to any external force, moves in a straight line and at a constant speed. We can, therefore, say that the world line of a free

particle is a straight line not just in space but also in 4D spacetime.

This geometric view of special relativity was not in Einstein's original presentation of the theory but was recognised shortly afterwards by Hermann Minkowski (1864–1909). SR had reformulated Newtonian mechanics but the only thing that was lacking was an independent theory of gravity. Einstein, however, was far from finished with relativity. He accepted Minkowski's geometric representation of the subject and developed it in an extraordinary way. As Galileo had first recognised, gravity is a unique force in that it affects all bodies in the same way. Consequently Einstein found a way of building the effects of gravity into the geometric structure of the spacetime. Whereas the geometry of SR was fixed as a modest extension of the geometry of Euclid, Einstein now developed the *General Theory of Relativity* (GR) in which the geometry of the spacetime is now determined by the distribution of matter and energy. The complicated equations that effect this determination are, naturally enough, called *Einstein's Equations*.<sup>15</sup>

An example of a non-Euclidean geometry is provided by the *surface* of a sphere. This is just two dimensional and therefore easy to visualise, unlike 4D spacetime. There are no straight lines confined to the surface of a sphere, but the shortest distance between two points is still defined. On the sphere it is a great circle and this is termed a *geodesic*. In spacetime, geodesics are similarly defined but are of three distinct kinds; they are *spacelike* and *timelike*, depending on which coordinate change dominates, and, where there is an exact balance between the two, they are termed null. Within GR there are the following geodesic principles: (i) the world lines of free particles are timelike geodesics; (ii) the world lines of light particles (photons) are null geodesics. It is often said that within GR 'Spacetime tells matter how to move, while matter tells spacetime how to curve'.

Einstein's GR has been subjected to many observational tests and to date has been successful in them all. Most recently there has been the successful detection of gravitational radiation, a prediction of Einstein's theory completely lacking in that of Newton. Indeed wherever the two theories have differed it has always been Einstein's that has proved correct. The first example of this was the 43 arc second advance in the perihelion of Mercury, which is completely accounted

for in GR but was a nasty lacuna in the fabric of Newtonian celestial mechanics.

It took Einstein nearly ten years to progress from SR to GR. Once completed, however, he recognised that GR was very well suited to cosmology and he produced the first cosmological model of the universe in 1917. At that time it was not known that the extragalactic universe was expanding; in fact most people believed our galaxy comprised the whole universe.<sup>16</sup> Einstein, therefore, was concerned to produce a model that was in static equilibrium. To achieve this he introduced a new feature into his equations, the *Cosmological Constant*. It is always represented by the Greek letter  $\Lambda$  and produces a long-range repulsive force. Einstein needed this to balance the natural attraction of gravity. This model was interesting in that space was finite and closed up on itself, a 3D analogue of the surface of a sphere. However, it was clearly wrong as twelve years later Edwin Hubble (1889–1953) demonstrated that the universe was expanding. Einstein then realised that  $\Lambda$  was not needed and he described its introduction as ‘the biggest mistake of my life’. But was it? In the 1990s it was recognised that the expansion of the universe is accelerating. This is now ascribed to *dark energy*, although nobody has any clear idea what that means. It certainly mimics the effect of a cosmological constant and one whose repulsive force now dominates over the attractive force of matter within the universe.

In this article I have concentrated on a historical account of the development of science; I have indulged in very little theological speculation. I feel, however, that some comment is required on the theological significance of the expansion of the universe. Recently I was asked ‘Do you believe in God or in the Big Bang?’ This struck me as an extraordinary question. The simple direct answer would have to be both! But the questioner clearly did not understand anything of the historical background of the Big Bang theory. The term ‘Big Bang’ was coined by Fred Hoyle (1915–2001) in a radio broadcast; it was intended to be pejorative. Hoyle along with a number of other cosmologists, most of whom had an atheistic worldview, were not prepared to accept that the universe had been created at some point in the finite past. They preferred to believe that it had always existed and that there was no need to account for an event of creation. They

accepted that the universe was expanding but argued that, as it did so, new material was created to fill the gaps caused by expansion.<sup>17</sup> This ‘Steady-state theory’ was for some time a genuine alternative to the Big Bang theory but was effectively demolished by the discovery of the Cosmological Microwave Background Radiation<sup>18</sup> by Arno Penzias (1933–) and Robert Wilson (1936–) in 1965.

Since that time the Big Bang has been effectively unchallenged, although presented in many different forms. I would argue that there is no detailed scientific consensus about the precise nature of the Big Bang of the kind that there was about gravitation after the discoveries of Newton and Einstein. Today, however, we must accept that the observed expansion of the universe presents us with an apparent singularity around 13.7 billion years ago. It appears that at this singularity the known laws of physics break down. I know we must be careful of arguments based on ‘God of the gaps’, as Charles Coulson (1910–74) warned us. But this is slightly different – maybe ‘God of the impasse’ – and there is at least a temptation to identify the Big Bang with the biblical account of creation. At first sight the existence of the Big Bang presents a bigger problem for science than for theology.

## Notes

1. Presented at the Scottish Church Theological Society Conference at Peebles Hydro on 16th January 2018.
2. Newton published three editions of his major work during his lifetime, all in Latin. The first English translation of the third edition was made by Andrew Motte (1696–1734).
3. Ptolemy’s original work written in Greek as *Mathēmatikē Syntaxis* was for many centuries lost in Europe. It was preserved through translation into Arabic and then later into Latin and was known as *The Almagest*.
4. In his book *The Sleepwalkers* (London: Hutchinson, 1959) Arthur Koestler described *De revolutionibus* as ‘The Book Nobody Read’. While disagreeing with this conclusion Owen Gingerich still used



- this as the title for his own book on Copernicus (New York: Walker & Co, 2004).
5. A minute of arc is one sixtieth of a degree. For comparison this means that Tycho was able to measure the position of planets to an accuracy of about a thirtieth of the angular diameter of the Sun or Moon. All this without the aid of a telescope!
  6. The other focus is empty! A point that probably displeased Kepler, who did not find the ellipse a particularly beautiful curve.
  7. This is a unique feature of gravity in that all bodies are affected in the same way. For other forces the effect depends on the nature of the body. For example, for an electric force, the effect of the electric field depends on the body's charge.
  8. Ellipses and hyperbolae are mathematically related as they are both plane sections of a cone. I have omitted the parabola which is the special case separating the two classes of conic section. Ellipses are closed curves but hyperbolae are open and formally extend out to infinity. Since planets are bound to their star, their orbits will be ellipses. Hyperbolae, on the other hand, represent fly-past orbits that are made use of with space probes.
  9. The velocity of light in a vacuum  $c$  is a basic physical constant equal to just under 300,000 km/s (299,792,458 m/s to be exact). It is exact because the number just quoted effectively defines the metre. The first estimate of  $c$  in 1676 by Ole Rømer (1644–1710) was an underestimate by about 25%.
  10. As in the case of Uranus, there had been a number of pre-discovery observations of Neptune, which is only about six to seven times fainter than Uranus and therefore, still well within the range of even a small telescope. The earliest such observation seems to have been made by Galileo in 1612.
  11. Perihelion is simply the point in a planet's orbit where it is closest to its star. A second of arc is one sixtieth of a minute of arc. The tiny precession mentioned here is what remains once all the planetary perturbations, which are much bigger, have been removed.
  12. An excellent account of the search for Vulcan is given in Thomas Levenson's book *The Hunt for Vulcan* (London: Head of Zeus, 2015). It has the intriguing subtitle *How Albert Einstein Destroyed a Planet and Deciphered the Universe*.

13. It might be said that it is all done by mirrors! A coherent beam of light is split by a semi-silvered mirror. The first part goes straight through and the second part is deflected at a right angle. Each part is then reflected back to the semi-silvered mirror. This time the first part is deflected at a right angle while the second part goes straight through. The two beams are combined to produce an interference pattern. This interference pattern showed no diurnal change despite the rotation of the Earth and the changing alignment of the apparatus with respect to the aether.
14. I mention this as the evidence from spectroscopic binaries is overwhelming. These binaries appear to be single stars but their binary nature is deduced from spectral analysis. In some cases there are two sets of spectral lines, and, from the varying Doppler shifts in these lines, the orbital velocity can be derived. Any difference in the velocity of light from the two stars would be immediately detectable. This is another negative result like the Michelson-Morely experiment but much clearer.
15. These equations are formidable tensor equations and it is their complexity that frightens off many people from GR.
16. Up until the late 1920s most people thought that there was just a single galaxy to which the Sun belonged, and beyond that there was just empty space. It was not recognised that the so-called spiral nebulae were actually external galaxies.
17. Hoyle's version of the Steady-State theory was the most complete in that he provided a revised version of Einstein's equations that included a term to account for the continuous creation of matter.
18. This Cosmological Background Radiation is recognised as the relic radiation from the Big Bang, emitted about 400,000 years after that singularity.