Chapter 2

History

2.1 Introduction

Cosmology is the speculative component of astrophysics, which is the science that interprets astronomical data by using the laws of physics and chemistry. Historically the three concepts, cosmology, astrophysics and astronomy, which included astrology, were integrated into a single pursuit, driven by religious dogma. As scientific data gradually became incorporated, religious considerations diminished in importance, but have still not been eliminated completely from the mix.

Before the invention of telescopes astronomy depended on naked-eye observations, using instruments like quadrants, gnomons, sextants and astrolabes. The Great Pyramid of Giza, in its original truncated form, is claimed (Tompkins, 1978) to have served as a naked-eye observatory. The sophistication of pre-dynastic Egyptian mathematics and astronomy, before its mysterious decline, was only matched again in the Western world during the 17th century CE[1]. Although it led to the development of incredibly accurate calenders, the evidence remained insufficient to challenge philosophical models of the cosmos.

Classical Greek science developed from the transfer of basic Egyptian know-how by visiting scholars, such as Pythagoras (*ca.*550 BCE), who worked as a priest in Egypt for more than twenty years. Of decisive importance was the recognition of a spherical Earth, which inaugurated a dramatic change in cosmological thinking. Immediately the observed cyclic motion of the heavenly bodies started to make logical sense, eventually culminating in the

[1] Common Era.

J.C.A. Boeyens, *Chemical Cosmology*, DOI 10.1007/978-90-481-3828-9_2,

Ptolemaic cosmology, which remained unchallenged in the western world for a thousand years.

Apart from Pythagoras, new ideas emerged in the Ionian commercial centres, inspired by Thales of Miletus and his intellectual descendants. The correct prediction of a solar eclipse enabled them to claim that the movement of heavenly bodies was dictated by natural laws, rather than the whims of gods.

The innovations of Thales and his followers are still rated as one of the greatest achievements of human intellect, but without experimental support could never develop into scientific cosmology. Thales himself had a problem to identify a means of support for his disc-like earth. His successor, Anaximander, saw the need to abandon the notion of absolute up and down, as being directed relative to the centre of the spherical earth, that hence needs no support. The difference between heaven and earth was still ascribed to the separation between the cold and wet that condensed into a solid earth with oceans, against the partially evaporated hot and dry, becoming air and mist surrounded by a fiery cosmic sphere. The remaining breathing holes through the rotating mist are visible to mankind as the sun, moon and stars.

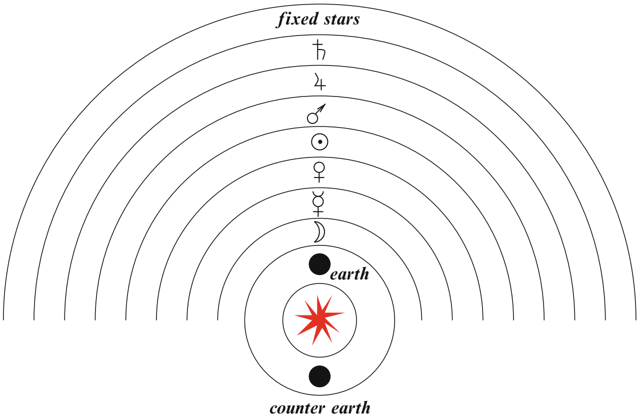
A major complication with this cosmic model was the Pythagorean demand of perfect circular orbits for all celestial bodies. The more accurate astronomical observations became, the more complicated the required corrections to restore the circular pattern. The authority of Pythagoras and Thales must have been enormous, especially as Plato also endorsed the geometrical perfection of the cosmic composition. The planets, including the sun and the moon, like the fixed stars, circled the earth on concentric spheres with numerical regularity, each contributing its harmonious pitch to the music of the spheres.

The enduring proposition of Pythagoras was that fundamental reality is not to be found in the elementary composition of matter, but in an underlying structure, that imparts a distinctive character to all things, and which can only be understood in terms of numbers. This conclusion generalized the discovery of an exact correlation between the lengths of musical strings and the notes they produce. This proposition was re-interpreted by Plato who substituted Form, for Number, as intelligible structure, instead of material elements. In these terms creation consists in bringing together the eternal forms with imperfect matter to produce the temporal world. By this procedure a demiurge fashioned the physical world on the model of forms, using space as his material[2]. This is not creation *ex nihilo*, out of nothing.

The evidence that musical scales and planetary motion both obeyed the same numerical rules was simply too attractive to discount as coincidence and nobody dared to contradict the interpretation of the masters.

2.1.1 A Heliocentric Model

Trying to bring the observed motion of the planets better into line with their philosophy, Philolaus, later in the 5th century BCE, modified the geocentric view and posited a model in which the earth, a counter-earth, the seven planets and the fixed stars all circle about an (unseen) central fire. The earth's revolution around the fire was believed to occur on its own axis during the period of a day and a night. However, the planetary orbits still deviated from ideal circles and the model was forgotten until it was mentioned again by Plato. When a lesser-known philosopher, Aristarchus of Samos developed the concept of a heliocentric universe (270 BCE), his ideas also fell victim to the authority of the great men, not to be revived again for almost two thousand years.



The world was to fall into the same trap again many times. Reluctance to question the pronouncements of Aristotle, the Hebrew Bible, Georg Stahl – the champion of the phlogiston theory – and many other authorities whose ideas became outdated, continues to plague the development of science.

[2]Plato, *Timæus*, 4th century BCE dialogue.

Equally distinguished savants like Galileo, Charles Darwin and Lavoisier suffered abuse for their temerity to contradict the demi-gods of science.

To conclude the story of Ionian and Pythagorean cosmology, their ideas were slowly degraded by those who lacked the ingenuity, but not the desire, to refine the original model. All manner of irrelevant data, supposedly in support of the perfect geocentric universe, were added to strengthen the argument, making it progressively more difficult to revise the basic model, in the teeth of public opinion. In effect, a variety of sequences were postulated to be sympathetically linked to the seven planets, as shown in the Table, reconstructed from a variety of sources (MacNeice,1964; Graves, 1966; Priesner & Figala, 1998). In the sense that cosmology should be consistent with all available scientific knowledge these correlations may be seen as an effort to demonstrate exactly that. Superficially it shows support of the model from number theory, geometry, astronomy, alchemy, natural history, poetry and theology. In reality the scientific content of these correlations is nil, being no more than a summary of mystic traditions, secret formulae and recipes for horoscopy. The serious astronomy of classical Greece became hopelessly

Number	*Planet*	*Symbol*	*Metal*	*Gemstone*	*Colour*	*Letter* *	*Tree* #	*Bird* #	*Day*	*Archangel*
1	*Moon*	☽	Ag	*Ruby*	*Orange*	S	*Willow*	*Hawk*	*Mon*	*Gabriel*
2	*Mercury*	☿	Hg	*Beryl*	*Green*	N	*Ash*	*Snipe*	*Wed*	*Raphael*
3	*Venus*	♀	Cu	*Lapis Lazuli*	*Blue*	H	*Hawthorn*	*Night-crow*	*Fri*	*Sariel*
4	*Sol*	☉	Au	*Sard*	*Red*	B	*Birch*	*Pheasant*	*Sun*	*Uriel*
5	*Mars*	♂	Fe	*Chrysotile*	*Yellow*	L	*Rowan*	*Duck*	*Tue*	*Michael*
6	*Jupiter*	♃	Sn	*Chalcedony*	*White*	D	*Oak*	*Wren*	*Thu*	*Raguel*
7	*Saturn*	♄	Pb	*Garnet*	*Violet*	F	*Alder*	*Gull*	*Sat*	*Remiel*

* ***Original seven consonants, invented by the three fates***

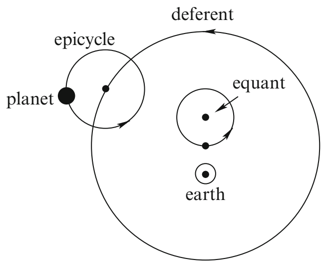
Ogham alphabet

entangled with astrology and dogma without producing further insight into the nature of the cosmos, despite the rhetoric of the famous classical philosophers, Socrates, Plato and Aristotle. Plato mooted the possibility of using various combinations of circular motion to predict planetary positions, without proposing the model as a physical description of the universe. However, in time this model led to the notion of epicycles, on the basis of which Ptolemy formulated the first standard model of cosmology that remained unchallenged in the western world from the second to the 17th century.

2.2 The Almagest

The cosmological model, which is generally known as the Ptolemaic system was formulated in the second century by Claudius Ptolemæus in Alexandria. It was published in his 13-volume treatise, which became known to the Arabs as the *Almagest*, the name, meaning *The Greatest*, still used today.

To prove that the earth was fixed at the centre of the universe Ptolemy used the observation that all falling objects drop to the centre of the earth. He accepted the traditional order of celestial objects, rotating on crystal spheres around the earth, but realized that the implied circular motion had to be replaced by auxiliary circular motion along epicycles on circular deferents. Deferents are large circles centred on the earth and epicycles are small circles whose centres moved around the circumferences of the deferents. The sun, moon and planets move around the circumferences of their own epicycles. This model was still insufficient to account in full for the motion of the



planets. The final refinement introduced by Ptolemy was to move the centre of the deferent away from the earth and to define an imaginary point, called the *equant*, on the diameter that contains the centres of both earth and deferent, at the same distance as the earth, but on the opposite side of the centre. To describe the orbit of a planet the centre of the deferent is now assumed to move along the circle centred on the equant and going through the midpoint between earth and equant. The oscillating deferent carries the planetary epicycle through the same rocking motion, with the planet following the circular motion along the circumference of the epicycle.

This ingeneous construction served several purposes. Perhaps the most important was to restrict the motion of each heavenly body to an orbit, defined by three perfect circles, while accounting for the irregular observed motion of the wandering planets through the skies. Of almost equal importance was the mathematically precise description of the periodic motion of celestial objects, that the model provided.

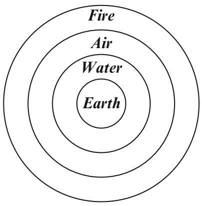
Beyond the outermost planet, the crystal sphere that carries the fixed stars, was located, showing the placement of the twelve constellations of the zodiac. For the first time it became possible to draw up accurate maps of the sky to coincide with important moments or events, past, present or future, in the life of individuals or nations. This is the basis of astrology, in which Ptolemy was as expert as in astronomy. For the purpose of our discussion this issue is of no importance, but for millions, over millenia, it provided a method to avoid disaster, make informed decisions and foretell the future.

Outside the sphere of the fixed stars Ptolemy proposed other spheres, ending with the *primum mobile* to represent the prime mover of Greek philosophy.

2.3 Medieval Cosmology

For a millenium, after the conversion of Constantine's mother, thinking in the western world was dominated by the spread of Christianity, orchestrated by the philosopher-saints, Augustinus and Thomas Aquinas. Their main concern was to align the Ptolemaic system, Aristotelian philosophy and the practice of astrology with their holy scriptures.

The major stumbling block that inhibited the development of commonsense cosmology in the middle ages was the dogmatic adherence to Aristotelian physics, and in particular, the theory of motion, based on the idea that terrestrial and celestial bodies moved in fundamentally different ways. This difference relates to the natural distribution of the four elements of which the world was made up, and shown in the diagram below.



Each element has a tendency to move towards its own sphere. If, by some unnatural action, an earthly object is moved beyond the sphere of earth, it strives to return where it belongs. The bigger the object the faster it falls back. On approaching its own sphere more closely the more friendly environment stimulates the natural motion as the object accelerates towards its target. By this theory an object which is launched in a horizontal direction should drop down to its natural place as soon as the thrust is discontinued. The observed inertia whereby the object maintains its horizontal motion was explained by assuming that the air continues to push the object in its initial direction.

The same argument implied that celestial objects should accelerate towards higher spheres. Beyond the ring of fire the realm of Ptolemaic planetary spheres commenced. The celestial bodies carried by these spheres consisted of more subtle matter than terrestrial objects. The god-like spirits which controlled the seven planetary spheres were now identified with the seven archangels. The fundamental characteristic of these crystal (transparent) spheres was that they moved in the perfect mode of permanent, uniform, circular motion.

The fixed stars were supposed to move with the eighth sphere, and beyond that was heaven, the ninth immovable sphere. Aristotle identified this sphere as the prime mover, responsible for initiating the motion of all the other spheres, down to all things that move on earth. Thomas Aquinas identified the prime mover as God, who was responsible for the creation of an orderly, harmonious universe. The natural tendency of celestial objects to approach the highest sphere provided the mechanism which enabled the ascension of sanctified beings such as Enoch, Elijah, Jesus, Maria and Mohammed.

The astronomy behind the Ptolemaic system was of secondary importance, if not totally irrelevant, to the philosophers of the middle ages. An idealized version of the system, stripped of irrelevant epicycles and deferents, was elevated into revealed dogma and vigorously defended against heresy. An important distinction was made between the perfection in heaven, with all celestial bodies in perfect circular motion, and the irregular motion of earthly objects. Escape from this dogmatic strait-jacket of Thomism was a long and arduous process. The authoritarian philosophy of biblicized Aristotelianism obviated the need of scientific enquiry and the activities of free-thinkers and heretics were jealously controlled by the catholic church.

What is commonly referred to as the Copernican revolution, started with the birth of Copernicus and lasted until the death of Newton – a period of 250 years. This period of renaissance corresponds to the transition from medieval cosmology to the first scientific description of the solar system. It is instructive to compare the lifespans of the major players:

Nicolaus Copernicus	1473 – 1543
Tycho Brahe	1546 – 1601
Galileo Galilei	1564 – 1642
Johannes Kepler	1571 – 1630
Isaac Newton	1642 – 1727

It was Copernicus who revived the heliocentric model proposed almost two thousand years earlier by Aristarchus. As before, the proposal failed to generate meaningful interest outside of a small circle of initiates. So little in fact that Copernicus postponed publication of his ideas literally to his dying day and, not to give offence, he dedicated his work to the pope. Perhaps he should not have bothered because it still raised no comment until 1616, when it was condemned by the church, save as a calculating device (Hall, 1963). Although Copernicus rejected the Ptolemaic system, he accepted the Aristotelian theory of motion, and only managed to account for the observed planetary positions by a combination of deferents and epicycles centred on the stationary sun. It was the moving earth that annoyed his peers.

Tycho Brahe, the great astronomer of the next generation clearly appreciated the simplicity of the heliocentric model but, even more conservative than Copernicus, refused to consider a moving Earth. As a compromise he made the five planets spin around the sun, while the sun and moon revolved about the earth. This device predicted the same relative motion of the heavenly bodies as the Copernican model.

Tycho's devotion to astronomy was stimulated first by the prediction of a solar eclipse and secured by his personal observation of the famous new star (nova) of 1572 in Cassiopeia. He managed to demonstrate that the shining object, brighter than Venus and visible in broad daylight, was one of the fixed stars in the process of disintegration. This observation was a serious blow to the Aristotelian concept of the immutability of the heavens.

He made it his life's work to correct the astronomical tables by more accurate observations. He devoted enormous effort to the enigmatic motion of the planet Mars and towards the end of his life invited his younger collaborator, Johannes Kepler, to use these data to find the correct description of the Martian orbit.

2.3.1 Johannes Kepler

Kepler studied the problem for twenty years before coming up with a solution, only to find that nobody, not even Galileo, took him seriously. However, Kepler himself was convinced that it was impossible to fit the orbit to Tycho's data by any possible combination of circles. He found the answer by assuming an elliptic orbit.

The Kepler solution for Mars was shown to work for all planets, including Earth, assuming the Copernican heliocentric model. Kepler formulated his results in the form of three laws (Stephenson, 1960):

1. The law of elliptic orbits: The planets move in ellipses about the sun

which is located at one focus of the ellipse.

2. The law of areas: The line joining any planet to the sun sweeps out equal areas in equal intervals of time.

3. The harmonic law: The square of the period of any planet about the sun is proportional to the cube of its mean distance from the sun.

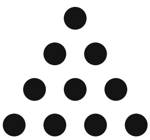
In symbols the harmonic law is formulated as $T^2/r^3 = k$.

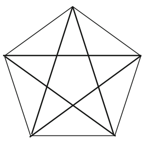
Nothing demonstrates the power of authority and dogma better than the failure of Kepler's description of the solar system to convince the renaissance world.

Whereas the dogma of uniform circular motion demanded that the moving planet traverse equal arcs in equal intervals of time, Kepler discovered the new uniformity of equal areas in equal times to be valid for any ellipse, including the circle. By adding an additional focus to planetary orbits the need of epicycles was eliminated and the wandering planets were shown, for the first time, to follow harmonious paths around the sun. This discovery should have destroyed the Ptolemaic system for good. It failed. Not even Kepler's discovery of a new supernova, that remained visible for 17 months, was sufficient to shake the world's faith in a permanent sphere of fixed stars.

Kepler's adherence to the Pythagorean ideal of an harmonious planetary system and astrology has been commented on negatively by several modern critics as misguided mysticism. My reading of Kepler's ideas is different.

He was familiar with the five regular Platonic solids. Like Pythagoras he accepted a fundamental relationship between physical reality and number, manifesting itself in constructs such as the tetraktys and the golden ratio, shown below. He surmised that the distances of the heavenly bodies from





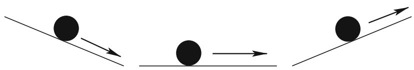
each other somehow correspond to musical intervals as in the Pythagorean harmony of the spheres. Although a final solution to the problem eluded him, he stated that ″this geometrical proportion (golden ratio) served the Creator as an idea when He introduced the continuous generation of similar objects from similar objects″ (Coxeter, 1989). He rejected the idea of an infinite universe, showed how to relate affine geometry to the more general projective geometry and explained the symmetry of snow flakes by the close-packing of equal spheres, self-similar to the regular bodies inscribed within planetary orbits.

2.3.2 Galileo

It seems odd that Kepler, who openly supported the Copernian system in writing, never had to face an inquisition, while Galileo was condemned for what appears to be legitimate astronomical observations. A likely reason is that the Aristotelian perfection of the heavens was dogmatically more important than the computational basis of astronomical and astrological predictions, whether Ptolemaic or Copernican. Galileo offended the dogma by reporting his suspect telescopic observations of irregular features on the perfect surface of the moon and spots on the face of the sun. He compounded this sin by argueing that there was no difference in type between terrestrial and celestial motion. Instead, he distinguished between natural motion, which is uniform and circular, and forced motion, which is accelerated and rectilinear. Accordingly it is logical that the earth should move in a circle, like the other planets, and for the solar system to be centred on the sun. Bodies that fall back to the surface of the earth are not seeking the centre of the universe, but are moving by their natural tendency to become re-united with their own.

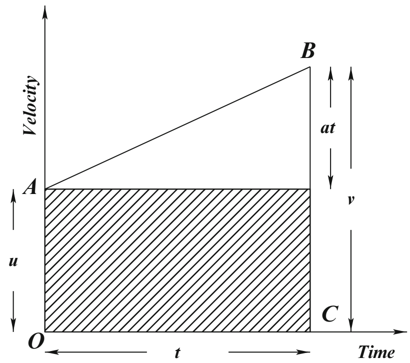
Galileo was right about many things, like contradicting Aristotle on the motion of different size bodies in free fall. They all fall equally fast. He was totally wrong in others. In a dispute with Kepler he argued that tidal motion was due to the rotation of the earth, rather than ″the moon's dominion over the waters″[3].

Galileo formulated some mechanical principles that enabled Newton to establish the physical basis of Kepler's laws. By noticing that a ball which rolls on a plane that slopes downward is accelerated and one on a plane that slopes upward is retarted, he argued that motion along horizontal planes should be uniform and perpetual. This view represents an important advance



[3]Translations of Galileo's work in English include: Drake (1953); Crew & de Salvio (1914)

on Aristotle, but falls short of Newton's law of inertia. When Galileo refers to a horizontal plane the motion is still implied to be circular, around the globe. The only objects in rectilinear motion are those found outside their proper places, arranged badly, and therefore in need of being restored to their natural state by the shortest path. Galileo's proposition that the distance (s) traversed during uniform accelerated motion is proportional to the square of the elapsed time (t^2) has a simple geometrical proof.



Galileo's Acceleration Formula The acceleration (a) represents the velocity increase in unit time. The total increase over a period t is therefore given by at. Hence the final velocity is $v = u + at$, where u is the initial velocity. A graph of the acceleration is given by the straight line AB, on axes of velocity *vs* time. The distance traversed at uniform velocity u over a period t is given, by definition, as $s = ut$, which corresponds to the area of the shaded rectangle. The total area OABC represents the distance traversed in the accelerated motion, *i.e.*

$$s = ut + \frac{1}{2}at^2$$

By equating uniform and circular motion it is natural for the earth to move in a circle, not an ellipse, but without a law of gravitation Galileo could never present a coherent discussion of centrifugal effects. Objects kept on flying away from the rotating earth as from a potter's wheel.

It seems that Galileo distanced himself from Kepler to demonstrate his respect for traditional dogma, but, by denying the difference between heaven and earth, this concession was not enough to protect himself against the Inquisition.

2.4 The Mechanical Universe

Once Galileo had demonstrated the inconsistencies in Aristotle's theory of motion and Kepler had formulated the laws of planetary motion, the only remaining obstacle to the development of a mathematical model of the solar system was the law of inertia, still based on uniform circular motion. This final problem was removed by the French mathematician and philosopher, Descartes.

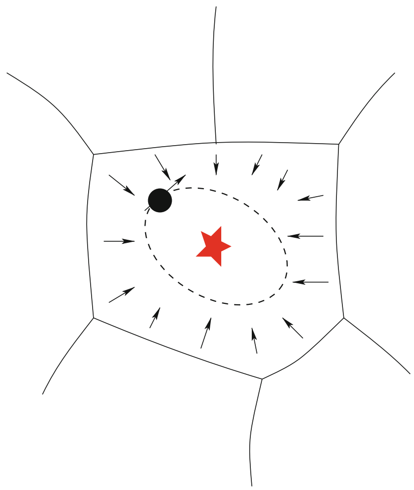
2.4.1 Descartes

René Descartes (1596 – 1650), who also published under the latinized name Renatus Cartesius, operated on the assumption that understanding of the physical world was contingent on the formulation of a sound metaphysical model or logical framework, drawing its first principles from reason. As the most fundamental principle he accepted a conservation law that demands the quantity of motion in the universe to remain constant. He equated matter with extension, which must therefore fill all space.

Motion in such a plenum would be impossible if all matter were rigid. In addition to opaque gross bodies he therefore postulated a transparent aether with the ability to transmit motion between solid objects, and material light, eminating from the sun and stars, plastic enough to fill all gaps between particles of matter and aether. As the universe is completely filled, motion consists of a rearrangement that involves constant impacts of particle on particle. To include aether and light with ordinary matter, these particles were assumed infinitely divisible.

Under these conditions any movement tends to create a vortex. The solar system is such an aetherial vortex with the sun at its centre. The planets are swirled around the sun by the aether. A planet, in turn, is at the centre of a subsidiary vortex, which may carry satellites, like the moon, around. On a larger scale the universe is made up of solar vortices centred on stars, like the sun, and fitting together like a foam, to fill all space.

The aether of a rotating vortex tends to recede from the central star under centrifugal pressure which becomes visible as light, emitted by the star and reflected by the planets. Because of its confinement in the foam-like structure the aether exerts an inward pressure on the planets. The reason why planets are not pushed into the central star is because they are in a state of uniform linear motion. Under aetherial pressure the direction of this motion changes continually and in the state of balance the planet stays on a closed characteristic orbit around the sun. Although Newton scoffed at the Cartesian model he gave the law of inertia in this exact same form,



replacing the inward pressure by the law of gravitation. Newton's third law is a paraphrase of the Cartesian conservation of motion.

On a local scale gravity was explained by fast-moving aether particles pushing down on more sluggish earthly matter, the same mechanism that shapes spherical water droplets.

Descartes described the sunspots discovered by Galileo as an accumulation of coarse material, which could eventually prevent emission of light and collapse of the vortex into a planet, to be captured into a neighbouring stellar vortex.

Cartesian cosmology, the first of several mechanical models of the universe, was taken seriously, especially in continental Europe, for a whole century. It was a theory of everything and a good example of rampant speculation, unchecked by experimental observation. Across the English channel Francis Bacon (1561 – 1626) inspired a generation of scientists to rely on empirical evidence, immune against experimentally untestable models, such as the Copernican system. The future of science clearly lay somewhere between these two extremes. The simplicity and beauty of a scientific hypothesis, if not in contradiction with observation, should be of decisive importance when comparing rival theories.

2.4.2 Newton

By the middle of the seventeenth century the final stage of renaissance cosmology by the synthesis of empirical data and reasoned conjecture was in sight. Tycho Brahe had generated the reliable data and Descartes had provided ideas to spare. Kepler was responsible for systemising Tycho's data into a useful form and Galileo started the revolt against authority that liberated Descartes' fertile mind. The final thrust required the refinement of Cartesian ideas to extract those features in common with Kepler's model.

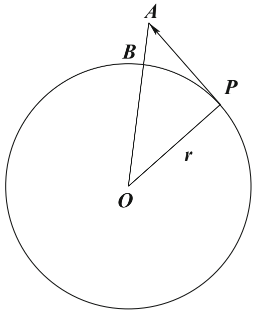
This final thrust, which centred around Isaac Newton, turned into an unseemly squabble with his contemporaries Robert Hooke (1635 – 1703), Edmond Halley (1656 – 1742), Wilhelm Leibniz (1646 – 1716), Christiaan Huygens (1629 – 95), Robert Boyle (1627 – 91), Christopher Wren (1632 – 1723) and whomsoever else contributed to the effort. Newton despised them all.

The important principles that enabled Newton's final formulation: the law of inertia, gravity without aether, the inverse-square law and reciprocal reaction, were in the minds of all scientists of that era. The central contentious issue was unmediated action at a distance. It was Newton who, like Kepler before him, took the plunge of proceeding with the mathematical description without physical understanding. Newton, unlike Kepler, shared his insight with others like Hooke, Halley and Wren, whom he obliquely acknowledged by stating, ″If I have seen further it is by standing on y^e shoulders of Giants″, (Hall, 1963). It is because of this collaboration that the ideas did not remain dormant like those of Kepler. Newton never acknowledged Leibniz, who developed the calculus which transformed Newtonian mechanics into the grand edifice that emerged in continental Europe.

It was widely appreciated by Newton and his contemporaries that the compressive effect of the Cartesian aether was equivalent to some hypothetical force, often likened to gravity, that pulls a planet towards the central star and bends its rectilinear motion around into a closed curve. The magnitude of such a force had to be sufficient to balance the centrifugal, potter's wheel, effect and so prevent the rotating planet from escaping. It became vitally important to calculate the centripetal acceleration that was needed to stabilize such a closed orbit.

Newton's Inverse-square Law Newton's calculation (Stirling, 1935) of the correct formula enabled the synthesis with Kepler's model.

If a body at P moves in a circle with uniform velocity v it travels from P to B in the time $T = (arcPB)/v$. Had there been no force on it acting towards O it would have reached the point A at the same time T. To stay on the circular path it may therefore be considered having travelled to A and, because of the central force, it fell the distance AB towards O. By the



theorem of Pythagoras:

$$(AP)^2 + r^2 = (OA)^2 = (r + AB)^2 = r^2 + 2r.AB + (AB)^2$$

For a small interval in time the square $(AB)^2$ becomes so small that, in the limit, it can be considered equal to zero, while AP and the $arcPB$ become equal in length. The result is that $AB = (BP)^2/2r$. From Galileo's formula the uniform acceleration moves the object through a distance $s = (1/2)at^2$ and $t = BP/v$, such that

$$\frac{(BP)^2}{2r} = \frac{a}{2}\left(\frac{BP}{v}\right)^2$$

or $a = v^2/r$.

For a satellite to complete one revolution along the circumference of the circle, $2\pi r$, in time T, the velocity is given by $v = 2\pi r/T$ and the acceleration follows as $a = v^2/r = 4\pi^2 r/T^2$. From Kepler's third law the relationship between orbital period and distance for a planet on a closed orbit is given by the formula $T^2/r^3 = k$, a constant. On combining the two equations, by eliminating T^2, it follows that $a = 4\pi^2/(kr^2)$. Stated in words, the acceleration is inversely proportional to the square of the distance from the centre.

Clearly, if this calculated acceleration is ascribed to gravity, it becomes possible, by inverting the calculation, to derive Kepler's laws of planetary motion from an inverse-square law of gravitation. That was Newton's assumption of celestial mechanics: the same law of gravity, recognized by Galileo for falling objects on earth, also accounts for the harmonious motion of heavenly bodies. In its most general form the model applies to any pair of massive objects, moving relative to each other as if a force, proportional to the product of their masses and inversely proportional to their separation, pulls them together. Mathematically,

$$F = \frac{Gm_1m_2}{r^2}$$

On earth, the gravitational force, $F = mg$, where m is the mass of the gravitating object and g is the acceleration due to gravity, in line with Galileo's observations.

Newton's Laws

In order to give a mathematically precise account of these observations Newton gave canonical definitions of the concepts mass (m), momentum ($p = mv$), inertia, force ($F = ma$) and centripetal force ($F = mv^2/r$), together with the three famous laws of mechanics:

1. Law of Inertia: Every body continues in its state of rest or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

2. Law of Force: The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

3. Law of Reaction: To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal and opposite.

In the case of elliptical orbits, Newton's mechanics relates the two parameters that specify an ellipse to the dynamic parameters that define orbital motion. The size of an ellipse depends on its semimajor axis, its shape depends on the eccentricity, and these respective parameters are proportional to the energy and angular momentum of the rotational motion.

It has been stated (Hall, 1963) about Newton's published work:

> No other work in the history of science equals the *Principia* either in originality and power of thought, or in the majesty of its achievement.... Order could be brought to celestial physics only once, and it was Newton who brought order.

However, like all scientific achievements, it raised as many questions as answers. While the concept of force was introduced to explain planetary motion, the question of interaction at a distance remained unanswered. The mathematical law of gravity that pertains to falling apples as well as solar satellites, had no clear physical basis. Was this divine mathematics or an innate property of matter to act at a distance? As Newton's reservations against the latter interpretation were gradually forgotten, so was the mystery around the law of gravity, as it became generally accepted and commonplace. Yesterday's heresy is today's dogma.

2.5 Cosmic Evolution

The development in celestial mechanics after Newton was largely in the hands of the French mathematician Pierre-Simon Laplace (1749–1827). The stability of the solar system was the major unsolved problem. Neither Kepler's laws nor Newton's mechanics could be applied successfully to more than a single orbit at a time. The universal law of gravitation must clearly apply to any pair of celestial bodies and with several planets and moons circling the sun it is inevitable that mutual perturbations of the predicted perfect elliptical orbits should occur. Newton himself could never precisely model not even the lunar motion and concluded that divine intervention was periodically necessary to maintain the equilibrium of the solar system.

Without this luxury Laplace set out to assess the natural stability of the system. When asked by Napoleon to clarify the role of God in this, he replied: ″I have no need of that hypothesis″. The first important result, which he demonstrated mathematically, was that the irregularities in the eccentricities and inclinations of planetary orbits oscillate about fixed values, without amplification, and hence never deviate too far from the ideal orbits. He could therefore theorize that the solar system remains indefinitely stable. Like some self-correcting clockwork, driven by the universal force of gravitation, the solar system was concluded to be inherently stable and predictable. Laplace saw no reason why the whole universe should not be dynamically stable in the same sense. He claimed that:

> ″An intelligence knowing, at any given instant in time, all forces acting in nature, as well as the momentary positions of all things of which the universe consists, would be able to comprehend the motions of the largest bodies in the world and those of the smallest atoms in one formula, provided it were sufficiently powerful to subject all data to analysis: to it, nothing would be uncertain, both future and past would be present before its eyes″.

Not everybody agreed with this deterministic philosophy, but the model proved hard to refute. It prevailed long enough to stimulate the world view of a well-organized cosmos, designed with a mathematical precision that guarantees its faultless operation. At about this time (1772) the independent observation by three German astronomers (Johann Bode in Berlin, Johann Titius in Wittenberg and Christian Wolfe in Halle) of a peculiar numerical regularity in the mean distances of the known planets from the sun, became known as the Bode –Titius law.

Starting with the sequence of numbers: 0, 3, 6, 12, 24, 48, 96, ..., in which each new term beyond 3 is obtained by doubling the previous term, adding 4 to each term, and divide by 10, the sequence of planetary distances is reproduced in astronomical units. 1AU equals the distance of planet Earth from the sun. Hence:

Planet	Observed distance	Distance according to B–T law
Mercury	0.39	(0+4)/10=0.4
Venus	0.72	(3+4)/10=0.7
Earth	1.00	(6+4)/10=1.0
Mars	1.52	(12+4)/10=1.6
?		(24+4)/10=2.8
Jupiter	5.20	(48+4)/10=5.2
Saturn	9.54	(96+4)/10=10.0

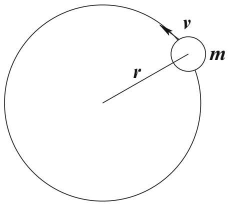
The subsequent discovery (1801) of the asteroid belt, consisting of thousands of minor planets on an orbit that corresponds with the gap in the Bode –Titius table elevated the law from a curiosity into a serious scientific observation. The physical basis of this law remained a mystery for more than two centuries.

Theologians of the day soon elaborated on the Laplace model by arguing that any system which functions like a machine must be the product of intelligent design, with a specific purpose in mind. The prime mover, or first cause, was back in another guise. To emphasize the fact that cosmology is the product of all human knowledge it is pointed out that astronomy and mathematics by themselves cannot successfully counter this teleological argument. It was left to a naturalist, Charles Darwin (1809–82) to show that, what may be perceived as purposeful design in Nature, arose through chance mutations that persist in organisms that happen to be more compatible with their environment. The theory even allows for the origin of life in lifeless matter and obviates the need of a designer of the world.

The first known instance where evolutionary development featured in cosmology came with the model, proposed by the philosopher Immanuel Kant in 1755, who postulated the origin of the solar system in a rotating nebula, rather than in creation. The idea was further developed on scientific grounds by Laplace in 1796. It gained general acceptance at about the time that the theory of biological evolution started to develop.

Laplace postulated a vast disc-shaped mass of cold gas and dust in slow rotation. As this nebula contracted under the mutual gravitation of its parts, its rate of rotation increasd to conserve angular momentum.

Motion on a circular orbit depends on three parameters: the mass of the object (m), its linear velocity (v) and its distance from the attracting centre (r). In such a system Newton's laws require that the momentm, $p = mv$,

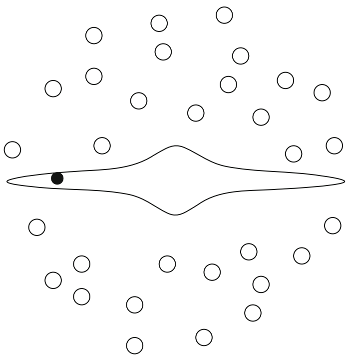


and the angular momentum, $L = mvr$, remain constant. Should the radial distance therefore decrease, the angular momentum must increase, speeding up the rotation and *vice versa*. The effect is illustrated by a ballerina folding her arms in a pirouette.

To continue with Laplace's model: As the rate of rotation increased to the point where the centrifugal force at the periphery exceeded gravitation, a ring of material separated from the main mass, eventually contracting towards a point. As the process continued, more planets condensed in the outer regions, while the inner region contracted to form the sun. The satellites were formed by condensation from the contracting planets. Excess material between the planets turned into comets and meteors.

The unequal distribution of angular momentum between the planets and the sun remains an unsolved problem, but not considered serious enough to finally abandon the nebular hypothesis. Rival theories such as the disintegration of one of a binary pair of stars to form the planets also leave many questions unanswered and a quantitatively correct model has not been formulated. However, after the time of Newton observational astronomy moved out of the solar system to examine the stars in the Milky Way, also known as the Galaxy, based on the Greek word for milk.

From his observations William Herschel (1738-1822) concluded that stars in the Galaxy were distributed in a disc-like structure, centred on the Sun. It remained the accepted picture until early in the twentieth century, when, based on the study of globular star clusters, Harlow Shapley proposed (1912) a disc-like Milky Way surrounded by a spherical arrangement of clusters and



with the Sun in the galactic arm as shown by the black circle. A large number of hazy nebulae were assumed to lie within the Galaxy. The idea, proposed by a few contemporary astronomers, that the nebulae were galaxies of stars like the Milky Way was either ridiculed or ignored. Even Shapley shared the majority view that all nebulae are part of the Milky Way.

The true nature of Shapley's disc became clear with the discovery of Lindblad and Oort in 1926 that stars in the Milky Way are moving in a pattern, consistent with rotation of the Galaxy, like the solar system, around a central attracting mass. It was confirmed much later (1952) that the Milky Way indeed has a rotating spiral structure.

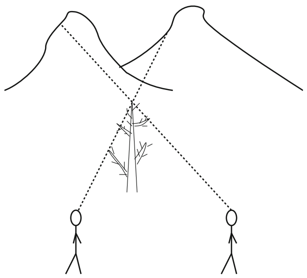
These new observations introduced a dramatic change in general cosmology. Not that it settled the dispute between evolution and design. Creation scientists responded by accepting stellar evolution as part of creation, starting with a single miraculous event, and guided forward by design, as described by the novelist Edgar Alan Poe (Beaver, 1976) in his essay, Eureka. Biological evolution, which gave impetus to evolutionary cosmology, is now hotly disputed again, following the dramatic developments in 20th century astronomy, which spawned a cosmology based on orthodox creation theory. No sooner had astronomy therefore managed to get rid of the mystic elements of astrology, which assumes a causal relationship between terrestrial and celestial events, when it became infected by a more virulent disease – creationist cosmology. Cosmology therefore came full circle since the time of Galileo by finding a new basis, which is compatible with religious dogma, and intolerant of heretics. As is often the case, this massive paradigm shift is credited to a single individual, in this case the astronomer, Edwin Hubble (1889–1953).

2.6 An Expanding Universe

The astronomical evidence that prompted abandonment of the concept of an equilibrium universe, in favour of an expanding one, is largely due to the work of Edwin Hubble, but without the explosive development of physics in the first quarter of the 20th century, his work would not have been possible. As with Newton and Darwin, new ideas were in the air, and Hubble was the one to complete the synthesis of ideas that created a new world view. Some of the other important players include James Clerk Maxwell (1831–79), Johann Balmer (1825–1898), Max Planck (1858–1947), Albert Einstein (1879–1955) and Niels Bohr (1885–1962). Without the insight of these scientists Hubble's observations make no sense.

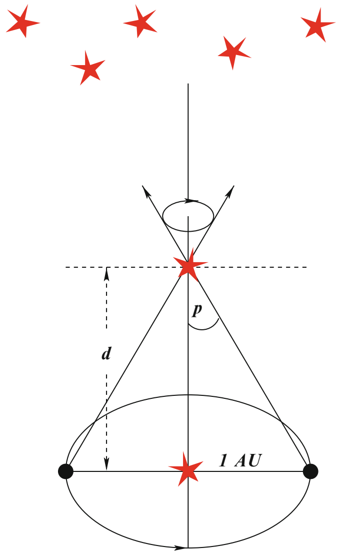
The most important development was the ability to make reliable estimates of astronomical distances. To establish the distance to a star, astronomers rely on the phenomenon of stellar parallax. The first successful measurement of this type was performed at the Cape Observatory in the early 19th century.

Parallax is the apparent shift in the position of an object against a distant background because of a change in the observer's point of view.



Stars exhibit the same phenomenon. As the earth orbits the sun nearby stars appear to move back and forth against the background of more distant stars. The parallax of the star is the half angle p which defines the shift of the star's apparent position viewed from opposite sides of the earth's orbit around the sun. To derive the distance d from the angular measurement it is necessary to know the distance between planet Earth and the sun, which defines the astronomical unit (AU) of distance. If the angle p is measured in seconds of arc, the distance d, defined as

$$d = \frac{1}{p}$$



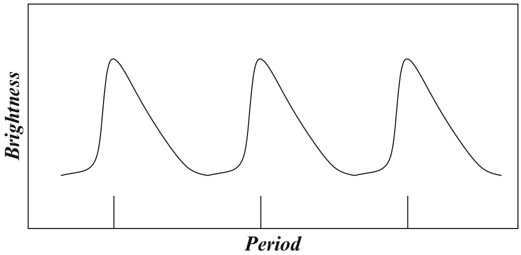
is obtained in *parsecs*. One parsec = 3.26 light years and 1 ly$\simeq 10^{13}$km.

The distance between Earth and Sun is obtained by measuring the parallax of another planet and use of Kepler's third law for the orbital periods of the planets. The closer an object is to the observer, the larger its parallax. On occasion the minor planet Eros approaches the earth more closely than any of the major planets and measurement of its parallax displacement during diurnal rotation of the earth at such time provides one of the best estimates of the AU.

Stellar parallax is measured most reliably by photographic methods. The most extensive set of early measurements were conducted from the Johannesburg station. The position of a star of interest is measured relative to a number of more distant reference stars over a period of months. The method has a serious limitation – for stars beyond a certain maximum distance the paralactic angle becomes too small to measure.

An alternative method based on following certain stars, known as Cepheid variables, allows measurement of much larger distances. The brightness of a Cepheid star fluctuates with a characteristic period of several days.

On assuming an inverse-square relationship between luminosity and distance and starting from a nearby Cepheid, a crude estimate of the distance to more remote Cepheids is derived by measuring their periods of fluctuation. Finally, the distance of any object, such as a star cluster or a nebula, which contains a Cepheid can be obtained by this method.



These new methods of measuring astronomical distances inaugurated modern astronomy and astrophysics and the interpretation of such measurements in terms of an expanding universe led on to the modern standard cosmology.

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