Chapter 1

From myth to reality

When we look up at the night sky on a clear night, what do we see; and how did the complex patterns and motions come to be? These seemingly simple questions have a long history. All religious traditions address them and they occupied the philosophers of antiquity for centuries. They fascinated Ptolemy,Copernicus, Galileo, and NewtonThe Vatican has a famous painting by Raphael that is commonly known as The School of Athens. Let us use the subject of this painting to explore the standing of astronomical enquiry in the ancient world. But first a brief summary of how the painting was commissioned.

When Julius II was elected in 1503, the ancient city of Rome lay in ruins, an immense rubble pile of shattered columns and collapsed arches.

Julius and his architect Donato Bramante spectacularly improved Rome with a huge development program, building wide boulevards, improving the drainage, and dredging the Tiber. Julius instructed Bramante to adorn the third floor as a gracious papal apartment, complete with a hall and library.

Raphael's decorative fresco for the philosophy section of the papal library captures the essence of ancient philosophy as a way of life. He assembles the greatest philosophers from ancient times, some fifty in all.

The two central figures in Raphael's allegorical academy are Plato and Aristotle. These are the philosophers of antiquity who had the greatest impact on the western, Christian world, though other later ones such as Archimedes and Aristarchus had more lasting influence on the development of science. In 387 BC Plato had founded in Athens a hugely influential academy devoted to philosophy. There is a legend that the gateway to the Academy bore the inscription "Let no one ignorant of geometry enter here". Geometry became the key to unlocking the endless cycles of the dance of the planets.

Raphael's Plato holds his right index finger aloft, gesturing towards the heavens. In his left hand he holds a copy of his book *Timaeus*. Written about 360 BC this treatise is a dialogue on the nature of the physical world, with Plato's cosmological speculations argued through the character of Timaeus

In order to understand the physical universe, Aristotle looked for causes, which back then was a novel idea. The book that Raphael's Aristotle is holding is the *Nicomachean Ethics* in which the central question can be phrased as: What does it take for an individual human to be a good person

An hour or so after sunset, in the year 134 BC, the astronomer Hipparchus, who lived on the island of Rhodes, gazed at the emerging starlit night. The moment he looked at Scorpius he saw that the constellation had an extra star. This had never happened before. No ancient watcher of the sky had ever recorded the sudden appearance of a new star, which was impossible in

Aristotle's cosmology. The appearance of the new star stimulated him to make a list of star positions, as a result of which he made a very great discovery.

But, from his systematic comparison he made a startling discovery. He found that the stars had moved eastward in position by about two degrees in 150 years. What this meant was that the entire celestial sphere, for the Greeks the outer limits of the cosmos, was in a slow motion. Hipparchus had discovered the precession of the equinoxes.

The last of the noted natural philosophers of classical antiquity was Claudius Ptolemaeus or PtolemyIn *The School of Athens*, Ptolemy is at the lower right with his back to us. He holds a terrestrial globe aloft with his right hand. Facing Ptolemy and holding a celestial globe is the bearded figure of the geographer Strabo, who lived in Alexandria a few decades before Ptolemy. Raphael's iconography has Ptolemy regally clothed with a crown on his head. In Raphael's time the philosopher Ptolemy was confused with the Ptolemies who ruled Egypt from 332 BC to 30 BC.

His exact dates of birth and death are unknown, and it is sufficient to say that he lived in the second century AD. From his recorded observations we can be certain that he worked in Alexandria. Nothing is known of his education or which books he read.

Ptolemy's greatest astronomical work was published in about 150 AD, with the title (in Greek) *Mathematike Syntaxis*, that is, Mathematical Treatise. However, it has come down to us through Islamic sources and is therefore referred to by its Latin-Arabic name *Almagest*, and that is the title we shall use. It consists of thirteen books and, although it was only his second publication, it is a work of great maturity that would have required many years of effort.

The *Almagest* is the first attempt at producing a synthesis and analysis of all the useful astronomical knowledge available to Ptolemy. As a didactic work it is a masterpiece of clarity and order. Its authoritative status made it *the* textbook of astronomy for nearly one and a half millennia. Books seven and eight, on stellar astronomy present a star catalog that is heavily based on Hipparchus, as well as a discussion of precession. Ptolemy lists 1022 stars (more than Hipparchus), arranged into 48 constellations that have ever since been described as the Ptolemaic constellations.

The five remaining books, devoted to the theory of planetary motion are entirely his own work. Here we see him at his most innovative. Book nine contains a riveting discussion of a major intellectual puzzle: Ptolemy's data was sufficiently good to reveal two distinct anomalies in the planetary motions that were difficult to untangle. His goal will be 'to save the appearances', a task first enunciated by Plato and of concern right down to the time of Galileo. This expression is anchored in reality: the task of the mathematicians is to refine (complicate?) their models so that as the accuracy of the data improves, the theory accords better with reality.

In the centuries after Ptolemy, classical learning declined, then collapsed, and ceased to exist in Christian western Europe. However, the Greek texts were rescued from oblivion during the dark ages by scholars in the Islamic world. We have reminders of the Islamic contributions to learning while Europe slept, through nouns such as algebra, algorithm, alkali, alcohol, alembic, Ptolemy's *Almagest*, star names such as Aldebaran and Algol, alidade (part of an astrolabe), zenith and nadir, and so on.

Although the Arabic astronomers were accomplished practitioners, with beautiful instruments and observatories, they did not make any major contributions to natural philosophy. And then, eight centuries years after Ptolemy, the spread of monasticism in western Europe led to the foundation of the first universities (Bologna 1088, Paris about 1150, Oxford 1167, Cambridge 1209) and the start of medieval learning.

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Nicolas Copernicus, born in 1473, was the fourth and youngest child of a wealthy merchant who had settled in Torun, then an important trading port on the Vistula river. His father died in 1483, and the children came under the protection and supervision of an uncle, who was a successful cleric and who would become bishop of the diocese of Warmia. The uncle prepared young Copernicus for a career in the church. In 1491 he enrolled at the university in royal Krakow (of which he is the most celebrated alumnus) where he first took a deep interest in astronomy. In 1495 the uncle secured him an administrative position as canon in the cathedral at Frombork, which would secure his finances for life. As a canon he managed the diocesan income from agricultural rents; he did not take holy orders. Two years later Copernicus took temporary leave of absence to resume his studies in Bologna where he lodged with a professor of astronomy, Domenico Novara. Copernicus finally graduated from the university of Ferrara with a doctorate in canon law. Family affairs (his uncle was ill) meant that he did not take up residence in the chapter at Frombork until 1510, and that's when he set seriously to work in astronomy.

We know that by 1514 the architect of the new solar system had made sufficient progress with his heliocentric theory that he felt confident enough to write a short essay, the *Commentariolus*, which he circulated to certain astronomers.

But why did he work on this new theory at all?

In the *Commentariolus* he tells of his motivation. According to the translation made by Edward Rosen in 1992:

> Yet the widespread [planetary theories], advanced by Ptolemy and most other [astronomers], although consistent with the numerical [data], seemed likewise to present no small difficulty. For these theories were not adequate unless they also conceived certain equalizing circles, which made the planet appear to move at all times with uniform velocity neither on its deferent sphere nor about its own [epicycle's] center…Therefore, having become aware of these [defects], I often considered whether there could perhaps be found a more reasonable arrangement of circles, from which every apparent

> irregularity would be derived while everything in itself would move uniformly, as is required by the rule of perfect motion

Copernicus claimed that his new model solved several of the problems of ancient astronomy. But the essay was no more than an extended letter, and Copernicus explained to the recipients that he was already writing a much larger work that would have the full mathematical derivations: the title is *De Revolutionibus Orbium Coelestium*.

Frombork was far from any large intellectual center or the printing presses of western Europe. We can imagine that the local market for paper was small and the cost high. In about 1520 when Copernicus started his revolutionary opus, he purchased a small supply of paper that has been traced to a mill in Middleburg, Holland. It must have reached Frombork by trading ship. Changes in the watermarks as well as the thickness of the paper tell us that he bought only a few sheets at a time. When he worked on his great manuscript he would generally take five sheets of handmade paper, fold them in half, nest them one inside the other, and thus produce a handy writing tablet of ten pages, twenty sides, known as a quire.

Sheet nine of the manuscript has the most famous diagram in the history of astronomy: in which the word *sol* is at the center of eight nested circles. The names and orbital periods of the planets, from Mercury to Saturn are written in the space between the circles. It is an error to describe these circles as the orbits of the planets. That is not what Copernicus intended. Rather they define the region of space within which each planet may be found: they delineate orbital domains not orbits.

But news of the daring scheme did percolate west. In Nuremberg one Georg Joachim Rheticus learned that Copernicus had thrown the static Earth into seemingly violent motion. We can only speculate that a copy of *Commentariolus* must have been available in Nuremberg. Imagine the scene then, when a twenty-five year old from explosive heart of Lutheranism rolls up in the spring of 1539 to learn of the new cosmology from the sixty-six year old Catholic canon. Fortunately, the aging cleric welcomed the young enthusiast as a long-term guest. We know that their discussions were detailed: on several occasions Rheticus picked up his quill and penned amendments in the margins. Famously, at some stage the pair crossed out a passing reference to the heliocentric opinion of Aristarchus.

As the details of the scheme unfolded day by day, Rheticus became convinced that the world should know what Copernicus had done. His gift of books was part of his strategy for convincing Copernicus that *De Revolutionibus* must be published. His gifts included Ptolemy's *Almagest* and Euclid's *Geometry*, a treatise on optics, and two books on trigonometry. On studying the latter Copernicus decided to incorporate some of the methods into *De Revolutionibus*. Furthermore, Rheticus brought recent observations of Mercury that Copernicus used to improve his treatise. So there would be no question of rushing to press: the great work had inconsistencies that needed fixing.

> Although Copernicus would not release the manuscript for printing he did allow Rheticus to publish a shortened report, a seventy-page booklet titled the *Narratio prima*, which to this day remains the best

introduction to Copernicus's work. Rheticus went to nearby Gdansk where a printer published the account in March 1540.

In 1542 Copernicus agreed that Rheticus could have a fair copy of the manuscript to enable publication in Nuremberg. After spending twenty-eight months at the right hand of Copernicus, Rheticus set out for Saxony, with the precious duplicate in hand. Finally, in the spring of 1543, the printing by Petreius in Nuremberg was complete. Hundreds of copies awaited distribution throughout Europe. On the title page the publisher's blurb claimed that the work is "outfitted with wonderful new and admirable hypotheses" from which the reader can "compute the positions of the planets for any time. Therefore buy, read, and profit."

The publication of the greatest scientific text of the sixteenth century, an epochal event, marks the dawn of modern scientific enquiry into the nature of the universe. There is no evidence that Copernicus feared the Church. At the time of his death, strong ecclesiastical opposition lay some decades in the future: it was placed on the Index of forbidden books only in 1616, and then allowed with nine corrections from 1620. Pope Clement VII had reacted favourably to a description of the new cosmology. Copernicus dedicated the book to Pope Pius III, and he took on the theologians by arguing that "astronomy is for astronomers" (by which he implied: theologians should not meddle with it). Martin Luther, a contemporary of Copernicus, was strongly opposed, describing Copernicus as a fool who went against holy writ. The proof reader, the Lutheran minister Andrew Osiander, had added an unauthorised and anonymous preface to *De Revolutionibus* in which he cautioned the reader that the book was a hypothesis and did not represent the real world. He may have been protecting the interest of the printer. But Rheticus was so furious with this unauthorised intervention that he crossed out the preface in his own copy and ceased to do business with Petreius.

***I now turn to Galileo's contributions to mechanics and cosmology. This pivotal figure in the development of modern physics and astronomy was pugnacious, brimming with sarcastic wit, properly respectful of authority in matters of church and state, but scathing with his scientific adversaries. He devised a series of ingenious experiments to test the behavior of bodies in free fall and down inclined planes.

Turning now to the other leg on which science walks, almost everyone knows the oft told account of Galileo's invention of the *astronomical* telescope and the discoveries made with it in 1609 – 10. Although spyglasses were already available in the Netherlands, it took the genius of Galileo to improve their optical performance sufficiently well for astronomical observation to be feasible.

By August 1609 Galileo had a telescope with 8X magnification, which he demonstrated to authorities in Venice, "to the infinite amazement of all".

Extending his vision beyond the solar system, Galileo made a marvellous discoveries concerning structure formation in the cosmos. Wherever he aimed his telescope, he spied far more stars than can be seen by the naked eye.

In The Starry Message he described how the telescope resolved nebulae into "groups of small stars herded together in a wonderful way."

Most spectacular of all, he resolved countless stars in the Milky Way thus revealing for the first time that its structure is composed of discrete populations of stars.

Here is his description of the Milky Way:

> *We have observed … the essence, namely the matter, of the Milky Way, which can be seen so clearly with the aid of the telescope that what for centuries philosophers found an excruciating problem has been solved with ocular certainty, thus freeing us from wordy disputes. For the Galaxy is nothing else than a collection of innumerable stars heaped together.*

The spectacular observations of Jupiter allowed him to prove that the Copernican system was the correct model, and he promoted Copernicanism through The Starry Message.

Galileo's championing of Copernicanism was controversial within his lifetime, when a large majority of philosophers and astronomers still subscribed to the geocentric view that the Earth is at the centre of the universe. After 1610, when he began publicly supporting the heliocentric view, which placed the Sun at the centre of the universe, he met with bitter opposition from some philosophers and clerics, and two of the latter eventually denounced him to the Roman Inquisition early in 1615. In February 1616, although he had been cleared of any offence, the Catholic Church nevertheless condemned heliocentrism as "false and contrary to Scripture",[10] and Galileo was warned to abandon his support for it—which he promised to do. When he later defended his views in his most famous work, Dialogue Concerning the Two Chief World Systems, published in 1632, he was tried by the Inquisition, found "vehemently suspect of heresy", forced to recant, and spent the rest of his life under house arrest.

At the beginning of the seventeenth century Copernicanism had few adherents, and yet by the mid-century it had pretty much swept the field, thanks in large measure to another of Galileo's books, *Dialogue Concerning the Two Chief World Systems.* Galileo fully understood that publication was the way to promote his new science. In fact he had to build an audience for scientific work, and in large measure (although not alone) he created the space for science within our intellectual culture

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Cartesian philosophy was all the rage when Isaac Newton arrived in Cambridge early in June 1661. From the outset of his undergraduate career he kept a student notebook, which is now in the manuscripts collections of the University Library at Cambridge. Newton found the official curriculum, established by statute nearly a century before, in a state of advanced decay.

In fact, Cambridge was still officially in the thrall of Aristotle, as it had been since its founding. Intellectual vigour had departed long before: learning was performed by rote, without enthusiasm. Newton acquired the books prescribed by the curriculum, but he found them unattractive and old-fashioned. Cambridge University was a backwater by European standards: two-thirds of the students left without a degree, and the only relevant professional training was for a career in the Anglican church. Almost everything useful that Newton learned at Cambridge was the result of his solitary reading rather than tuition given by masters.

A disaster descended on England in 1665. As Emmanuel College later put it: it has "pleased Almighty God in his just severity to visit this towne of Cambridge with the plague of pestilence." At Trinity College the steward posted a notice at the Great Gate on 7 August 1665 stating that "All Fellows & Scholars which go now into the Country on the occasion of the Pestilence shall be allowed the usual Rates for their Commons in ye space of ye month following." In other words, a month's wages jingled in their purses. . and returned to normal only in the spring of 1667.

According to Newton's biographer Richard Westfall: "The miracle lay in the incredible program of study undertaken in private and prosecuted alone by a young man who thereby … placed himself at the forefront of European mathematics and science."

Newton came to gravity through mechanics. Newton was elected a Fellow of the Royal Society in 1672. His new contemporaries in London hotly debated the mysterious influence that caused the planets to revolve around the Sun in ellipses. What force prevented them from shooting off along a straight line into space? In the 1684 three famous men came to the brink of the solution. The trio comprised the young Edmond Halley (of comet fame), Robert Hooke (Curator of Experiments at the Royal Society), and Christopher Wren (a founder of the Royal Society and a highly esteemed architect).

For some time natural philosophers had been distancing themselves from Descartes' vortices by speculating that the Moon and planets had a "tendency to recede" from their parent body. By this the sages meant that the natural motion was in a straight line, so a single force directed to the centre must cause the circular motion about a parent body such as the Sun. By this time Halley knew that for *circular* orbits the force of attraction from the Sun had to vary as the inverse square of the distance, but he was uncertain if the same law would apply to *elliptical* orbits. Wren, a professor of astronomy first at Gresham College and then at Oxford, declared his inability to solve the mathematical puzzle. Hooke, a brilliant scientist who continues to be underrated, perhaps because he was ugly and grumpy, had been carrying out excellent experiments on gravity for many years.

In 1679 Hooke had written to Newton saying that planetary orbits could be explained by "A direct straight line motion by the tangent and an attractive motion towards the central body." Hooke had lacked the mathematical skill to follow this up, and his letter invited Newton's opinion on the hypothesis. Newton replied that he had more or less given up natural philosophy for "other studies". The following year Hooke again wrote to Newton, stating explicitly this time that he supposed "the Attraction is always in duplicate proportion to the Distance from the Centre Reciprocall." That's the inverse square law.

At a meeting of the Royal Society on 14 January 1684, Hooke claimed that all laws of celestial motion could be derived from an inverse square law. Halley again admitted that his efforts had failed, while Wren remained a skeptic. Hooke refused to show his proof. Afterwards they adjourned to a coffee house to warm themselves: London was in the grip of the coldest winter, with the Thames frozen from bank to bank. In the fuggy coffee house, Wren offered Hooke and Halley a £2 book prize if one of them could find a mathematical proof within two months. This friendly rivalry kept the problem before all three for the next few months.

Halley quizzed Newton about "what he thought the Curve would be that would be described by the planets supposing the force of attraction towards the Sun to be reciprocal to the square of their distance from it." Newton's face brightened: he replied without hesitation that it would be an ellipse, at which Halley was "struck with joy and amazement". He asked for a copy of the proof. Isaac shuffled a great jumble of papers, and then apologised for losing it. He told Halley he would work it out again and send it off in a few weeks. This "lost" paper story is a charade: the paper has survived. What happened is that Newton played for time because he didn't want yet another public row with the irascible Hooke about priority and plagiarism. After thinking about it for a couple of months, he finally trusted the confidence of his friend Halley and despatched a neat nine-page paper explaining the mathematical basis for Kepler's three laws. This paper is mathematical: there are four theorems and the solutions to five problems.

Importantly, the nine-page paper hinted at an entirely new general science of dynamics, as well as an enormous advance in celestial mechanics. Edmond now hot-footed it back to Cambridge, where he persuaded Isaac to expand his short treatise. The end result was a full-length book that is now always known by its short title: the *Principia.*

Newton threw himself into the project. In a letter to the Astronomer Royal he comments: "Now I am upon this subject I would gladly know the bottom of it before I publish my papers." In getting to the bottom of it he did nothing else for eighteen months, from the fall of 1684 until the spring of 1686. No alchemy. No theology. He forgot to eat. College servants attending to his needs complained that they saw "his Mess was untouched" when they went to service his rooms. There are evenings when Isaac sets off for high table in the college dining hall, then wanders as if in a trance across the Great Court of Trinity to the street outside, and returns directly to his chamber to write standing at his desk in a study littered with unfinished papers, chaotic essays and unorganized notes. When the university library asked for a file copy of his lecture notes he despatched a package of his latest drafts of the *Principia.*

Within weeks Newton had taken a ground-breaking step: he decided that all the celestial bodies attract each other. It wasn't just a case of the Sun attracting the planets, but rather the planets attract each other. Eventually this step would lead him to the concept of universal gravitation: all clumps of matter, from atoms to clusters of galaxies, attract each other. It would be an awesome synthesis.

Newton's world picture was utterly transformed, at a stroke. When he started his research on gravitation, the world was a confused plenum, utterly crammed with vortices of Cartesian matter crashing around in chaos. But the Newtonian world was almost a vacuum, empty space in which isolated bodies were diverted from straight paths by invisible forces exerted by other isolated bodies. Furthermore, in the Newtonian universe all motion was now subject to exact laws that applied throughout the entire universe. The very structure of that universe would be influenced by the action of gravitational forces. Newton achieved all of this at a pace and with a degree of clarity that is unique in the history of science.

It is to Halley's eternal credit that he could see the revolutionary implications of all of this. It was he who by turns persuaded, coaxed, and cajoled a reluctant Newton to publish. Like Copernicus before him, Newton was too sensitive of criticism, and he was scared that his peers would not believe him. After all, his break with the past, with its postulate that invisible forces control the universe, was enormous. However, the new scientific method demanded that he give a full written account.

Newton's *Principia* appeared in 1687, thanks to Halley's personal generosity in paying the production costs. The Royal Society was in desperate financial straits at this time and could not afford the risk of the book failing to sell. Publication completed the scientific revolution that Gilbert and Galileo started. In the *Principia* the key insights are the universal law of gravitation and the three laws of motion, which together provide the bedrock of the new physics. Newton's gravitational force was action at a distance. Unlike Descartes, Newton had no need of an intervening medium to transmit force. This was an absolutely dramatic development for the time. *Principia* made a big impact because it finally established that the world ran according to mathematical laws that ordinary human beings could find and could apply. It is worth stating too that this is the first time we have a cosmological framework in which deviations from perfection can be solved be the ever more detailed application of the laws, rather than by appeal to special cases "to save the phenomenon". So, for example, eventually some 1500 anomalies in the actual orbit of the Moon would be fully explained on the basis of universal gravitation alone. Newton was not the sole originator of the laws of Newtonian physics, but he was the first to pull everything together into a logical framework that he titled "the mathematical principles of natural philosophy." His greatest contribution was to unify the laws of heaven and Earth into a single framework, a thoroughly modern simplification. And the method, the combination of precise observation with the mathematical formulation of a "law of nature" became the model of science for centuries to come.