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Prologue

From Myth to Reality

■ Astronomy: The Endless Frontier

When we look up at a clear, dark sky and are inspired with wonder and curiosity by the sight above us, we share a long and vibrant story with our ancestors—a quest to understand the nature, origin, and behavior of the glimmering points and patches of light above and around us. What are the heavens made of? And what is our own planet Earth's place within the cosmos that surrounds us? These questions occupied the philosophers of antiquity for centuries. They fascinated such luminaries as Nicolas Copernicus, Galileo Galilei, and Isaac Newton, and they continue to captivate the leading scientists of the present century. Ambitious surveys of millions of remote galaxies, as well as missions to map the energy released at the origin of the universe down to an exquisite level of detail, have since brought us tantalizingly close to understanding the nature, evolution, and fate of the universe. Yet, throughout the centuries since antiquity, we share the same source of inspiration: questions that first kindled the varied stories of mythology now inspire hypotheses driven by astronomical observation and our knowledge of the laboratory-based laws of physics. We also now understand that, in the 1945 words of Vannevar Bush, science is an "endless frontier": new discoveries will always lead to an expanded understanding and to still more questions.

Throughout the history of cosmology, natural philosophers and, later, scientists based their theories on the world they could see. They constructed the best hypotheses they could using our excellent human vision until their view could expand through improved technologies, like better telescopes and eventually space-based instruments of observation. Therefore, as we mentioned earlier, cosmology is a story of expansion—of vision, mind-set, and of the physical universe itself. As our ability to observe farther out into the cosmos developed, an expanding universe was revealed to us—and our understanding of the nature of the cosmos became both broader and more refined, while yet remaining incomplete.

The more we have discovered about the universe in which we find ourselves, the more clearly we have come to see that a darkness, a mystery, lies at its heart. While we have by now an extraordinarily good working model of the cosmos—so good that every prediction we make is validated by the subsequent, exquisitely precise measurements—yet the two most vital components of this model, dark matter and dark energy, remain shrouded from our understanding.

In this prologue, we will embark on the story of how humankind came to this modern understanding of the universe. This is a tale that, after a short excursion through the discoveries of antiquity, will lead us through the Renaissance and the birth of modern science and the scientific method, the Copernican revolution, Galileo's ground-breaking observational work, and Newton's foundational work on gravitation, up to the eighteenth and nineteenth centuries, in which we came to know that we are part of a congruence of stars called the Milky Way, and that our galaxy is just one in a vast sea of other such island universes (though this possibility was not confirmed till later). At that point in our narrative, we will find ourselves about to be swept into chapter 1 and the twentieth-century revolution that formed the basis for our modern paradigm of cosmology. However, before we rush headlong into the present, let us return to the beginning and consider the worldviews developed by other very thoughtful, inquiring minds of earlier times. The best way to comprehend our present view of the universe is through history, to see how, from a simple start, it developed over time, as observations and calculations were steadily assembled into the larger and more comprehensive picture that we have today

■ Charting and Modeling the Heavens

An hour or so after sunset, in the year 134 BCE, the astronomer Hipparchus (190–120 BCE) gazed at the emerging starlit night from his home on the island of Rhodes, and made an astonishing discovery. In the constellation Scorpius, he spied an extra star. No ancient watcher of the sky had ever before recorded the sudden appearance of a new star. Excited by this extraordinary event, he decided to compile an accurate catalog of the stars, perhaps thinking that it would be handy to have a checklist of star positions to refer to the next time a new star appeared from out of nowhere. In a burst of intense activity, from 134 BCE to about 127 BCE, Hipparchus spent long hours in his observatory, measuring angles. He used this information to compile a catalog of the positions of 850 stars. Hipparchus compared certain of his star positions with observations of about twenty stars made about 150 years earlier in Alexandria.

This led him to another startling discovery: 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 slowly moving. Hipparchus had discovered the precession of the equinoxes. Supposedly fixed reference points that lay at the heart of the cosmic coordinate system were slowly but steadily sliding eastward due to the slow precession of the Earth's axis by gravitational forces. By way of his careful observations, Hipparchus introduced vastly improved data into the geometrical models that were developed to explain the motions of the celestial bodies, and his elegant refinements lasted for three centuries.

Hipparchus was not the first in this tradition. Greek philosophers brought to the western world the belief that the natural world might be understood through measurements, mathematics, and reasoned argument. In the third century BC, Aristarchos of Samos had proposed a Sun-centered solar system with the planets in the correct order, and he had estimated the size and distance of the Moon and Sun from the Earth using valid geometrical arguments—but of course very approximate measurements. He realized that the proof of the Earth's annual motion around the Sun should show up in the slight apparent wobbling motion of the nearest stars ("parallax"), but it was too small to be measured with the naked eye.

The next young mathematician after Aristarchos to work on what we might term evidence-based astronomy was Eratosthenes. In the third century BC, he determined the size of the Earth using a geometrical method. He knew that on a midsummer's day the Sun is directly overhead at Aswan in Upper Egypt. In Alexandria, which is more or less due north of Aswan, he measured the size of the small midday shadow cast by a vertical stick (or gnomon). From the measured ratio of the length of the shadow to the length of the stick he used a geometrical argument to find that the distance from Alexandria to Aswan is 2 percent of the Earth's circumference. What is important here is not so much his accuracy, but his boldness in deciding that a property of the real universe could be established by combining geometry and measurements.

The Greek philosophers who had the greatest influence on later western thought until the Renaissance were Plato and his pupil Aristotle, best known for his contributions to political, moral, and aesthetic philosophy. Unlike the later, observationally motivated astronomer-mathematicians we have been discussing, Plato and Aristotle belonged to a legalistic and axiomatic tradition that did not rely on experiment and measurement. For example, Aristotle asserted that heavy bodies fall faster than light ones without mentioning tests of the claim. His brilliant rhetorical skills prevailed in the end, and his contributions to natural philosophy, while pernicious in retrospect, overshadowed the extraordinary methodolog-

Figure P.1. In the School of Athens there is a group of geometers looking at a slate. This reminds us that geometry had a central role in Greek cosmology. Claudius Ptolemy stands with his back to us, wearing a crown (he was often confused with the Ptolemies who ruled Egypt).

ical and observational contributions of the more pragmatic Greek astronomical investigators, who showed how, with only their eyes, their wits, and elementary geometry, they could determine the size of the Earth and Moon, the distance to the Moon and much else.

The Hubble Space Telescope and modern technology were not needed for the discoveries that the Greek astronomers made; every reader of this book has the equipment required to understand correctly our astronomical surroundings. And the methods they utilized, which were principally geometrical, were revived and extended by the Renaissance scientists who led in the true “rebirth” of natural philosophy.

By the peak of the Classical Era, the observational catalogs had become ever more detailed and accurate. Claudius Ptolemy (90–168 CE), a Roman citizen living in Alexandria, was a philosopher, geographer, astrologer, and astronomer who flourished 300 years after Hipparchus. Ptolemy's greatest astronomical work was published in about AD 150. We know it by its Latin-Arabic name, *Almagest*. It was the first attempt to produce a synthesis and analysis of all the useful astronomical knowledge then known to the ancients. Its authoritative status made it *the* textbook of astronomy for nearly one and a half millennia. (Copernicus is known to have used it.)

In the parts of *The Almagest* devoted to planetary motions, we see Ptolemy at his most innovative. He made two important adjustments to the model of planetary motion refined and used by Hipparchus. First, he allowed the Earth to be displaced a little from the geometrical center of the circular planetary orbits. Second, by a rather technical move, he arrived at an improved representation of the motion of Mars, which had long confounded (and would continue to puzzle) mathematicians.

In the centuries after Ptolemy, classical learning declined, then collapsed, and ceased to exist in Christian, western Europe. However, scholars in the Islamic world rescued the Greek texts from oblivion during the dark ages. Today we have reminders of the Islamic contributions to learning while Europe slept, through nouns such as algebra, algorithm, alkali, alcohol, zero, as well as star names such as Aldebaran and Algol, and so on. And then, eight centuries 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, through which the masters and their pupils rediscovered ancient philosophy. In Arabic and European centers of learning, Ptolemy's *Almagest* was the standard work on planetary motion for about 1,400 years, until it was displaced by the Copernican revolution in thinking.

■ Copernicus: "The Last of the Greek Cosmologists"

Nicolas Copernicus (1473–1543) broke ranks with the medieval past by reviving the model of Aristarchos of Samos and postulating something quite incredible to those trained in the scholasticism of Aristotle and Thomas Aquinas: the idea that the Sun is the center of the planetary system. 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* (*Little Commentary*), which he circulated to certain astronomers. Copernicus claimed that his new model solved several of the problems of ancient astronomy. He had Earth as a center of gravity and the center of the lunar orbit. Otherwise, all planetary orbits, including the Earth's, encircled the Sun. The moving, rotating Earth itself created the apparent motion of the heavens. 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 contain the full mathematical derivations, *De Revolutionibus Orbium Coelestium* (*On the Revolutions of the Heavenly Spheres*).

Copernicus continued to work on planetary motions for as long as two decades, slowly gathering more observations in an attempt to refine the orbital elements. However, while this theory lived in only a single manuscript, it could not affect cosmological thinking. But news of the daring scheme did percolate west. In Nuremberg, Georg Joachim Rheticus learned from a copy of *Commentariolus* that Copernicus had thrown the static Earth into seemingly violent motion. Rheticus decided that the radical cosmology of Copernicus needed further investigation. In 1539, he set out from southern Germany for the Baltic shores of northern Poland. Fortunately for Rheticus, the aging cleric welcomed the young enthusiast as a long-term guest.

Like a modern professor and a graduate student, the pair worked through the manuscript, taking many weeks to do so. We can imagine that at their initial academic sessions, Copernicus would have explained that several hypotheses were involved. The big idea was the cosmological device that put the Sun at the center of the solar system with the planets in orbit around it. As the details of the scheme unfolded day by day, Rheticus became convinced that the world should know what Copernicus had done. In 1542, Copernicus agreed that Rheticus could have a fair copy of the manu-

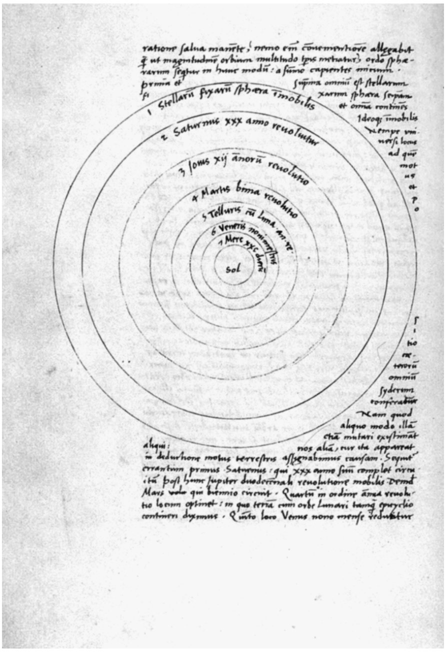


Figure P.2. The heliocentric model of the solar system in the duplicate manuscript that Copernicus kept. The circles are often described as planetary orbits. In fact, this is a two-dimensional representation of the nested spheres on which each planet's orbit is inscribed.

script to enable publication in Nuremberg. After spending many 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 Johannes Petreius in Nuremberg was complete. Hundreds of copies awaited distribution throughout Europe. On the title page the publisher's blurb boasted 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 this greatest scientific text of the sixteenth century, an epochal event, marks the dawn of modern scientific inquiry into the nature of the universe: its origin, its history, its architecture, and our place in the immensity of the cosmos. The scientific revolution that would transform Europe and then the rest of the world can be said to date from 1543, with the publication of *De Revolutionibus*. The revolutionary spirit that was spreading through the scholarly world is well summarized by the English scientist William Gilbert, an early advocate of the Copernican model, who wrote in 1600:

> In the discovery of hidden things and in the investigation of hidden causes, stronger reasons are obtained from sure experiments and demonstrated arguments than from probable conjectures and the opinions of philosophical speculators of the common sort.

The most persuasive advocate of the new approach and an extraordinary propagandist for what we would call the scientific method was Galileo Galilei.

■ Galileo: A New Approach to Mechanics and Cosmology

In recounting the events during the period from the birth of Copernicus (1473–1543) to the passing of Isaac Newton (1643–1727), we shall first turn to Galileo's (1564–1642) 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 (or literary) adversaries. To this day he continues to be a controversial figure. In early life and middle age, he fizzed with energy regarding every aspect of physical sciences as then defined within the scope of his inquiries. He argued that science (establishing the term for the first time) must be based on measurement and on testable, mathematically formulated laws.

As is well known, Galileo laid the foundations for how objects move on the surface of the Earth (the science of mechanics). It was he who first realized that we should focus on acceleration, not velocity, and that forces on bodies cause their motion to accelerate, the increase in velocity being a by-product. Over a period of time, he devised a series of ingenious experiments to test the behavior of bodies in free fall and on sloped surfaces. It was through Galileo that the laws and language of dynamics developed. He tested his concepts of motion through the use of inclined planes. From these experiments he developed quantitative concepts of force, as a cause for accelerated motion.

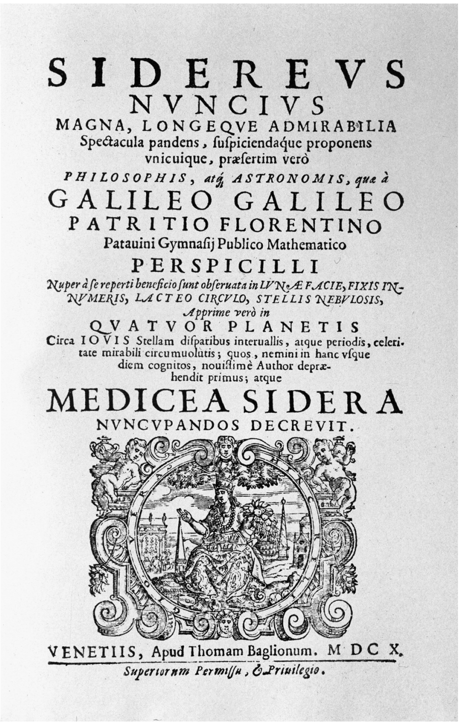
Galileo understood that objects fall because a force, gravity, pulls them down, and of course he is most famous for establishing that all falling bodies, regardless of their weight, are accelerated by gravity at the same rate. While he may or may not have actually done the experiment from the Leaning Tower of Pisa, his conclusion was fundamental in encouraging Newton to propose that the gravitational force on all bodies was in proportion to their masses. He concluded that the natural state of an object experiencing no force is rest or uniform motion. Finally, in what some scholars have described as his greatest contribution to physics, he articulated the principle of inertia: a moving object will remain in its state of motion unless an external force acts on it.

Galileo must also be credited with persuasively advancing another fundamental tool of modern sciences: the mathematical method. The ancients considered natural law as a given, whereas Galileo showed that the laws of motion could be described using mathematics. He established a new and powerful mode of analysis that was followed by Newton and all successors in the physical sciences.

Galileo was not only an innovative mathematician, but also an observer. Many readers will have heard 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." By early 1610 he had improved the magnification to 20x and then to 32x, at which point he started to look at the night sky. What did he see? Much is made, and rightly so, of his observations of Jupiter and its four moons collectively named in his honor, as well as his observation of the phases of Venus. At a stroke, these observations decisively demolished the Aristotelian cosmos; but they were perfectly consistent with the Copernican model. With his keen eye and brilliant mind, Galileo confirmed that the structure of the solar system was in accord with the Copernican heliocentric hypothesis.

Our interest lies in what Galileo discovered when he shifted his vision beyond the solar system, to the starry realms beyond. Wherever he aimed his telescope, he spied far more stars than can be seen by the naked eye. In 1610, Galileo released his findings in a popular book *Sidereus Nuncius*, or, *The Starry Messenger*. It had taken him just three months to complete, and it made Galileo a



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, ſuſpiciendaque proponens
vnicuique, præſertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnaſij Publico Mathematico
PERSPICILLI
Nuper à ſe reperti beneficio ſunt obſeruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam diſparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vſque diem cognitos, nouiſſimè Author deprændit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M D C X.
Superiorum Permiſſu, & Priuilegio.

Figure P.3. Title page of *Sidereus Nuncius*, the book in which Galileo describes his great telescopic discoveries of 1609–10.

Figure P.4. Title page of Galileo's popular book on the geocentric and heliocentric models of the solar system. The engraving is a representation of Aristotle, Prolemy, and Copernicus with a maritime scene in the background. This was a popular book that got Galileo into serious trouble.

celebrity. In the constellation Orion alone, he quickly found five hundred new stars. He described how the telescope revealed "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:

> 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.

In 1611 he made a triumphant visit to Rome, where Cardinal Robert Bellarmine, head of the Roman College, asked his mathematicians for their opinion of Galileo's discoveries. They confirmed them all. From then on, until 1633, the infamous Galileo Affair clattered along in Rome, culminating in Galileo's trial for heresy and his conviction. Despite the continuing hostility of Catholic theologians to Galileo's work, by the mid-century the heliocentric model had pretty much swept the field, thanks in large measure to another of Galileo's popular science books, *Dialogue Concerning the Two Chief World Systems.* His international fame was such that the young English poet, John Milton, visited him during Galileo's confinement under house arrest in 1638.

■ The Impact of Copernicus: Kepler's Laws

Johannes Kepler, the German mathematician and astronomer, borrowed from Galileo the idea that one material object can invisibly exert a force on another. The concept that an invisible force field was at the heart of the solar system was to have extraordinary influence: as we shall see, it formed the basis for Newton's discoveries. Kepler imagined that the Sun was rotating and sending out an invisible influence that weakened with distance from the Sun. This leap of intuition led to Kepler's biggest breakthrough: the Sun controlled the planets through three laws. Expressed in modern form, the first law states that each planetary orbit is an ellipse, not a circle, with the Sun at one focus. At a stroke, one simple device—an ellipse—demolished all the perfect circles of antiquity and the medieval period. And, since the circles did not actually fit the orbits of the planets, the extra smaller and smaller epicycles, which had been added, could also be tossed aside at one stroke.

Kepler's second law states that the straight line drawn from a planet to the Sun traces out equal areas in equal times. When the planet is close to the Sun it moves more rapidly than when it is far from the Sun. This law swept aside the classical obsession with uniform motion (and in modern terms expresses the constant value of the angular momentum of a body in orbit). Finally the third law, the one that satisfied Kepler the most, is about heavenly harmony: the squares of the periods (the period being the time it takes for one rotation around the Sun—a year for the Earth) of planets are proportional to the cubes of their distances from the Sun. Through these laws, Kepler created celestial mechanics, in a final break with Aristotle. For the first time, an astronomer had demonstrated that the orbits in the solar system followed a common mathematical structure. Again, mathematics, specifically geometry, had triumphed in the heavens.

Working during much the same period as Galileo, the French philosopher René Descartes produced major works, but he was of a younger generation. A striking feature of Descartes' methodology is that it is driven by philosophy. He reveled in mathematics, becoming much impressed by the certainty that mathematics made possible, by way of its axioms, theorems, and proofs a precise description of reality. This led him to believe that geometrical reasoning could be used to probe the structure and mechanics of the universe. The cosmological structures that Descartes deduced from his metaphysics were extremely radical. The Cartesian model of the universe was packed solid with matter—there was no vacuum anywhere. Had there been no motion, there would be no difference from one part of the universe to another: the entire universe would have no structure. However, Descartes' philosophy supposed that there is structure in the cosmos, because matter is in motion; and, Descartes pictured matter in motion as vortices. The solar system was one such vortex, mostly made of invisible matter. In a period in which machinery, particularly astronomical clocks such as the one in Strasbourg Cathedral, offered a model of the universe, Descartes and his followers developed a mechanical philosophy. But—and the distinction is important—this philosophy was not science" in the terms spelled out by Galileo, as it did not involve measurements and testable hypotheses.

The next move forward came from Isaac Newton, who was born in the year of Galileo's death.

■ Isaac Newton and Gravity

Cartesian philosophy was all the rage when Isaac Newton arrived at Trinity College, Cambridge early in June 1661. The University was still officially in the thrall of Aristotle, as it had been since its foundation. Intellectual vigor had departed long before: learning was performed by rote, without enthusiasm. Cambridge was then a backwater: two-thirds of the students left without a degree, and the only relevant professional training was for a career in the Anglican Church. Newton found the official curriculum in a state of advanced decay. He became an autodidact: almost everything useful that Newton learned at Cambridge was the result of his own reading in solitude rather than from formal teaching.

Newton devoured the works of Galileo, Kepler, and others, and his student notebooks also reveal an interest in Descartes, though his investigations of light and vision eventually led him to reject Descartes' system of thought. He pointed out that, in the Cartesian system of vortices and pressure, eclipses would be impossible. He also made sketches, based on his own experiments, of the refraction of light through a prism. Crucially, he had the insight to realize that ordinary light is a mixture of colors. With that discovery, he understood that glass lenses would always produce colored halos around images. It was then a small step to invent the first reflecting telescope for astronomical research.

A second aspect of Newton's agenda interests us because he addresses the cosmic order and the nature of matter. He first taught himself Kepler's astronomy, after which he began to ponder the cause of gravity. What force exerted by the Sun could result in planetary orbits that satisfied Kepler's three laws with such precision? In December 1664, he sat up for many nights observing a comet, recording its changing position in his notebook. But then a natural phenomenon of a different order interrupted his research.

A disastrous plague had descended on England. When it reached Cambridge, the university was disbanded. At Trinity College the steward posted a notice at the Great Gate on August 7, 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, everyone was sent packing with a month's wages. The university returned to normal only in the spring of 1667.

Newton, now with his BA degree, returned to Woolsthorpe to live with his wealthy mother. Newton's genius first flourished through private study during 1665–66. According to his 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."

It is worth recounting the steps Newton made toward his universal theory of gravitation. During the plague years he plunged deeply into mathematics, and developed the differential calculus that would be important to him because it gave him the tool needed for calculations on things that vary, such as the changing position of an orbiting planet with time. He also made advances in optics, obtaining the first good-quality spectrum of the Sun by projecting it with his prism onto a white surface and showing that it was composed of the colors of the rainbow.

What are we to make of the story of the apple? Numerous writers of popular science assert that Newton hit upon the law of universal gravitation as a flash of inspiration. In an early biography, his half-niece, Catherine Conduitt, said that the fall of an apple led young Newton to compare the gravitational force at the Earth's surface with that on the Moon. Yet, it is more likely that insight came more gradually. When the elderly Newton had reached celebrity status, he said: "I keep the subject constantly before me, and wait 'till the first dawnings open slowly, little by little, into a full and clear light." By 1666, he had the first dawning, but the bright light lay well in the future. Newton was elected a Fellow of the Royal Society in 1672. His new contemporaries in London were then hotly debating the mysterious influence that caused the planets to revolve around the Sun in ellipses. The sages asked: What is the mathematical form of the force law that stops planets from shooting off along a straight line into space?

In 1684, three famous men came to the brink of a mathematical solution to this question. The trio comprised the young Edmond Halley (of comet fame), Robert Hooke (Curator of Experiments at the Royal Society), and Sir Christopher Wren (a founder of the Royal Society, a former Savilian Professor of Astronomy at Oxford, and a highly esteemed architect). Halley already 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 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, this time stating explicitly that he supposed "the Attraction is always in duplicate proportion to the Distance from the Centre Reciprocall." That's the inverse square law. At the meeting of the Royal Society on January 14, 1684, Hooke claimed that all laws of celestial motion could be derived from an inverse square law.

Later in 1684, Halley quizzed Newton in Cambridge 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." Two months later, Newton sent his friend a neat nine-page paper explaining the mathematical basis for Kepler's three laws.

An ecstatic Halley pored over that paper. In it, he found a grand synthesis: a single statement replaced Kepler's three empirically derived rules. 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 Mathematica*.

Newton immersed himself in the project. While he was writing *Principia*, Newton did nothing else for eighteen months. No alchemy. No theology. He forgot to eat. College servants attending to his needs complained that they saw "his Mess was untouched." 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 *also* 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. In the Newtonian universe, all motion was subject to exact laws that applied throughout the entire universe, the structure of which would be influenced by the action of gravitational forces. Newton's path to the law of universal gravitation was a combination of precise observation with the mathematical formulation of a law of nature. It was to be an awesome synthesis, not to be improved upon until 1915.

As we have seen, Kepler's laws applied just to the planets, while Newton's synthesis gave a single force law that applied throughout the universe and could predict equally well the trajectory of an artillery shell or the orbit of a planet. 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" which sets out three laws of motion, as well as the law of gravitation. His greatest contribution was to unify the laws of heaven and Earth into a single framework. 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.

Figure P.5. Pierre-Simon Laplace (1749–1827), French pioneer of celestial mechanics whose work was translated into English by Mary Somerville. (Engraved by J. Pofselwhite and published in *The Gallery of Portraits: With Memoirs* encyclopedia, London: C. Knight, 1833. Shutterstock, Copyright Georgios Kollisdas)

While his three laws of motion worked exceedingly well for describing the motion of point particles, the mathematician Newton was presciently doubtful that they could apply to the universe as a whole. He was aware that, strictly speaking, the force of gravity could lead to instability; since the force is always attractive, the heavens might therefore collapse under their own weight. For that reason, the theologian Newton speculated that supernatural intervention would occasionally be required to prevent chaos in the cosmos.

In the eighteenth century, the impact of Newton's theory was most noticeable in France, where a succession of brilliant mathematicians applied themselves to analyzing motions in the solar system using Newton's laws of motion. Their soaring achievements did not in the end contribute to the quest to understand the origin of structure in the universe. However, we note in passing that, in 1796, Pierre-Simon Laplace (deservedly called the French Newton) published a popular account of the origin of the solar system. It is in complete conflict with the ideas that Newton had on this subject; he believed that the solar system had been created in its present form only a few thousand years earlier, and invoked a "God of the gaps" to explain the observed harmony and symmetry. In contrast, the same inexplicable harmony led Laplace to the concept that the system had arisen far in the past from a primitive rotating cloud, a "solar nebula." Laplace viewed the solar system as originating from the cooling and contraction of a flattened, slowly rotating cloud of incandescent gas. That picture survives to this day as a likely account of the nebular origin of the solar system. And on the largest scales, the contraction under gravity of great clouds of matter is today regarded as an important process for understanding why the universe has the structures we see and call spiral galaxies.

Now our journey will assume a different trajectory: we will pause in our exploration of theoretical developments in order to see how the remarkable astronomer William Herschel (1738–1822) discovered the stellar universe in the 1780s through observation.

■ William Herschel Discovers the Universe

In 1757, the musician and army bandsman William Herschel arrived in England as a penniless refugee from the Seven Years' War in which the French had ravaged his homeland, Hanover. In our narrative, the gripping story of how William picked himself up by his bootstraps and eventually established himself as an accomplished musician in the fashionable city of Bath Spa would be out of place. William enters our account in 1779: he has developed a keen, vocational interest in astronomy and is already accomplished at building superb, reflecting telescopes, which he uses to sweep the heavens. In this period, professional astronomers in London and Paris remained obsessed with applying mathematics to the solar system, neglecting the starry universe that was visible outside the planetary realm.

As an amateur astronomer, Herschel introduced a new methodology into astronomy: the concept of conducting a complete sur-

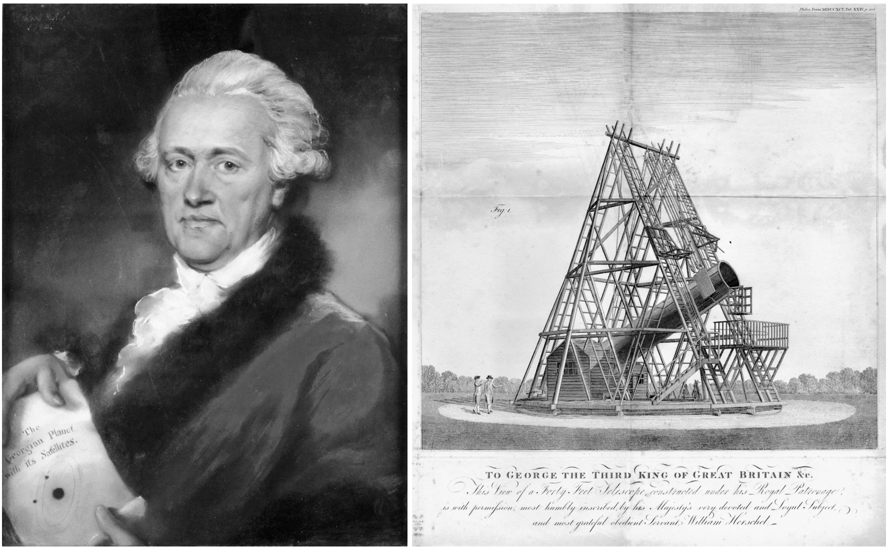


Figure P.6. *Left:* William Herschel, astronomer and musician. (Herschel Family Archives) *Right:* William Herschel's great 40-foot telescope (completed in 1789 for Observatory House, Slough, England) had a focal length of 12 m and a mirror with a diameter 1.2 m. It was the largest telescope in the world for more than half a century, being overtaken by the Rosse telescope in 1845. (Royal Astronomical Society Archives)

vey of all visible examples of a particular class of celestial body. One can think of this as an update of Ptolemy's catalog of a bit more than 1,000 stars, but with the enormous advantage that the telescope had replaced the human eye. Herschel's decision to survey the universe beyond the solar system is a key moment in the long history of attempts to understand the origin of structure in the cosmos (the largest current catalog, resulting from the Sloan Digital Sky Survey, contains data on over 260 million stars). He leaped ahead of the professionals by focusing on making new observations, rather than precisely measuring motions in the solar system.

In the cultured society of Bath, Herschel rubbed elbows with natural historians; and, following their example, he applied their methodology, of collecting specimens, classifying them, and then constructing a life history, to the realm of the stars. Before long, he decided to explore the entire universe on the same principles: observe the variety of celestial species, and arrange the specimens to create an evolutionary sequence. He was the first to apply this approach (natural history) to astronomy, a technique that the future Edwin Hubble would invoke in 1929 to classify galactic structure. When Herschel commenced in astronomy as an amateur, he read about a mechanical universe that ran like clockwork. He went on to breathe life into this machinery of cogs and wheels by showing that the milky nebulae had a life of their own, in which the force of gravity would cause nebulae to evolve, to become more compact with the passage of cosmic time.

Herschel swept the vault of the heavens with his trusty seven-foot telescope whenever there were clear skies. Then it happened. On March 13, 1781, the world's most accomplished amateur astronomer scoped a new planet during the course of his second survey. To cash in on the discovery, Herschel named the new planet *Georgium Sidus* in honor of King George III. The grateful king vested on Herschel a lifetime pension so that he could work full time on astronomy, and he later provided grants for new telescopes. We now know this "Georgian star" as Uranus, the seventh planet. Herschel became famous overnight. Renowned visitors descended on the Herschel household at 19 New King Street, Bath, anxious to meet the discoverer and examine his telescopes. Awards followed: in 1781, the Royal Society handed him the Copley Medal and elected him to Fellowship. The following year George III appointed the celebrity as his personal astronomer.

In 1783, Herschel began his epic work by sweeping his incredible 20-foot hand-made telescope across the heavens to record the distribution of both stars and nebulae across the entire, visible sky. The word "nebula" had been used since antiquity to describe celestial objects that present a blurred, misty, or milky appearance. Initially Herschel believed that all of the nebulae were just that: cloudy objects rendered misty by distance. He would later change his mind on that subject. At the outset, he knew that the survey would take many years; but, as he wrote to a friend, "it is to me far from laborious . . . it is attended with the utmost delight."

From this survey he attempted the first basic classification of the nebulae, according to their shape and structure, and with the explicit aim "to investigate the Construction of the Heavens." In the case of star clusters, he classified them according to their degree of clustering, ranging from "very compressed and rich" to "coarsely scattered." And, Herschel began to do what we would term astrophysics. He sensed that, within a cluster of stars, an attractive force is at work, and that the degree of clustering is a measure of the length of time over which the attractive forces have acted. Crucially, he realized that the variations he was seeing in the structure of nebulae and clusters indicated that some are older than others, and that they lie at different distances.

In a highly imaginative move, he began to investigate the structure of our galaxy. The general shape of the Milky Way—which is the insider's view of the galaxy—had been known since ancient times. But, to accurately delineate the structure of the Milky Way, Herschel invented a new observing technique that he named star-gauging. He simply counted how many stars he could see through the field of view of his 20-foot telescope, and then stepped across the sky, field by field, taking an inventory of the number of stars in each field of view. By 1785, he had made a systematic slice through the Milky Way galaxy, which he described as "a very extensive, branching, compound Congeries of many millions of stars," and sketches made in his notebooks illustrated the Milky Way's cross-section.

By 1790, he had come to the firm conclusion that nebulae were systems composed of stars. He felt that misty nebulae, such as Orion, were vast systems of stars at great distances. However, on the question of whether the universe was composed only of our Milky Way, or whether nebulae were starry systems, "island universes," outside our own galaxy, he changed his mind. The construction of the heavens beyond the solar system was, he thought, only made of stars, and nebulae were not actually other galaxies like our own.

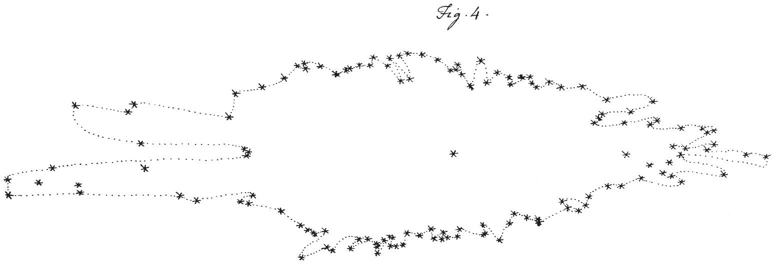


Figure P.7. One of William Herschel's cross-section sketches showing the structure of the Milky Way. This structure was deduced by the method of star counts. Herschel was of course not aware of the effects of interstellar dust, which obscured distant stars and unfortunately invalidated his method. (Royal Astronomical Society Archives)

Professional astronomers had essentially no interest in any of this, because none of them had telescopes that could compete with Herschel's. So the next step in resolving the puzzle of the nature of our universe, and whether it was composed only of the Milky Way, had to await the construction of even larger telescopes.

■ Understanding the Universe Becomes a New Kind of Science

By the middle of the nineteenth century, thanks to the work of Galileo, Kepler, Newton, and Herschel, in particular, the spirit of intellectual enquiry in Europe and the United States had turned decisively toward the goal of expanding humanity's vision of the cosmos and explaining how and why objects behave as they do in terms of mathematics and physics. In other words, the quests to understand the nature of stars, the meaning of the nebulae, and the overarching construction of the heavens were problems for which the solutions lay in classical physics and astrophysics, rather than positional and dynamical astronomy. In fact, the word and the scientific field of astrophysics was invented at the turn of the century when, in 1895, George Ellery Hale launched the *Astrophys-*

ical Journal to be the place where discoveries in the new science were to be published.

Among the most major problems that would occur to someone trained in physics was the one that any child might ask: why does the Sun shine? No known earthly fuel could provide enough energy, and if the energy was being provided by gravitational contraction, then a simple calculation made by physicists at the end of the nineteenth century showed that the Sun would only last for millions of years, much briefer than the age of the Earth, as known from the geological record. This obvious question and a host of others could be and were being asked for the first time as the laws of laboratory physics began to be applied to the universe surrounding us.

This was the intellectual *zeitgeist* leading up to the time in which our first chapter begins. A dramatic transformation was under way, in terms of the tools scientists would use to understand the cosmos and our place within it. Not everyone recognized this, and at the turn of the twentieth century, many thought that the laws of physics dominating the observable universe were so well-defined and complete that only a few, small refinements were still needed. The gaps in our understanding were overlooked. The majority of astronomers were also persuaded that there was little left to discover from an observational standpoint; the majority view was that the entire universe was composed only of our galaxy, the Milky Way, and that the well-understood solar system was to be found in the center of that disk-like assemblage of stars.

From our perspective in the current day, we can see that—in spite of the extraordinary leaps of thinking that occurred since we began this prologue—cutting-edge astronomy and physics at the turn of the century still had a long way to go. As it would turn out, the most astonishing advance in humanity's understanding of the laws of physics since Newton's proposal of a law of universal gravitation was yet to come. From the smallest structures, atoms, to the largest ones, galaxies and the universe, the new physical laws of quantum mechanics and relativity brought a revolutionary change to our understanding of the natural world. This is the subject of the next chapter. We will begin it immersed in the spirit of scientific hubris and complacency that characterized the turn of the century. While most scientists felt their toolkit of physical principles was essentially complete, a young physicist was about to show the world otherwise.

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