Stargazers

Allan Chapman

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Copernicus, Galileo, the Telescope and the Church

The Astronomical Renaissance 1500–1700

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To Rachel: Wife, Scholar, and Best Friend

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Preface

Galileo is probably the most written-about figure in the entire history of astronomy. His life, and in particular his condemnation on a technical charge of heresy in 1633, has inspired poets, artists, novelists, playwrights, and hagiographers, especially in the wake of the "Romantic" movement after c.1780, and the post-Russian-Revolutionary and Nazi eras. Yet was Galileo really the "martyr" to intellectual freedom that popular legend intones?

And a century before him, was poor Copernicus – the "Timid Canon" of Arthur Koestler's excellent *The Sleepwalkers* (1959) – really the publicity-shy lone genius keeping his great thoughts to himself, and only daring to disclose them to the world when he felt death's hand upon him?

What I hope to do in *Stargazers* is not only to re-visit these stories and re-examine them within the wider context of well-documented history, but also to look at the significance of the achievements of other figures whom the popular historical perception has cast into a mere supporting role. These include Tycho Brahe, who appeared to be famous because he was an irascible Danish aristocrat, with a golden nose and a pet dwarf, who did arcane things with big instruments from his exotic island castle observatory. Then there was Tycho's "lapdog", the German Johannes Kepler, who had strange theories about occult forces, and said that the planets moved in ellipses.

What is unfortunate, however, is that this legendary history of astronomy rarely addresses awkward recorded facts: that the sun-centred astronomical theories of the "Timid Canon" Copernicus, for example, were already well known long before he died, and that in his own lifetime Copernicus was both a highly respected ecclesiastical lawyer and a medical doctor of considerable standing. And if being a "Copernican" was so dangerous, how was it that the Lutheran Protestant Kepler, who published his first overtly pro-Copernican treatise aged 25, in 1596, would go on to be employed, and respected, by two deeply Catholic Holy Roman Emperors in Prague, and would *never* be hauled up before the Inquisition?

Instead of being concerned with the supposed "confrontations" of legend, *Stargazers* looks at the bigger picture, setting the great astronomical discoveries and innovations within the wider context of the Renaissance: the Italian Renaissance for Galileo, and what I style the "Northern Renaissance" for Copernicus, Tycho, Kepler and a good few others. For the astronomical discoveries were part of a pan-European cultural movement which included not only Leonardo, Machiavelli, and Monteverdi, but also Shakespeare, Luther, and Rembrandt. And that pan-European movement was not just about art, literature, and music, but also about business, global exploration, religion, education, politics, medicine, science, and much else besides.

Nor does the tale end with the death of Galileo. The full story is much more multi-faceted than the received opinion that Galileo's condemnation somehow terminated scientific progress in Catholic Europe, thus enabling enlightened "work-ethic"-driven Protestants to bound ahead unimpeded by the heavy hand of "the Church".

Stargazers also reminds us that the Renaissance astronomical enterprise was about much more than the debate on whether the earth rotated around the sun, while the Renaissance scientific enterprise was larger still. This enterprise, indeed, included rapidly-advancing sciences such as optics, geomagnetism, experimental and theoretical physics, chemistry, terrestrial and lunar cartography, anatomy, biology, medicine, physiology, early fossil geology, geophysics, and even aeronautics.

Discoveries and innovations abounded: from Jesuit missionary priests building model steam engines for the Emperor of China, to Italian professors discovering new planetary satellites, to Dutch Calvinists wrestling with elliptical orbits, to Anglican clergymen not only founding the Royal Society of London, but also electing scientifically-distinguished overseas Catholic and Calvinist colleagues into the Fellowship.

Not only was "modern science" coming into being, but also the truly international "brotherhood" (and more recently, the "sisterhood") of science. Nationality, religious denomination, and political loyalties mattered less than did an individual's "genius", or ability to advance science yet further. As Latin was still the international tongue of learned Europe, a German could easily correspond with an Italian, and a Scotsman read a book written by a Pole.

What all these men possessed was a growing realisation that scientific advancement in all fields was not solely about big, inspired ideas; it was also about the down-to-earth recognition that any scientist was only as good as his *facts*. The "big ideas" were all well and good, but would only be of enduring value if they squared up to the reality of increasingly precise observation and measurement that could be cross-checked and confirmed by colleagues using state-of-the-art precision instruments – telescopes, microscopes, barometers, magnetic and optical devices – and rigorous experimental procedures.

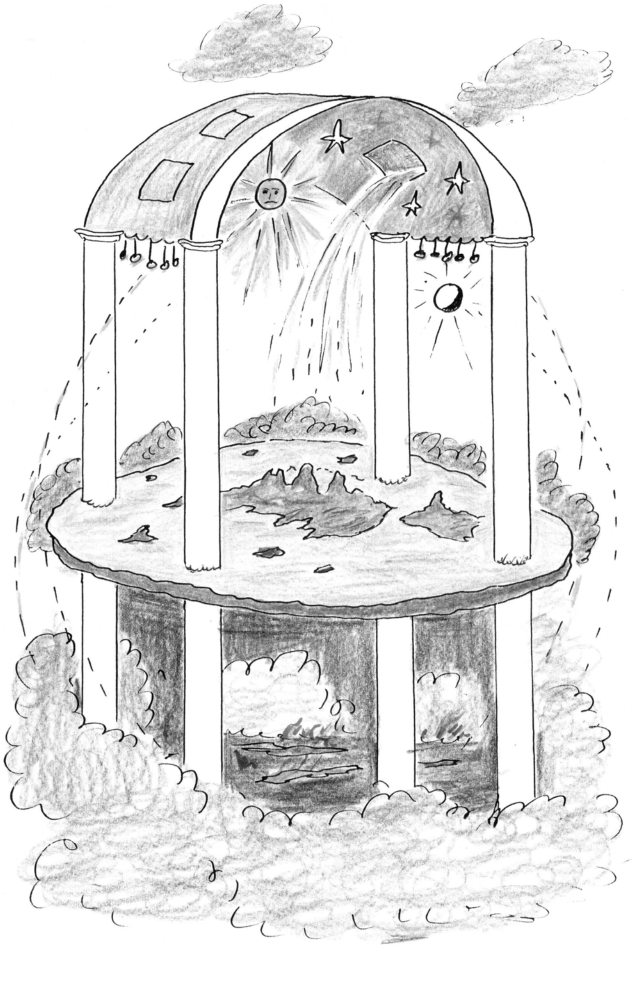
So a big idea about any aspect of the natural world now had to stand up to rigorous international peer review. And for that, precision instruments were becoming absolutely crucial. For an instrument enabled a researcher to detect, measure, and quantify things in nature of which our five unaided senses were oblivious. Things such as the craters on the moon, the individual stars that made up the Milky Way, microscopic "animalcules" in body fluids, barometric pressure, and meteorological changes – and those exceedingly tiny angles that would demonstrate beyond all dispute whether or not the earth really did move around the sun.

The acid test of Copernicus's theory lay not in brilliant rhetoric or philosophical argument, but in the measurement of the exact angular position of astronomical bodies, made with instruments of increasing accuracy. The clinching physical argument was the discovery and exact quantification of those phenomena which, in 1728, would be called the aberration of light, and then, in 1836, the stellar parallax. That is why our story does not end with Galileo, but carries on for a good eighty years after his death, and ultimately, a further century after that.

During this odyssey of human ingenuity, it is hardly surprising that many ancient cultural "truisms", such as astrology and alchemy, bit the dust: truisms that made perfect sense in an earth-centred universe of planetary and starry spheres, but evaporated in the new sun-centred solar system and possible cosmological infinity of 1730.

And as the truth is often stranger than fiction, so, I would argue, the full story of Copernicus, Galileo, the telescope, the Church, and beyond, becomes even more fascinating when placed in context within the wide sweep of European Renaissance civilisation. So read on.

Allan Chapman
Oxford
August 2014



1.1 The "three-decker universe" of *c.* 1,000 BC, broadly shared by the Old Testament Jews, Babylonians, and Egyptians. Four pillars support the starry "Firmament", sometimes likened to a tent. Above the "Firmament" are waters, the source, for example, of Noah's Flood. The sun, moon, and planets move beneath the starry Firmament, and probably go under the earth when not visible in the sky. The earth is flat, and perhaps upheld by a primordial ocean: the biblical "Deeps", or the Babylonian "Apsu". Beneath it all is the "Pit", Hades, hell, or the Underworld. (Reconstruction: Allan Chapman.)

Chapter 1

New Brightness from Old Light. Part 1: The Classical Cosmology

When Nicholas Copernicus was born, in Torun, Poland, in 1473, many of the leading figures of the age believed that the world was approaching its last days, and Armageddon would soon be upon us. All the signs were there. Contemporary people, for instance, did not live to the great ages achieved by Adam and Eve, Methuselah, or Abraham, and since 1346 Europe had been struck by wave after wave of the supposedly new disease, bubonic plague, which was winnowing the population away. Nor did there seem to be giants on the earth any more, as were reported in the Old Testament, with figures like Goliath, and the Anakims who had so terrified the ancient Jews. As Thomas Paynel put it in the "Dedication" to his *Regimen Sanitatis Salerni* ("Rules of Health of Salerno"), 1541, a man who now reached his forties was reputed "happye and fortunate". Not only did the total human population seem to be shrinking due to plague, but we were getting smaller in size and feebler. Who of the "present age" could compare in power of intellect with Pythagoras, Plato, and Aristotle of classical Greek times, whose writings still constituted the bedrock of learning in 1473? Where could we now find men of the spiritual power of Isaiah or St Paul, or generals of the stature of King David, Alexander the Great, or Julius Caesar? Humanity had become a puny, feeble, dull-witted, worn-out race.

The heavens themselves also seemed to provide further substantiation for this end of the world scenario. Several ominous comets were reported, and on 25 December 1471 a comet with a large tail hung in the winter skies of Europe for over a month.[1] Comets were believed, in accordance with Aristotle's physics, to be the relatively local products of noxious "effluvias" rising up from the earth into the atmosphere, and catching fire from the sun's heat; hence their perceived relevance to the human race. Could it also be that the very heavens were approaching the end of time? It was becoming increasingly clear that even the calendar was running into ever-deeper error, as dates slipped backwards against the seasons. It was becoming difficult, from the existing astronomical tables, to obtain a Europe-wide consensus for the central feast of the Christian year, Easter, the moveable date of which was computed afresh for each year from the full moon at the spring equinox.

Then, when Copernicus was nineteen years old, in 1492, a terrifying red-hot fireball suddenly fell from the skies at Ensisheim, Alsace[2] – another portent, no doubt. No one could have doubted that the devil was more active in the world now than he had been in previous centuries. Who could fail to notice the growing number of witches up to their malevolent activities across Europe, occasioning Heinrich Kramer and Jacob Sprenger to write their subsequently notorious *Malleus Maleficarum* ("Hammer of the Witches", 1487) treatise in an attempt to curb the burgeoning menace? Witchcraft, contrary to present-day belief, had never been seen as a serious problem in the Middle Ages, but by 1480 it was thought to be at the root of every mischief. In addition to descending fireballs, calendar problems, witches, and a miscellany of other portents, there were dire prophecies of the approaching end; for Jewish, Christian, and classical pagan numerologists and number-jugglers had predicted, and were predicting, that the end of time would come in AD 1500, on the basis, generally speaking, of permutations of the number three, the Holy Trinity.

To top it all, Christendom was under visible threat of extinction from "the Turk", for in May 1453 the ancient Christian Greek city of Constantinople (Byzantium) fell to the besieging armies of Sultan Mohammed II, and what was left of the great late classical and medieval civilization of the Byzantine empire was extinguished. Mohammed's armies surged north into the Greek Orthodox and Roman Catholic Balkans, and it seemed touch and go whether heartland Europe would be invaded and whether Christian civilization would survive.

This period in history, the late fifteenth century, is generally portrayed as one of "rebirth", or what nineteenth-century historical scholars would style "The Renaissance". Was not this the age, in which European civilization reawakened from its long sleep of the "Dark Ages", an epoch which had blanketed and stultified Europe across the 1,000 years that followed the end of Greek and Roman classical glory? Was this not an age, in particular, when the pursuit of science had been effectively killed off by an ignorant, totalitarian church which would condemn you to the stake if you so much as dared to think? To understand the magnitude of what happened in European civilization, and in particular, the profound changes that took place in astronomy, cosmology, and science between 1500 and 1700, it is essential that we become aware of the "big picture". For while Copernicus, Galileo, and others were, without doubt, men of genius, they were *not* the isolated figures of legend; they were *not* men who could simply see further than everybody else, or somehow grasped "the truth" while their contemporaries floundered in ignorance, nor did they stand out as lighthouses in a sea of authoritarian obscurantism and murky darkness.

Crucial to understanding the "Astronomical Renaissance" is a clear appreciation of what went before, and of the already existing firm foundations of philosophy, culture, and science upon which Copernicus and Galileo built. This was the "Old Light" from which they were to draw their "New Brightness". Even by 1500, this old light was a good 2,000 years old and, far from being obscured during the medieval centuries, had even taken on a new focus that Pythagoras, Aristotle, and Ptolemy could scarcely have imagined. Copernicus, Tycho Brahe, Kepler, Galileo, and even Newton, along with many others, would fruitfully draw upon it.

As the sixteenth and seventeenth centuries moved on, the omens of decline that haunted the imagination of the late fifteenth century began to lessen in their immediacy. The dreaded year 1500 passed without incident, as did 1533 – five times the number of the Holy Trinity plus the 33 years of age which Jesus Christ had reputedly been at his crucifixion and resurrection –

although the new breed of prognosticators and chronologists that grew up with the Reformation and Counter-Reformation after 1517 brought their own doom warnings, as we shall see in the following chapters.

Bubonic plague epidemics, though continuing to haunt Europe until they mysteriously disappeared after 1670, seemed to claim fewer lives overall. Europe's population was clearly expanding again by 1550 and would continue to do so down to our own times. Witches also came to be regarded differently, as the so-called "Age of Reason" began to view them in a way that more closely resembled the old, more reasonable, medieval view: witches clearly *existed* because they are mentioned in Scripture, but extreme behaviour, delusion, and misfortune could arise from causes other than spiritual malevolence. Burning crazed females solved nothing.

Global politics also changed radically and fundamentally between the fall of Constantinople in 1453 and the Polish King Jan Sobieski's deliverance of Vienna from further Turkish menace in 1683. Improving Western weaponry and military organization, and European domination of the world's oceans, both commercially and militarily, decisively shifted the global balance of power in favour of Europe. The future of Christian Europe seemed far brighter and more hopeful by 1650 than it had two centuries before. These circumstances created the stage upon which the Astronomical Renaissance, from the days of the juvenile Copernicus, through Galileo's 78-year lifespan, and into Sir Isaac Newton's middle age, would be acted out, and made their achievement both possible and culturally relevant.

Yet in all branches of science, great minds are not enough. One also needs perceptive eyes and dexterous hands: scientific instrument technology. Building upon a European tradition of progressive technology going back to the eleventh century – geared windmills, clocks, glass spectacles, and printing, to name but four key European inventions – the astronomers of the "long Renaissance" of 1500–1700 were able to devise a series of instruments that would transform the science of classical antiquity. They would show the world that the "moderns" – the men of 1540 – far from being runts of the litter of history, could, when empowered by a new research technology, leave the ancients standing when it came to making fundamental new discoveries.

Firstly, the great three-masted ocean-going sailing ships of the Renaissance overturned classical geography by discovering continents and oceans that the ancient Greeks had never dreamed of. Next, this new world had to be surveyed, mapped, and published from the new printing presses, demanding a rapid development of practical geometry, precision mathematical instrument making, and cartography. Without these new technologies, Nicholas Copernicus and his great Danish admirer, Tycho Brahe, would never have come to the starting line of discovery.

Secondly, practical optics and the study, manipulation, and use of light advanced rapidly, especially from the late sixteenth century onwards, as the glass-maker and lens-figurer began to improve upon the thirteenth-century technology of magnifying and "visual" glass-making. This optical technology would produce two of the most radical and far-reaching inventions in the history of human ingenuity: the telescope and the microscope. When one combined individual lenses possessing the right geometrically shaped optical curves into deliberate optical *systems*, the ancient bounds of "reality" changed for ever. Two new realms of knowledge were immediately opened up: the telescopic realm of the universe, and the microscopic realm of exceedingly tiny things, both organic and inorganic. Galileo pioneered the telescope as an astronomical instrument, but he also pioneered an early microscope, and was amazed at the complex beauty of insects.

In 1665, Robert Hooke, in *Micrographia*, would sum up the Renaissance age of scientific discovery, and especially the stunning impact of the telescope and microscope upon the intellectual culture of the age. Instruments, said Hooke, were "artificial organs" that gave a new power to our natural and ancient organs of sense. By "artificial" Hooke did not mean *false* (our common modern-day usage of artificial). Rather, he used the word in its seventeenth-century sense, signifying a work of *art* or *ingenuity*, in contrast with something that occurred naturally: a clever piece of devising and contriving, such as a naturalistic oil painting or a microscope, as opposed to a natural object, such as a flower. The

Renaissance not only opened up new domains of light and optical wonder. It also revealed a vast new realm of natural forces, once thought to be mysterious, but now susceptible to measurement and quantification via a range of newly devised "artificial organs". By 1665, these included instruments for the physical study of the earth's magnetic field (compass and dip-needle), atmosphere and weather (barometer, thermometer, hygrometer), and of combustion, flame, and organic respiration (air or vacuum pump). Then there was a panoply of precision-engineered time- and angle-measuring devices (pendulum clock, screw micrometer, precision graduated scales) which propelled astronomy into a realm of accuracy beyond anything that Copernicus could have imagined in 1540, and which would, by 1728, provide the *physical* demonstration of the earth's motion in space, over 200 years after Copernicus devised his original heliocentric model of the solar system.

All of this took place *not* – as the familiar mantra goes – because the "Dark Ages" had ended and brave men dared to "stand up to church tyranny", but because the sheer weight of new physical discovery had revealed things that the wisest Greek philosopher and the most rationally deductive medieval schoolman could never have imagined. Many of these discoveries were actually made by churchmen, Catholic and Protestant, as well as by devout Christian laymen, as we will see in the following chapters. Honest discovery was neither persecuted nor suppressed.

The Astronomical Renaissance came about *not* from the deliberate breaking of the bounds of classical and medieval knowledge, daring radical philosophies, or conscious revolutionary zeal. It came about, rather, as a response to the floodtide of new factual data deriving from explorers in ships and from observatories and laboratories, and by a serendipitous chain reaction of ingenuity and rethinking of what knowledge was and how we could – in the words of Sir Francis Bacon – accomplish its "advancement". The physical discoveries came before the new ideas, as has largely been the pattern of science from 1500 onwards. Discoveries such as that of the American continent, the mountains on the moon, the presence of microscopic creatures in stagnant waters, and the changes in barometric pressure with approaching storms compelled a rethinking of what we already knew as a result of sheer pragmatic necessity if we wanted the world to make sense. When the "big ideas" did appear, be they of Copernicus, Galileo, Newton, or Einstein, they did so because the old theories could no longer adequately explain the new body of data, and we needed to rethink reality.

If these were the circumstances that drove Western scientific culture towards a "New Brightness", then what was the "Old Light" which the men of 1500 inherited from their classical and medieval ancestors?

Classical cosmology

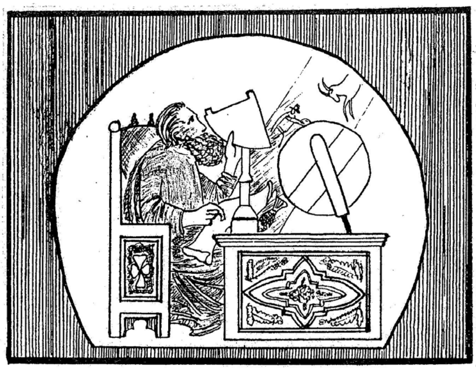
The earth moving around the sun, as proposed by Copernicus, the curious geometry of planets moving in elliptical orbits through the void of Kepler, and the telescopic universe of Jupiter's satellites and – perhaps – the infinitely receding stars of Galileo seemed an affront to common sense in their time. The classical cosmos of the ancient Greek and medieval scholars it came to replace was not only elegant, but was delightfully commonsensical.

It interpreted the facts of the heavens and the earth, as they were then understood (and would continue to be understood for nearly two millennia to come) in accordance with what appeared to be natural and obvious to the eye and to normal experience.

So what did the classical cosmos, as it was still studied and taught in 1500, actually look like? At no time, since early classical Greece, did educated and mathematically literate people believe that the earth was anything but a *sphere*. The story of the brave Christopher Columbus just *knowing*, from a species of superior wisdom, that he would *not* sail over the edge of the earth, and going on to defy all odds, is a modern legend. It dates from early-nineteenth-century American patriotic histories, in particular from Washington Irving's 1828 popular "biography" of Columbus, and later American anti-Christian-church writers such as William Henry Draper and Andrew Dickson White. Though for a long time enshrined in the United States elementary education system, the idea of a flat earth would have made any half-educated person of 1490 – or indeed of AD 490 – roll over laughing. In the sixth century BC, Pythagoras worked on the assumption that the earth was spherical, while Aristotle's *De Caelo* ("On the Heavens") of two hundred years later gives clear evidences of this. Did not a ship gradually disappear from view because of the earth's curvature? Was not the shadow cast by the earth upon the full moon at a lunar eclipse always circular? Eratosthenes around 290 BC even made a remarkably good estimate of the size of the earth in *stadia* (or Greek miles) from the length of the shadows cast between Syene and Alexandria in Egypt.

To the Greeks, geometry was the key to understanding astronomy, for while we transient humans lived within a world of change and decay, we could nonetheless make contact with the realm of the eternal, the perfect, and the beautiful through geometry, mathematics, and logic. Long before the time of Christ, Greek philosophers had come to realize that our minds enabled us to transcend our weak bodies and contemplate the changeless beauty of the divine principle in astronomy and mathematics.

In addition to the philosophy and theology, the Greeks invented practical astronomy, devised the earliest known scientific instruments, and, through a combination of observation, measurement, mathematics, and theoretical deduction, came up with an earth-centred or *geocentric* model of the cosmos which would endure until Galileo's time. After going through several developmental stages in the hands of Eudoxus (*c.* 380 BC), Hipparchus (*c.* 140 BC), and others, it achieved its mature and enduring form in the *Magna Syntaxis* ("Great Synthesis" or "Treatise") or *Almagest* of Ptolemy of Alexandria in around AD 150.

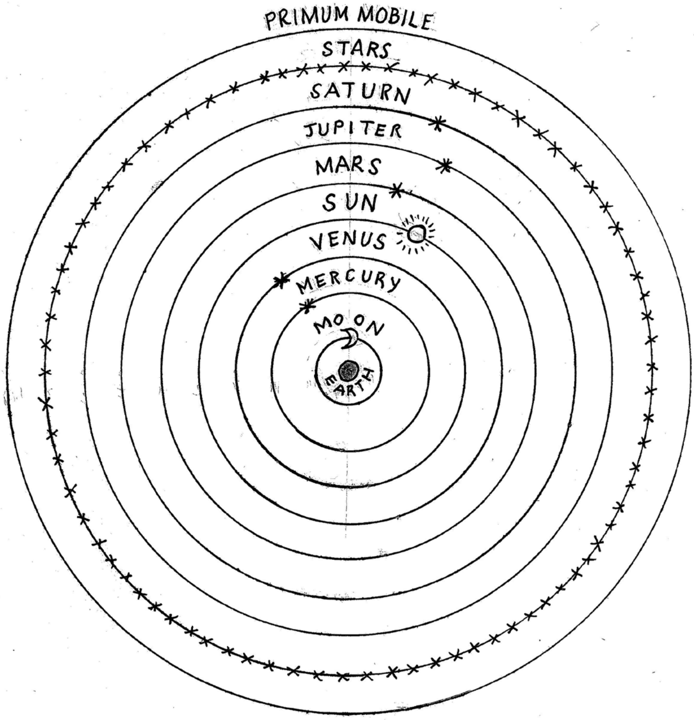


1.2 "Astronomy", on Giotto's Campanile in the Piazza del Duomo, Florence, fourteenth century. An astronomer, thought to represent Ptolemy, observes the altitude of the stars with a small quadrant. (Drawing by Allan Chapman.)

In Ptolemy's synthesis, as developed through his predecessors, the earth was a large sphere set at eternal rest in the centre of nine perfectly transparent "crystalline" spheres that nested concentrically inside each other rather like the skins of an onion, and which rotated around a common polar axis. Seven of these spheres carried the then known planets: the moon, Mercury, Venus, the sun, Mars, Jupiter, and Saturn, while the eighth, black sphere carried the "fixed stars" or constellations. Beyond the stars lay the theoretically postulated ninth sphere, or primum mobile ("prime mover"), which somehow regulated the motion of the others, and beyond this lay the realms of the blessed, the Christian heaven, or the endless void, depending upon one's wider beliefs.

Each of these spheres rotated at a speed unique to itself, and at a perfectly uniform velocity. To understand Greek geometrical astronomy, it is essential to realize that perfectly circular orbits upon perfect spheres, and perfectly uniform orbital velocities were logical prerequisites of the system. As the heavens were, by definition, perfect, it was philosophically impossible that incongruity or irregularity of any kind could be present in their operations.

The nearest, lunar, sphere went around the earth in twenty-eight days, the sun in 365¼, Jupiter in twelve years, Saturn in 29½



1.3 The Greek geocentric universe, with the planetary and starry spheres and *primum mobile* rotating around a spherical central earth. (Drawing by Allan Chapman.)

years, and the fixed stars in one day. All the planets rotated within the relatively narrow zodiac band of the stars, so that when one measured the planetary velocities against the star positions, the moon moved rapidly to define the lunar month – new moon to new moon – the sun went round in one year, and Saturn took nearly three decades to complete a circuit of the zodiac. Each of the planets received its motion from the rotation of the sphere to which it was attached, yet all of the perfect crystalline spheres, except the outermost one of the fixed stars, were thought to be rotating at the same velocity. This meant, therefore, that while

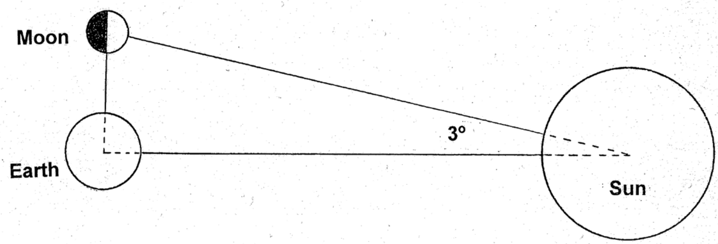
Saturn and the moon were probably travelling at the same speed – in miles per hour, as it were – Saturn *appeared* to move much more slowly because it was tracing a vastly greater circuit across the heavens than did the moon.

Try this experiment. Go to a large field with two friends. Set one friend at a measured distance of 10 feet from you, then ask the other to pace out 300 feet from you. Position them so that, at the outset, the three of you form a straight line: a radial line, with you at the centre. Then, at a signal, ask your friends to walk around you in a circle at the pace of one equal step per second. The friend walking in the 10-foot-radius circle will appear to move rapidly, covering their 63-foot-circumference circuit in 63 seconds, whereas the person 300 feet away will only have paced out 63 of their total circumference of 1,887 feet in that time, yet both will have walked at exactly the same speed.

This is how the ancients explained the perfect, even, synchronous motion of the planets, while at the same time observing a variety of different *apparent* motions. In their highly geometrized way of thinking, this was seen as providing a key to the very distance of the astronomical bodies, for if you could reliably measure the distance of one body, such as the moon, which the Greeks correctly realized was the closest, then by extension it should be possible to calculate the distances of the rest.

Somewhere around 280 BC, Aristarchus of the Greek island of Samos (who, among other things, developed a sun-centred model of the solar system 1,800 years before Copernicus) proposed a geometrical model for measuring the distance of the sun and moon from the earth. It was based upon establishing the exact time of half-moon, or quadrature – a very hard thing to do in practice. He then realized that exactly at the half-moon phase the moon, sun, and earth formed a perfect right-angled triangle with each other; and already knowing the earth's radius in *stadia*, or Greek miles, he proceeded to calculate the lunar–solar distance from the narrow angle of the long right-angled triangle. Aristarchus concluded from this that the sun was nineteen times farther away from the earth than was the moon. (It is around 400 times farther away.)

While his figure fell massively short of the true value known today, his *theory* was actually correct. What Aristarchus, Hipparchus,

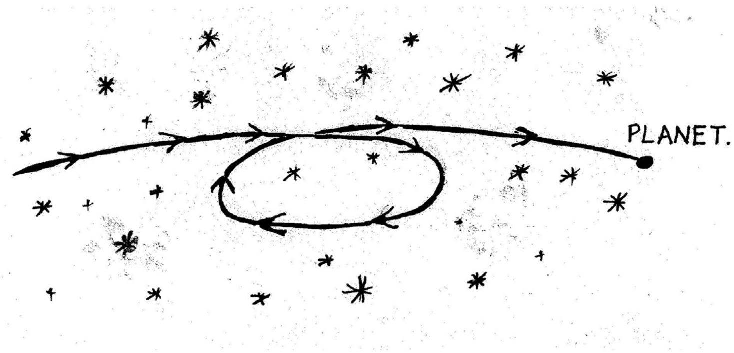


1.4 Aristarchus' attempt to measure the solar distance from the exact half-moon. (Drawing by Allan Chapman.)

Ptolemy, and all the Greeks lacked were instruments of sufficient accuracy to measure the very tiny angles involved: an instrumental problem that would still bedevil Copernicus, Tycho Brahe, and Galileo nearly 2,000 years later. The heart of the matter is that, through their grasp of geometry, their attempted observation and measurement, and logical deduction, the Greeks set astronomy on the right lines, and people were still guided by them when both Copernicus and Galileo were students. By extension, so are we today.

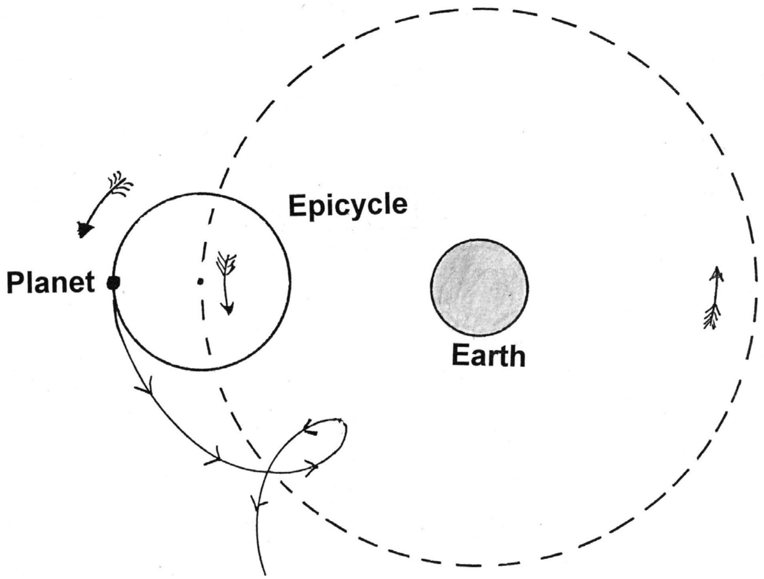
The actual heavens did not behave as neatly as geometrical and philosophical theory demanded. The *observed* planets of reality, as opposed to the ideal planets of philosophical theory, did *not* move at even speeds and unchanging velocities, but sped up, slowed down, and described strange loops in the sky: the *retrograde* motions, as they were technically styled. The moon was the biggest brain-teaser of all, for while it did not describe retrograde loops in the sky, it moved in an extremely complicated orbit that seemed to come full circle in just over eighteen years: what came to be called the Saros Cycle – a cycle that appeared to lie at the heart of the lunar–solar system and which produced eclipses. (This cycle was first noted by those Babylonian astronomers whose earlier work so inspired the Greeks.)

Various "mechanisms" were devised over the ensuing centuries in an attempt to explain the moon's behaviour. Could it be that



1.5 A planetary retrograde, as seen from the earth. Mars, Jupiter, and Saturn appear over weeks and months to perform strange "loops" in their orbits, when viewed among the fixed stars. (Drawing by Allan Chapman.)

while moving in a perfectly circular orbit about the earth, that orbit was *eccentric*, with its centre not corresponding to the earth's centre, thereby causing the moon to swing around us, and be slightly closer at some times than at others? Surely, if the lunar and solar orbits had been perfectly concentric, we should either have lunar and solar eclipses on a monthly basis, or not at all? Then there was the behaviour of the planets themselves, especially Mars, Jupiter, and Saturn, each of which described baffling retrograde loops at certain times in their orbits. Mars, for example, made two such loops for every one of its rotations around the earth, yet Jupiter made twelve, and Saturn nearly thirty. They seemed to make as many loops as they took years to complete a full circuit of the zodiac, as viewed from the fixed and central earth – a point Copernicus would struggle with many centuries hence. Eudoxus, Hipparchus, Ptolemy, and others all wrestled with the retrogrades, each making his own contribution to what would serve as the solution that would survive until, and beyond, Copernicus's day. By the time of Ptolemy, in the second century AD, this *epicyclic* theory had been brought to its mature development, in which a planet-carrying circle rotated around an empty point which itself rotated around a centre, such as the earth, to describe a geometrically elegant loop, or *epicycle*, all within the geometry of perfect albeit eccentric circles.



1.6 The epicycle. Two perfect circular motions – the motion of the epicycle's centre around the earth, *and* the planet's rotation around the epicycle's centre – can be made to create a forwards–backwards looping of the planet as seen from the earth. (Drawing by Allan Chapman.)

As the centuries rolled on, all those astronomers and cultures that had inherited the classical universe of the Greeks, and especially Ptolemy's great *Almagest,* began to find that the observed heavens were not squaring up to predicted theory. This discrepancy would fuel the great astronomical enterprise of medieval Arabia and Europe. Yet before examining astronomical developments during the Middle Ages, let us first look at classical ideas about the forces of nature, for they too would mould the thinking of Copernicus, Galileo, and other figures in the Astronomical Renaissance.