Astronomers' Universe

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Peter Grego • David Mannion

Galileo and 400 Years of Telescopic Astronomy

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Foreword

Galileo Galilei's life and work is one of the great dramas of science, part success and part near-tragedy. His name is honoured, and remembered, by the naming of 2009 – the 400th anniversary of his seminal observations. Galileo's work marks the starting point of an in-depth study of the history of astronomy by David Mannion and Peter Grego – and what a study it is.

The scholarship in this book is excellent. Although a book for school and amateurs – of which there are very many in the world – the depth of treatment is considerable. Nevertheless, all can read it with both pleasure and instruction. The audience should also include professional scientists, indeed anyone with an enquiring mind will find considerable pleasure in its pages.

An unusual but useful feature are the frequent "projects" that the reader is invited to carry out.

The historical chapters form a fine introduction to the eventual description of contemporary astronomy with its own excitements and puzzles.

Galileo Galilei would have been proud of the modern astronomers and also, I think, of Mannion and Grego – who have described so well his discoveries and the exciting science to which they led.

Sir Arnold Wolfendale FRS,
14th Astronomer Royal
July 23, 2009

Preface

For many thousands of years – from the moment that the first thinking human gazed at the skies with curiosity up until the early seventeenth century – people were restricted to viewing the Universe without the use of telescopes. Seasonal cycles, the phases of the Moon, and the motions of the five "wandering stars" were among the first celestial phenomena to be noted. Ever hungry for explanations, humans needed to invent cosmologies to make sense of our place in the Universe. Needless to say, speculation about the cosmos, based partly on observational evidence but mixed with a great deal of conjecture, led to sky lore and saw the incorporation of the heavens into religion. Glorious yet untouchable, the heavens were thought to be an abode of the gods. Throughout the world, in many different human cultures, the heavens were studied in order to divine the plans of the gods, to foretell the future, and to explain great events.

By about the second century BCE, the brilliant work of a number of Greek astronomers such as Aristarchus, Anaxagoras, and Eratosthenes led to the use of mathematics and geometry to attempt to measure the size of the Sun, the Moon, and Earth, and to determine the distances from Earth to the Moon and Sun. The culmination of the astronomical work of the Greeks was brought together by Ptolemy in his great book, the *Almagest*. Fortunately this book was translated by the Arabs in the ninth century CE as Europe passed through the Dark Ages, but the knowledge was passed back and translated into Latin throughout Europe in the eleventh to fourteenth centuries.

It was during the fifteenth and sixteenth centuries that the widely held western view of the Universe as propounded by the Church and based on the *Almagest* was challenged by the likes of Nicholas Copernicus, Johannes Kepler, Tycho Brahe, and Galileo Galilei – great intellects whose own observations forced them to call into question the "unquestionable old knowledge." With his fervent desire to publish the results of his experiments and observations, and his use of the newly invented telescope to make astronomical observations, we have come to regard Galileo as the father of modern science.

A complete change from the long-established geocentric view that anchored Earth firmly to the center of the Universe, to a heliocentric universe with planets and their moons orbiting the Sun, was ushered in at the dawn of the era of the telescope. Later that century Isaac Newton (1643–1727) explained the workings of the Universe with his theories of gravity and kinematics; in the following centuries the distances to the nearest stars were determined, it was realized that our small Solar System is orbiting a vast conglomeration of stars that make up our home Galaxy, and we have discovered that our Galaxy is just one of 100 billion galaxies in an expanding and accelerating universe.

This book is devoted to telling the amazing story of how our knowledge of our Universe was built up during the past 400 years, from the early beginnings of telescopic astronomy through a series of remarkable visual discoveries and to the opening up of the whole of the electromagnetic spectrum and the new astronomies. It is a celebration of the work of generations of astronomers and looks to the exciting future of astronomical research.

While intended to paint a broad picture of the development of telescopic astronomy, a number of intriguing vistas in astronomical history are explored. A complete and exhaustive portrayal of astronomy is, of course, beyond our remit, and if we've neglected to describe certain areas that might have interested the reader, it's not through lack of insight, just lack of space!

Anyway, it is hoped that the excellent work of Galileo and subsequent generations of astronomers will serve as an inspiration to some readers to go and emulate their work: coming soon we have a round of intense solar activity, with sunspots on the Sun reaching maximum due around 2012/2013 and a rare transit of Venus in 2012. Meanwhile, the rest of the Universe is no less amazing to explore and enjoy. Anyone with a small telescope can, for example, marvel at the perpetual waltz of the four Galilean moons of Jupiter, have their eyes opened by the countless stars and deep-sky gems of the Milky Way, and have their retinas tickled by photons millions of years old arriving from the furthermost reaches of the galactic Universe.

Happy observing!

August 2010 Peter Grego and David Mannion

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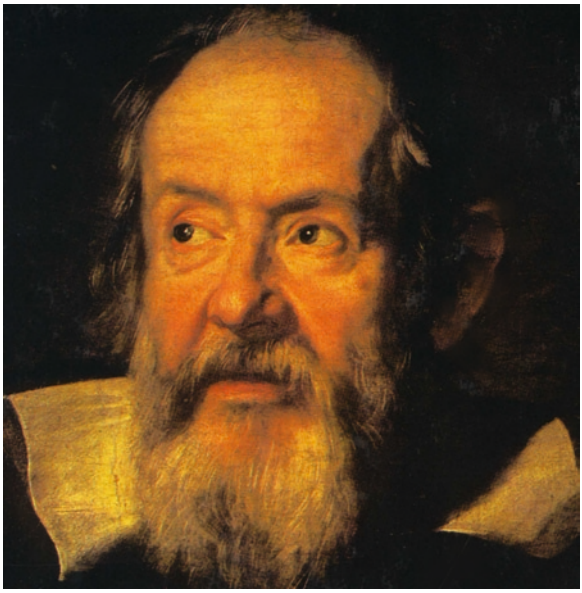
1. Eyes on the Skies

Our story's central figure, the Italian physicist Galileo Galilei (1564–1642), was intellectually active during the late Renaissance, an exciting and unprecedented period in history. Discoveries in the New World were opening eyes to the idea that our own planet was far vaster and more diverse than anyone had previously dared to suspect. Not only were new discoveries easily disseminated to the educated masses by the printing press, but new ways of thinking about the world were promulgated through pamphlets and books, often couched in the medium of fictional literature.



Galileo Galilei, portrayed by Justus Sustermans in 1636

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Living and working from within some of the Catholic Church's strongest domains – first as Professor of Mathematics at Pisa and later in the Venetian Republic at Padua – Galileo's line of solid scientific reasoning led him to challenge many of the tenets about the Universe that the establishment held dear. Yet, Galileo didn't arrive on the scene amid a vacuum of ideas about how the Universe worked; the trouble was that many of the ideas prevalent at the time were only promulgated through the medium of accepted dogma. Religion has never been very good at shifting its ground once its leaders have proclaimed something to be true, and Galileo's work was truly Earth-shaking.

Some of Galileo's evidence-based notions were far from new – for example, the theory that Earth was a planet in orbit around the Sun had been around since the third century BCE and had famously been postulated by Nicolaus Copernicus (1473–1543) a century before Galileo. However, it was the manner in which Galileo presented his ideas – theories based on sound observations backed up by solid mathematical foundations – that gave the scientist's work such potency. It was with good reason that Albert Einstein (1879–1955) bestowed Galileo with the accolade "the father of modern science." Galileo's work – especially his stance on the correctness of the heliocentric theory – led him to a famous historical clash with the then-powerful Church authorities.

Before looking at the life and work of Galileo, particularly with respect to his work in astronomy and his astonishing telescopic discoveries, it's important to understand how our human view of the Universe and our place within it has been shaped over time.

Pre-Telescopic Astronomical Ideas, Inventions and Discoveries

Although astronomy, the oldest of all natural philosophical pursuits, experienced its dramatic introduction to the telescope just four centuries ago, this age-old science was no stranger to its practitioners' use of mechanical devices for computation and observation. For many centuries astronomical calculations had been aided by wonders such as abacuses and astrolabes, and the heavens had

been charted and monitored with quadrants, cross staffs, and a variety of other finely crafted naked-eye instruments.

Regardless of the substantial body of astronomical knowledge that had been acquired since ancient times, though, the telescope proved to be such a potent invention that it changed everything overnight. Not only were the heavens discovered to be more complex and more beautiful than anyone had dared to imagine, it's no overstatement to claim that humanity's perspective upon its own position and status in the Universe changed forever.

Enquiring and observant people throughout the ages have made remarkable efforts to understand the Universe and its workings using nothing but their unaided eyes and raw brain power. So, before exploring the extraordinary development of the telescope, from its humble beginnings through progressively larger and evermore optically perfect instruments to the incredibly sensitive eyes on the Universe planned for the twenty-first century, let's review some of the important events of pre-telescopic astronomy.

For most of human history, most people lived in small rural settlements and enjoyed truly dark night skies that were untainted by the glare of artificial lighting. Our remote ancestors of millennia gone by could not have failed to have been struck by the sheer grandeur of the heavens. This is a point often unappreciated by most twenty-first century people. More than 3.3 billion people (half the world's population) now reside in cramped towns and sprawling cities. Few occupants of Earth's urban areas appreciate that beyond the orange-tinted artificial sky glow of their night sky lies one of nature's most glorious sights. As urban communities are bathed in permanent light and the night air above glows with countless particles reflecting the glare of street lighting, industry, and commerce, their residents are simply never given the chance to appreciate the darkness. Sadly, few people realize just how magnificent the night skies can be when viewed with the unaided eye.

Our remote ancestors enjoyed incredibly dark skies, where people with average eyesight could easily discern the Milky Way, glowing like a phosphorescent river spanning the skies from horizon to horizon, with dozens of nebulae and star clusters punctuating its course like brighter eddies in the current. Further afield, the nebulous patches of the two close galaxies in Andromeda and Triangulum can be made out indistinctly against the blackness

of pristine skies, and southern hemisphere viewers blessed with dark skies delight in the diffuse brightness of the two Magellanic Clouds, our Galaxy's nearest cosmic neighbors.

Against this splendid stellar backdrop – a celestial vault that seemed to revolve around Earth with the passing of the seasons – the Sun made its way unerringly in its annual course along a path known as the ecliptic. The Moon's monthly path among the stars was roughly in line with the Sun's path – hence the name "ecliptic," since every so often the Moon occasionally eclipsed the Sun, and in turn the Moon was eclipsed by the broad shadow of Earth. Eclipse phenomena, along with the regular cycle of lunar phases, gave the Moon an air of profound mystery. Mercury, Venus, Mars, Jupiter, and Saturn – the five brightest planets, all of which have been known since antiquity – each appeared to follow their own individual paths near the ecliptic, but at varying speeds. Their motion among the stars caused them to be known as the "wanderers" (the word "planet" derives from the ancient Greek).

In addition to the more readily visible celestial objects there were many sky phenomena whose appearance was dramatic, unpredictable, and often alarming to our ancestors. From time to time, meteors and fireballs streaked across the night skies; comets sometimes appeared from nowhere to develop into fiery torches with streaming tails; now and again, aurorae lit up the skies in intricate, shifting multicolored displays; occasionally, new stars blazed among the familiar constellations, only to fade into obscurity before long.

The glorious heavens and their remarkable occupants were distant, mysterious, and untouchable. It's hardly surprising that references to celestial objects were deeply embedded in every ancient human culture that we know of, and many ancient religions are full of reverence for sky-related gods. Today it may be tempting to find some amusement at the idea of people fervently praying to the Moon or frightened folk running indoors when an eclipse took place, or an entire nation in panic believing that their world was about to end because of a bright comet that appeared in the skies. But we have the advantage of understanding the nature of these phenomena. Nobody is fond of disorder. People like to have some form of understanding about the world around them. Religious, mythological, and unscientific explanations – however vague, weird or wildly off the mark we might consider them today

– were comforting, and they sat more comfortably with our psyche than any frank acknowledgement of utter ignorance.

One way in which the skies might be better known and understood was to become aware of the motions of its chief players, the Sun and Moon. As well as rising and setting each day, the Sun made a complete circuit around the skies every year, and the highest point it reached above the southern horizon each day appeared to vary with the seasons. Early northern hemisphere cultures based on farming had a great interest in the Sun, and the stones of megalithic structures such as Stonehenge on Salisbury Plain in Wiltshire, England, are chiefly aligned with the cardinal points and the rising point of the midwinter Sun – an important time marking the furthest southern declination of the Sun, after which it begins to climb northwards once more, heralding longer days.

One of the most familiar symbols found in prehistoric sites is the crescent shape, representing the Moon, along with markings indicating the monthly cycle of lunar phases. A lunar calendar comprising 29 markings – one for each day of the lunar month – has been identified in the famous caves at Lascaux in France, and dated to around 15,000 BCE.

That the Moon should be considered important is obvious. The Moon's light was immensely valuable in terms of hunting and nocturnal survival, and the phases of the Moon represented a marker of the passage of time. Carved markings on animal bones found in the Aurignac cave in Haute Garonne, France, clearly show that from about 30,000 years ago the European Aurignacians were avid Moon-chroniclers, for these markings are thought to be meticulous recordings of the passage of lunar cycles. Similar records are found in the art of the western European Azilians (named after a cave near Mas d'Azil in France) made around 4,000 BCE or earlier, and they include narrow crescent shapes that appear to mark New Moons in successive lunations.

One of the earliest depictions of the Moon's physical features (showing the dark patches known as "maria," Latin for "seas") may be a rock carving discovered at a prehistoric tomb in Knowth, County Meath, Ireland, and dating back five millennia; known as Orthostat 47, the carving consists of a set of nestled arcs that bear some resemblance to an impression of the lunar features as viewed at full Moon.

This simple set of lines, taken from an ancient rock carving at a prehistoric site in Ireland, may be the earliest known representation of the Moon's features (Credit: Peter Grego)

It's clear that the skies and its phenomena were initially incorporated into human affairs for practical reasons, and it's not such a great leap from this to astrology – the belief that that the movements of the Sun, Moon, and five planets have an influence on the lives of individual people and the course of world events. A great deal of brain power expended by the earliest civilizations was devoted to watching the skies, noting the movements of the Sun, Moon, and planets, and using this information to predict celestial events, from the movements of Venus to eclipses of the Sun and the Moon. Great civilizations, such as those of ancient Babylon, Egypt, and China, considered it vitally important to observe, record, and predict heavenly phenomena. Astrologer-priests kept a constant vigil on the skies, ostensibly for society's well-being and to keep their rulers informed of any celestial portents that might affect the status quo. Astrology was considered such a precious asset that its use without the ruler's permission was often punishable by execution.

Eastern Skies Under Scrutiny

Ancient China – frequently referred to as the Celestial Empire because of its deep reverence for heavenly events – had an advanced understanding of astronomy. The first Chinese lunar calendars

came into practical use around 4,000 years ago. Ancient Chinese astronomers created a catalog of every star visible with the unaided eye, divided the skies into constellations known as "palaces," and referred to the brightest star in each palace as its "emperor star," surrounded by less brilliant "princes." In the fourth century BCE, the astronomer Shih-Shen had cataloged 809 stars and had recorded 122 individual constellations.

Thousands of astronomical phenomena are recorded in Chinese annals dating back many centuries. Over an almost continuous period spanning the sixteenth century BCE to the end of the nineteenth century, Chinese court astronomers were appointed to observe and record changes in the heavens. This legacy of almost 3,500 years' worth of astronomy, in which sunspots, aurorae, comets, lunar and solar eclipses, and planetary conjunctions were recorded in some detail, has provided us with a rich source of reference material.

Astrology played a tremendously important role in ancient China. There were 28 constellations that formed the ancient Chinese zodiac, the band of sky through which the Sun, Moon, and planets appeared to progress. Each of the five planets was designated its own element – Mercury, water; Venus, metal; Mars, fire; Jupiter, wood; Saturn, earth. A person's fate was supposedly determined by the relative position of the five planets, the Moon, Sun, and any comets that happened to be in the sky at the time of that person's birth.

Astrologers to the emperor's court were held in such great esteem that many of them resided within the Imperial Palace itself. Astrologers' advice, based on careful astronomical observations, was highly respected by the emperor, and helped him to make important decisions about the running of the state. Should the emperor's stellar soothsayers make a mistake in their predictions, then dire consequences were bound to befall them; for example, the ancient Chinese *Book of History* records that two court astrologers were executed for having failed to announce a total lunar eclipse in 2,136 BCE.

Relatively infrequent celestial phenomena, such as mutual planetary conjunctions and eclipses, were imagined to be especially potent astrological signs, but the most potent of all heavenly phenomena – those happenings with the power to cause fear and panic – were unpredictable events that took skywatchers

completely by surprise. None of these celestial signs was as feared as the arrival of a bright comet. Only a few hundred years ago, comets were almost universally regarded as omens of impending change on Earth, preceding some form of natural catastrophe, famine, pestilence, death of monarch, or war. Ancient astrologers were used to making astronomical observations with the unaided eye (in an era long before the telescope was invented) so the two subjects of astrology and astronomy were once closely intertwined.

Ancient Greek Philosophy

Notwithstanding the penchant our ancestors had for linking events in the skies with happenings on Earth, a substantial amount of astronomical knowledge was built up by ancient civilizations. We know that much of this ancient knowledge has been lost through poor recording combined with cultural changes; for example, much of our knowledge of ancient Greek philosophy comes from texts that were rescued and preserved by Arab scholars during the European Dark Ages. A great library and learning center called the House of Wisdom was instituted in ninth century Baghdad by the Abbasid caliphs Harun al-Rashd and his son al-Ma'mun. Operational until the thirteenth century, the House of Wisdom became the world's greatest center for the study of humanities and the sciences. Ancient Persian, Indian, Greek, and Roman texts – including those of Pythagoras, Plato, Aristotle, Hippocrates, and Euclid – were collected and translated into Arabic. Ancient Greek ideas eventually found their way back into the European arena during the High Middle Ages, as these works were translated into Latin.

Ancient Greek philosophy saw a move away from the age-old acceptance that mysterious supernatural forces under the guise of a pantheon of gods controlled the workings of nature and towards the use of reason and enquiry. A rationalistic approach to philosophy was first espoused by Thales of Miletus (mid-620s–547 BCE), who proposed that it was possible for nature to be understood by humans and that the Universe could be explained in physical terms. Sadly, none of Thales' works survive, but it is thought that he predicted a famous solar eclipse, notable for its occurrence during the Battle of Halys between the Medes and Lydians, an event that appears to have startled the two warring parties into hastily arranging a truce. Using

basic geometry Thales estimated that the Sun and Moon – each half a degree across – measured 1/720th of their respective celestial paths.

On the Ball

The popular media often make a joke out of the image of Christopher Columbus's fifteenth-century sailors being afraid that their voyage west was doomed because their little ships would eventually tumble down a stupendous cataract at the edge of the world. While belief in a flat, finite Earth was certainly current in ancient Babylon, Egypt, pre-classical Greece, and China, nobody in Columbus's time seriously thought that our planet was flat. The idea of a spherical Earth was firmly postulated by Plato (427–347 BCE), who imagined that if one could soar high above the clouds our planet would resemble a colored ball similar to those found in an artist's studio. Plato's pupil, Aristotle (384–322 BCE) provided ample evidence to back this up. In *De Caelo* (*On the Heavens*) he rightly claimed that Earth's shape naturally gravitates towards the center, forming a sphere. He explained that the further south one travels, the more southerly or higher the constellations rise in the sky, a phenomenon that could only be explained if Earth had a spherical surface. Moreover, he pointed out that Earth's vast outline can actually be seen during a lunar eclipse, when our planet's curved shadow sweeps across the face of the Moon.

Eudoxus of Cnidus (c. 408–355 BCE) built an observatory and extensively wrote and lectured on astronomy. He invented the astronomical globe – a ball upon which the stars are plotted as though Earth were positioned at its center – a valuable teaching aid that is still used to this day. Eudoxus' *Book of Fixed Stars* contains descriptions of many constellations, including the 12 zodiacal constellations; these star patterns bear a striking resemblance to ancient Babylonian constellations devised several centuries earlier. Eudoxus devised a complete system of the Universe, envisaging Earth at the center of a series of no fewer than 27 transparent crystal spheres upon which were attached the Sun, Moon, individual planets, and stars. Solar, lunar, and more complex planetary movements were explained by the rates at which these spheres rotated. The idea of an Earth centered amid a nest of celestial spheres was to permeate philosophical thought for many centuries.

Aristarchus Takes Center Stage

One notable challenger to the notion of an Earth-centered Universe was Aristarchus of Samos (310–c. 230 BCE), who used observations to support his view that the Sun instead lay at the hub of the Universe. Aristarchus's heliocentric theory of the Universe may possibly have stemmed from his research into determining the Sun's distance using size calculations based on careful observation of the Moon's half phase (dichotomy). With the unaided eye, he judged that at the moment of dichotomy the angle between the Sun, Earth, and Moon was 87°. Since the Moon and Sun have the same apparent angular diameter of half a degree, a simple trig calculation was enough to show that the Sun was 19 times the Moon's distance and was therefore 19 times greater in diameter than the Moon.

With the knowledge that the Sun was nearly seven times Earth's diameter (equating to a volume of around 300 Earths), Aristarchus may have found it a trifle difficult to go along with Eudoxus's notions of an Earth-centered Universe. It turns out that Aristarchus's naked-eye measurements of lunar dichotomy weren't precise enough to give him an accurate figure for the true distance and size of the Sun; he was off by several orders of magnitude. The Sun is actually 400 times further away than the Moon and is 400 times the Moon's diameter (109 times the diameter of Earth and 1,300,000 times Earth's volume).

Eratosthenes Takes Measures

Mathematics and geometry proved invaluable tools in attempting to understand the scale of the Universe. Eratosthenes of Cyrene (276–194 BCE) used observation and trigonometry to derive a number of astronomical distance measurements, among them a remarkably accurate measurement of Earth's circumference in 240 BCE, for which he is best known.

Eratosthenes's logic was simple but powerful. Summer solstice at local noon is the highest point to which the Sun climbs above the southern horizon. He knew that at this date and time the Sun appeared directly overhead at the ancient Egyptian city of Syene (now Aswan), but from his home town of Alexandria,

known to be 5,000 stadia (950 km) north of Syene, the solstice noon Sun was 1/50 of a full circle (7° 12′) south of the zenith. From this, Eratosthenes deduced that Syene and Alexandria were separated by 1/50 of the total circumference of Earth, which he calculated to be 252,000 stadia – equivalent to 39,690 km, a result within just 1% of the actual value we know today.

Among Eratosthenes's other accomplishments, he developed a system of terrestrial latitude and longitude, drew one of the most advanced maps of the known world, invented the notion of the leap day, accurately calculated the tilt of Earth's axis to its orbit around the Sun, and attempted to work out the Sun's distance from Earth.

Project #1: Measure the Earth's Circumference

If you have a far-off friend on the Internet, you can repeat Eratosthenes's experiment to measure the size of the Earth. For your experiment you need to choose two sites roughly on the same line of longitude, i.e., one site will be due north of the other. Use a vertical gnomon, i.e., a 1 m stick, to cast a shadow on flat ground. The shadow from the gnomon could be measured every 10 min just 40 min before and after noon. The shortest shadow will be at local noon. Using trigonometry you can then measure the altitude of the noon Sun at each site:

Tan θ = height of gnomon/shadow length
Tan θ = 1.00 m/shadow length (in meters)
θ = Tan^{-1} (1.00 m/shadow length) – find the inverse tan (Tan^{-1}) also known as arc tan button on your scientific calculator.

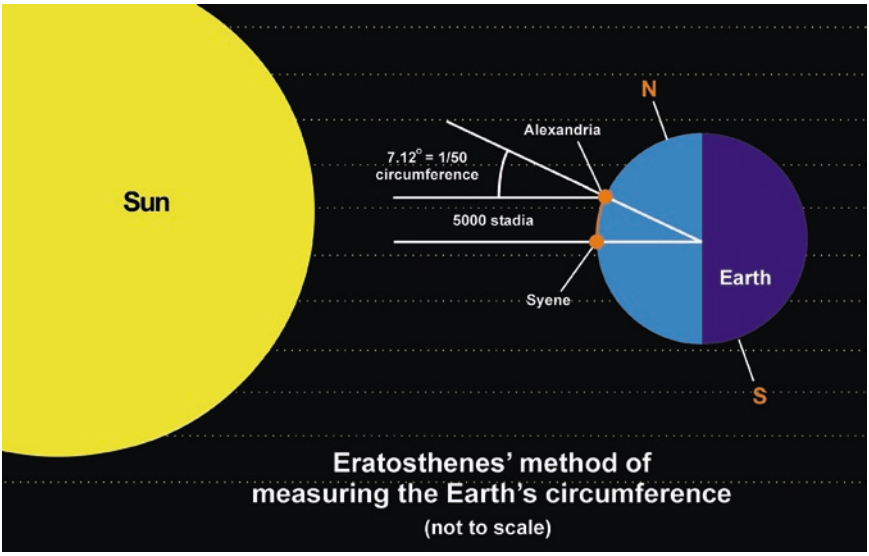
The distance between sites can be found from the Internet – here are four examples based in the UK and United States.

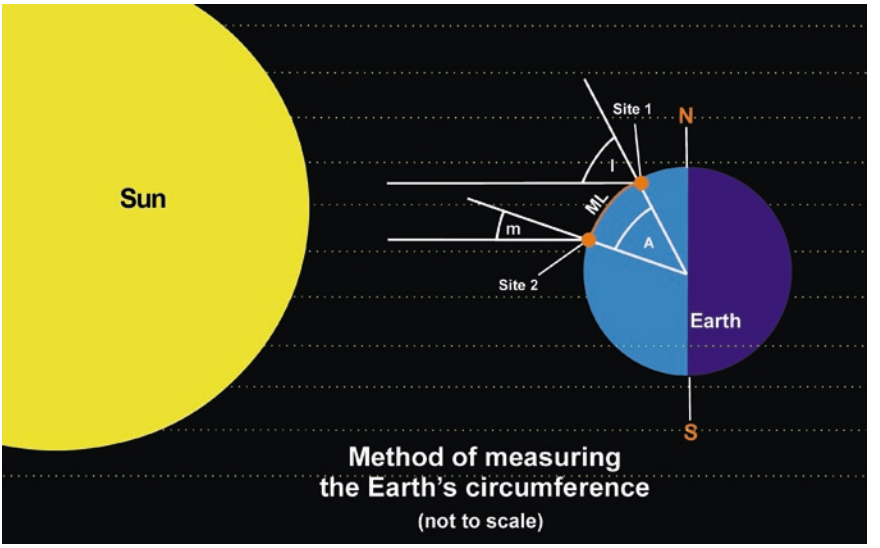
City 1	City 2	Distance km (miles)
UK		
Cardiff	Edinburgh	497 (309)
Plymouth	Glasgow	609 (378)
United States		
Seattle, WA	San Francisco, CA	1,102 (684)
Pittsburgh PA	Miami, Florida	1,634 (1,015)

The expected difference in altitude of the noon Sun for the four cases would be (assuming the circumference of Earth along a meridian to be 40,008 km) is:

City 1	City 2	Difference in angle (in degrees)
UK		
Cardiff	Edinburgh	4.5
Plymouth	Glasgow	5.5
United States		
Seattle, WA	San Francisco, CA	9.9
Pittsburgh PA	Miami, Florida	14.7

Uncertainties in the measurement of shadow length will produce uncertainties in the final answer, so assuming a simple case of two sites being 7° apart in latitude and the noon Sun having an altitude at the two sites of 40 and 47°, then trying to measure Tan θ you would find the shadow lengths to be 1.19 m and 0.93 m, respectively. A ± 1 cm error in shadow length at both sites would lead to a maximum error of 0.4°, which in turn would lead to error of 2,300 km in Earth's circumference. It is important to make sure the gnomon is vertical – a plumb line using string and a small weight is useful – and that the ground on which the shadow falls is level and horizontal.



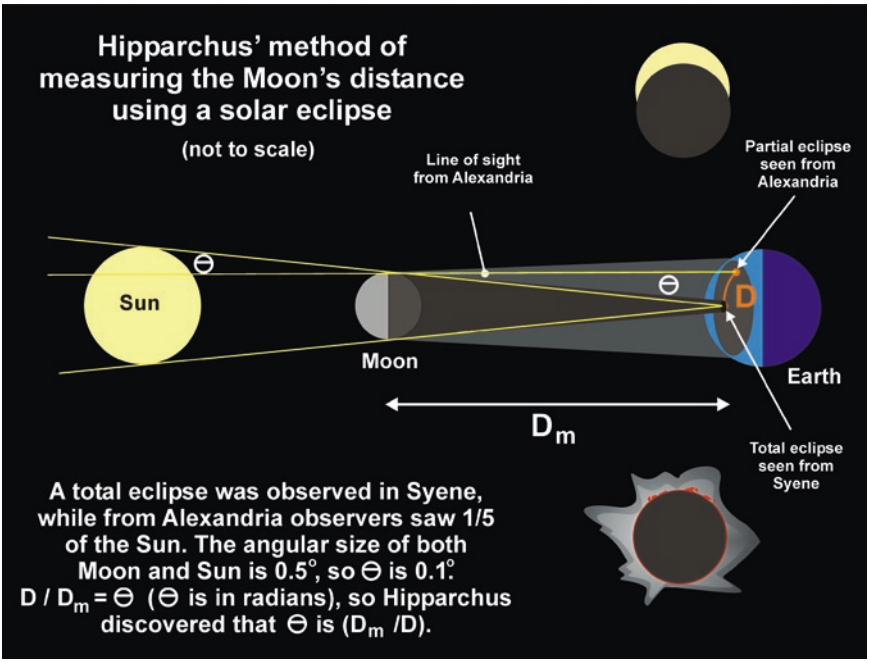


Hipparchus' Heavens

Of all the great astronomers of antiquity, the Greek astronomer Hipparchus' (190–120 BCE) is most widely considered to be preeminent in terms of observational astronomy. In addition to contemporary observations, his work was based upon references to astronomical knowledge and techniques that had been developed in Babylonia long before his time. For example, Hipparchus' possessed an extensive list of ancient Babylonian eclipse observations (records of celestial phenomena originally marked in cuneiform text on clay tablets) spanning many centuries, probably dating back to the eighth century BCE. Using this data, along with contemporary observations and advanced trigonometric tools that he himself had developed, Hipparchus' determined the Moon's motions so accurately that he was able to make reliable predictions of solar and lunar eclipses.

Hipparchus' calculations of the size and distance of the Sun and the Moon were based upon trigonometric reductions of observations. He established, by the use of a naked-eye measuring device called a diopter, that the apparent angular diameter of both the Sun and Moon were half a degree across. Hipparchus' also detected a small variation in the Moon's apparent diameter due to varying distance of the Moon as it orbits Earth. He went

on to measure the Earth-Moon distance based upon a solar eclipse of 190 BCE, which happened to have been total at Syene and partial at Alexandria, where one fifth of the Sun (measuring 0.1° across) was visible at maximum. Expressed in radians, this angle enabled the ratio of the distance between Syene and Alexandria to be applied to the distance between Earth and the Moon. Hipparchus' calculated that the Moon lay between 59 and 67 Earth radii distant, the range being based upon assumptions of both the likely minimum distance to the Sun and an infinite distance to the Sun. The average value is actually 60 Earth radii, so his result was remarkably good.

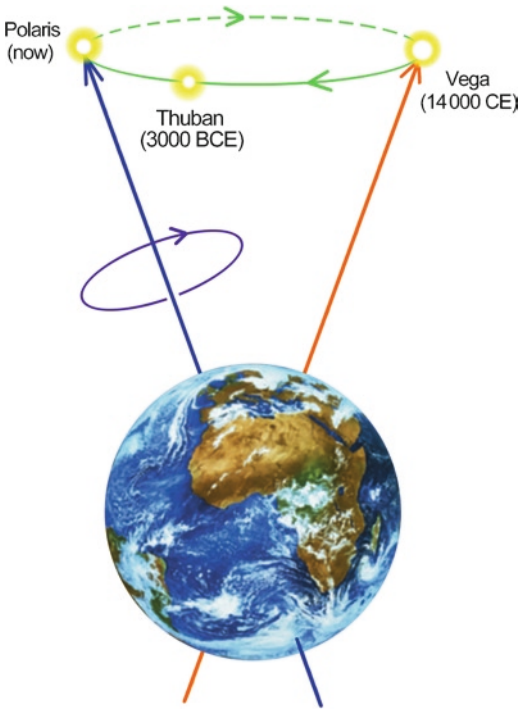


Hipparchus' detailed observations of star positions, made using naked-eye sighting devices including astrolabes and armillary spheres of his own design, enabled him to create the first known stellar catalog around 129 BCE. The catalog featured some 750 stars whose position on the celestial sphere was pinpointed according to his own novel system of celestial longitude and latitude coordinates.

A magnitude scale devised by Hipparchus' denoted each star's apparent brightness; the brightest 20 stars were classed as being of the first magnitude, followed by the next brightest, which were second magnitude, and so on, down to the faintest stars visible, which he classed as sixth magnitude. A similar magnitude scale is used today, although each division between magnitudes corresponds to a precise jump in brightness by a factor of 2.512, and the brightnesses themselves are gauged by photoelectric means. Although no copy of Hipparchus' star catalog exists, it is thought that a representation of it may possibly feature on the intricately sculpted globe borne aloft by the Farnese Atlas, a second century CE marble statue (a Roman copy of an older Greek work) on display at the Naples National Archaeological Museum.

The Farnese Atlas, on display at Naples Archaeological Museum (Courtesy of Gabriel Seah, Wikimedia Creative Commons)

One of Hipparchus' greatest accomplishments was the discovery of the precession of the equinoxes, which he outlines in two books: *On the Displacement of the Solsticial and Equinoctial Points* and *On the Length of the Year*. After measuring the position of the star Spica and comparing his measurements with positional data obtained by Timocharis and Aristillus 150 years earlier, he concluded that Spica had moved by 2° with respect to the point of the autumnal equinox. This, along with discrepancies in the lengths of the tropical year (the time taken for the Sun to return to an equinox) and the sidereal year (the time taken for the Sun to return to a point relative to a star), led Hipparchus' to conclude that the point of the equinoxes was moving along the zodiac from east to west (precessing) at a rate of 46 arcseconds per year. The modern figure for precession is very close, at 50 arcseconds per year, meaning that one complete cycle takes 25,800 years – quite remarkable for such a phenomenon to have been detected in ancient times.

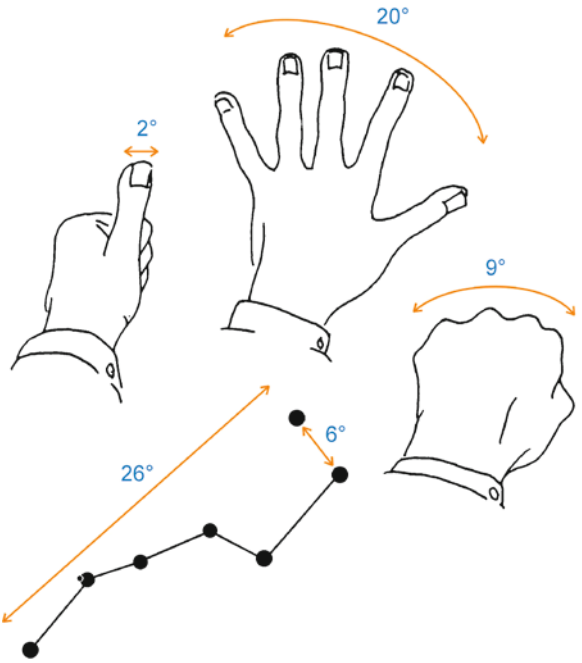


First magnitude Polaris (the Pole Star) is currently the nearest bright star to the north celestial pole. About 5,000 years ago the fainter third magnitude star Thuban was the pole star; in 12,000 years' time, precession will have brought brilliant Vega to the north celestial pole (Credit: Peter Grego)

Loopy but Long-Lasting

Claudius Ptolemaeus (around 83–161 CE) borrowed heavily from earlier philosophers, including the pioneering work of Hipparchus', to produce the *Almagest*. He took care to compile an encyclopedia of ancient Babylonian and Greek knowledge, including the production of a definitive atlas of the stars – no fewer than 1,022 of them, contained within 48 constellations. Expanding on Eudoxus's idea of an Earth-centered Universe, Ptolemaeus explained that the peculiar occasional looping motions (called "retrograde motions") of the planets at some points along their paths were produced when the planets performed smaller circular movements called "epicycles" along their wider circular paths as they orbited the Earth.

While the idea of epicycles seemed to answer a lot of problems and appeared to go some way in explaining the clockworks of the cosmos, careful observations over extended periods of time was later to prove their downfall. These important observations were not to be made for many centuries after Ptolemaeus's time, and the transition from a widespread belief in a geocentric Universe to a heliocentric Universe marks the beginnings of modern astronomy.



It is possible to make estimations of angles in the sky using just your hand and the unaided eye (Credit: Peter Grego)

Ancient Astronomical Equipment

Nearly everyone owns the most basic of astronomical equipment – brain, eyes, and hands. It's possible to make estimations of angles in the sky using just your hand and naked eye. Here are a few examples. The Moon is half a degree wide – so small that it can be covered with the tip of one's little finger, which is about 1° wide; each day the Moon moves by around 15° towards the east, about the distance between the tips of the outstretched index and little fingers.

Dubhe and Merak, the "pointer" stars in Ursa Major which indicate the direction of the north celestial pole, are separated by 5°, or the width of the three middle fingers. From northern Italy, the midwinter Sun rises to an altitude of around 20°, which equates to the distance between the tip of the thumb and little finger in an outstretched hand; on the same date in Fairbanks, Alaska, the Sun heaves itself to just under 2° above the southern horizon, about the width of a thumb.

A seventeenth-century mariner 'shoots the Sun' using a cross-staff

Carefully constructed instruments will of course enable more accurate measurements to be made. Simple naked-eye devices enabling the measurement of celestial angles have been used since antiquity. More complicated astronomical instruments that permitted calculations to be made in advance included the planisphere and the astrolabe, both of which first appeared in ancient Greece. Consisting of a map of the stars and an overlay that could be rotated to approximate the position of the horizon at any given date and time, the planisphere is an elegant, though rudimentary, device that allows the operator to calculate the rising and setting times of the Sun and stars, and their elevation above (or below) the horizon at any given time. Planispheres are still beloved by amateur astronomers; indeed, most modern astronomical computer programs contain a facility to create a planisphere display.

Astrolabes are a potent combination of the planisphere and a sighting device called a dioptra; thought to have been invented by Hipparchus', astrolabes permitted calculations to be made on the basis of observations, enabling numerous problems in spherical astronomy to be solved. Perhaps the most prolific and proficient exponents of the astrolabe were astronomers of the medieval Islamic world, where they were employed for astronomy, navigation, and surveying, in addition to being put to use for timekeeping for religious purposes.

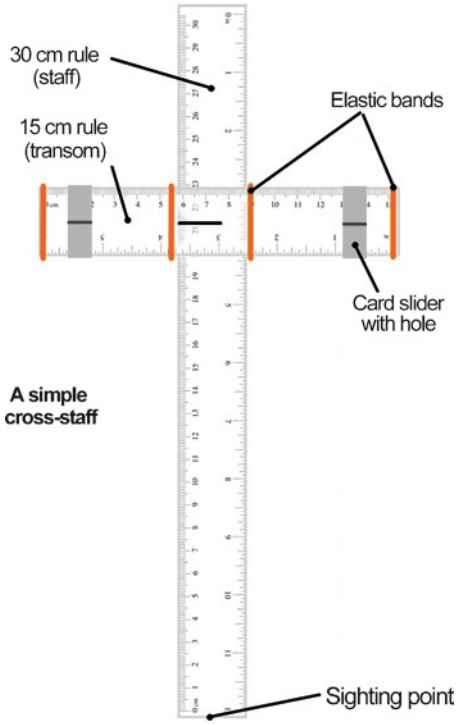
Instruments to aid naked-eye observations were used extensively in ancient China, as they were in the west. In the first century Lo-hsia-Hung constructed an armillary sphere – a device representing the celestial sphere – upon which were marked 365.25 divisions (for the days of the year) and rings for the celestial equator and the meridian. Lo-hsia-Hung's charming analogy for the Universe likened Earth to the yolk within an eggshell, stating "the Earth moves constantly, but people do not know it; they are as persons in a closed boat; when it proceeds they do not perceive it." In the fifteenth century an observatory was built on the southeastern city wall of ancient Beijing and was equipped with a number of accurately calibrated sighting devices made out of bronze.

A relatively simple naked-eye device called a cross-staff enabled early astronomers to measure the angular distance between individual stars, ascertain the angular heights of stars above the horizon, and track the motion of the Moon and planets against the sky background over a period of time. These simple

instruments, whose principles have been known since antiquity, were used extensively by mariners in the late sixteenth and early seventeenth century to take bearings on the angle of the Sun above the horizon at noon (or the altitude of Polaris at night), enabling the ship's latitude to be determined.

The cross-staff consists of a long straight stick upon which is attached a movable vane, known as a "transom," at right angles to it. The observer positions an eye near the bottom of the staff and points it towards the objects whose angular distance from each other is to be measured. The transom is slid up or down the staff so that both objects appear to just touch points (or appear in slits) at either end of the transom. A reading is then taken of the distance of the transom from the eye along the staff.

Since the distance between the two points on the transom is also known, simple trigonometry allows the angle between the two sighted objects to be determined fairly accurately to angular separations of up to 50°, which is the maximum separation of objects that



Construction of a simple cross-staff (Credit: Peter Grego)

can comfortably be sighted with the unaided eye. Some of the more elaborate cross-staffs had multiple transoms, or the distances between their transverse points could be adjusted for greater accuracy; calibrated scales on the staff took out the trigonometric work and enabled a direct reading of the angular separation of objects to be made.

Project #2: Make Your Own Naked-Eye Cross-Staff

Materials: 30 cm plastic rule, 2 × 15 cm thin transparent plastic rules, 4 elastic bands, 2 narrow (1 cm) strips of thin card (length = 4 times the width of the smaller rules). CD marker pen.

Construction: Using a CD marker pen, draw a line lengthways down the center of one of the small rules. Place the small rules on either side of the larger rule at right angles to it, the one you've marked being uppermost. The flat sides of each small rule ought to face each other. Tightly wrap an elastic band around both small rules immediately on either side of the longer rule, so that the two smaller rules are bound together and can be moved up and down relative to the longer rule. The long rule will form the staff, while the smaller rules form the transom. Place a strip of card between the two small rules, one on either side of the main staff, outside of the elastic binding. Fold the card around the small upper rule and create a small tab sticking up from it at the center; tape it firmly so that it maintains its shape. Tightly wrap the other two elastic bands around the ends of the small rules, so that the cardboard tabs can slide along the transom but will stay put whatever position the cross-staff is pointed to. Depending on your preference, punch a hole at the center of each card tab or cut a narrow slit in them. At this scale, this particular cross-staff can be used to measure angles ranging between 15 and 50°.

Observation method: Select two fairly bright stars near to each other in the sky (separated, say, between around one and two outstretched hand widths). Position the eye close to the 0 cm point on the staff and angle the transom so that it's parallel to an imaginary line joining your target stars. Slide the transom so that your target stars can be seen through each hole (or slit). To increase the accuracy of your sighting, try to keep as still as possible during this procedure. Leaning against a wall or bracing your elbows on a suitably solid structure may help. Smaller separations may