History of Astronomy

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Summary

This short survey of the History of Astronomy provides a brief overview of the ubiquitous nature of astronomy at its origins, followed by a summary of the key events in the development of astronomy in Western Europe to the time of Isaac Newton.

Goals

• Give a schematic overview of the history of astronomy in different areas throughout the world, in order to show that astronomy has always been of interest to all the people.
• List the main figures in the history of astronomy who contributed to major changes in approaching this discipline up to Newton: Tycho Brahe, Copernicus, Kepler and Galileo.
• Conference time constraints prevent us from developing the history of astronomy in our days, but more details can be found in other chapters of this book.

Pre-History

With dark skies, ancient peoples could see the stars rise in the eastern part of the sky, move upward, and set in the west. In one direction, the stars moved in tiny circles. Today, when we look north, we see a star at that position – the North Star, or Polaris. It isn't a very bright star: 48 stars in the sky are brighter than it, but it happens to be in an interesting place. In ancient times, other stars were aligned with Earth's north pole, or sometimes, there were no stars in the vicinity of the pole.

Since people viewed the sky so often, they noticed that a few of the brighter objects didn't rise and set exactly with the stars. Of course, the Moon was by far the brightest object in the night sky. It rose almost an hour later each night, and appeared against a different background of stars. Its shape also changed; this is what we now call phases.

But some of these lights in the sky moved differently from the others. These came to be called wanderers or planets by the Greeks. Virtually every civilization on Earth noticed, and named, these objects.

Some ancient people built monuments such as standing circles, like Stonehenge in England, or tombs such as the ones in Menorca in Spain that aligned with the Southern Cross in 1000 BCE. The Babylonians were great recorders of astronomical phenomena, but the Greeks built on that knowledge to try to "explain" the sky.

The Greeks

Most ancient Greeks, including Aristotle (384 BCE – 322 BCE), thought that Earth was in the center of the universe, and it was made of four elements: Earth, Air, Fire, and Water. Beyond the Earth was a fifth element, the aether (or quintessence), that made up the points of light in the sky.

How did these wanderers move among the stars? Mostly, they went in the same direction that the stars went: rising in the east and moving toward the west. But sometimes, they seemed to pause and go backwards with respect to the stars. This backward motion is called "retrograde" motion, to tell it apart from the forward motion, called "prograde."

The Greek astronomer Claudius Ptolemy (c. CE 90 – c. CE 168) worked in Alexandria in North Africa in the second century AD. Ptolemy wanted to be able to predict the positions of planets and came up with a mathematical solution. Following Aristotle, he placed the Earth at the center of the universe. The Moon and the planets go around it in nested circles that got bigger with distance from Earth. What if the planets really move on small circles whose centers are on the big circles? Then, on some of the motion on the small circles, they'd be moving faster backwards than the centers of these circles move forward. For those of us on Earth, we'd see the planets move backwards.

Those small circles are called "epicycles," and the big circles are called "deferents." Ptolemy's idea of circles moving on circles held sway over western science for over a thousand years. Going from observation to theory using mathematics was a unique and important step in the development of western science.

Although they didn't have the same names for the objects they observed, virtually every culture on Earth watched the skies. They used the information to set up calendars and predict the seasonal cycles for planting, harvesting, or hunting as well as religious ceremonies. Like the Greeks, some of them developed very sophisticated mathematics to predict the motions of the planets or eclipses, but this does not mean that they attempted what we would call a scientific theory. Here are some examples:

Africa

The standing stones at Nabta in the Nubian Desert pre-date Stonehenge by 1000 years. Egyptians used astronomy to align their pyramids as well as extend their religious beliefs to include star lore. Petroglyphs at Namoratunga (Kenya) share aspects of modern cattle brands. Star lore comes from all areas of Africa, from the Dogon region of Mali, to West Africa, to Ethiopia, to South Africa.

Islamic Astronomy

Many astronomical developments were made in the Islamic world, particularly during the Islamic Golden Age (8th-15th centuries), and mostly written in the Arabic language. It was developed most in the Middle East, Central Asia, Al-Andalus, North Africa, and later in the Far East and India. A significant number of stars in the sky, such as Aldebaran and Altair, and astronomical terms such as alidade, azimuth, almucantar, are still referred to by their Arabic names. Arabs invented Arabic numbers, including the use of zero. They were interested in finding positions and time of day (since it was useful for prayer services). They made many discoveries in optics as well. Many works in Greek were preserved for posterity through their translations to Arabic.

The first systematic observations in Islam are reported to have taken place under the patronage of Al-Maâmun (786-833 CE). Here, and in many other private observatories from Damascus to Baghdad, meridian degrees were measured, solar parameters were established, and detailed observations of the Sun, Moon, and planets were undertaken.

Instruments used by the Islamic astronomy were: celestial globes and armillary spheres, astrolabes, sundials and quadrants.

Fig. 1: Arabic astrolabe.

The Americas

North America

Native peoples of North America also named their constellations and told sky stories which were passed down through oral tradition. Some artifacts, such as stone wheels or building alignments, remain as evidence of their use of astronomy in every-day life.

Mayan Astronomy

The Maya were a Mesoamerican civilization, noted for the only known fully developed written language of the pre-Columbian Americas, as well as for its art, architecture, mathematical and astronomical systems. Initially established during the Pre-Classic period (c. 2000 BCE to 250 CE), Mayan cities reached their highest state of development during the Classic period (c. 250 CE to 900 CE), and continued throughout the Post-Classic period until the arrival of the Spanish. The Mayan peoples never disappeared, neither at the time of the Classic period decline nor with the arrival of the Spanish conquistadors and the subsequent Spanish colonization of the Americas.

Mayan astronomy is one of the most known ancient astronomies in the world, especially due to its famous calendar, wrongly interpreted now as predicting the end of the world. Maya appear to be the only pre-telescopic civilization to demonstrate knowledge of the Orion Nebula as being fuzzy, i.e. not a stellar pinpoint.

The Maya were very interested in zenithal passages, the time when the Sun passes directly overhead. The latitudes of most of their cities being below the Tropic of Cancer, these zenithal passages would occur twice a year equidistant from the solstice. To represent this position of the Sun overhead, the Maya had a god named Diving God.

Fig. 2: Chichén Itzá(Mexico) is an important archaeological remains of the Maya astronomy.

Venus was the most important astronomical object to the Maya, even more important to them than the Sun. The Mayan calendar is a system of calendars and almanacs used in the Mayan civilization of pre-Columbian Mesoamerica, and in some modern Maya communities in highland Guatemala and Oaxaca, Mexico.

Although the Mesoamerican calendar did not originate with the Mayan, their subsequent extensions and refinements of it were the most sophisticated. Along with those of the Aztecs, the Mayan calendars are the best documented and most completely understood.

Aztec Astronomy

They were certain ethnic groups of central Mexico, particularly those groups who spoke the Nahuatl language and who dominated large parts of Mesoamerica in the 14th, 15th and 16th centuries, a period referred to as the late post-classic period in Mesoamerican chronology.

Aztec culture and history is primarily known through archeological evidence found in excavations such as that of the renowned Templo Mayor in Mexico City and many others, from indigenous bark paper codices, from eyewitness accounts by Spanish conquistadors or 16th and 17th century descriptions of Aztec culture and history written by Spanish clergymen and literate Aztecs in the Spanish or Nahuatl language.

The Aztec Calendar, or Sun Stone, is the earliest monolith that remains of the pre-Hispanic culture in Central and South America. It is believed that it was carved around the year 1479. This is a circular monolith with four concentric circles. In the center appears the face of Tonatiuh (Sun God), decorated with jade and holding a knife in his mouth. The four suns or earlier "worlds" are represented by square-shaped figures flanking the Fifth Sun, in the center. The outer circle consists of 20 areas that represent the days of each of the 18 months that comprised the Aztec calendar. To complete the 365-day solar year, the Aztecs incorporated 5 sacrificial, or Nemontemi, days.

Like almost all ancient peoples, the Aztecs grouped into associations the apparent bright stars (constellations): Mamalhuaztli (Orion's Belt), Tianquiztli (the Pleiades), Citlaltlachtli (Gemini), Citlalcolotl (Scorpio) and Xonecuilli (The Little Dipper, or Southern Cross for others, etc.). Comets were called "the stars that smoke".

The great periods of time in the Aztec cosmology are defined by the eras of different suns, each of whose end was determined by major disasters such as destruction by jaguars, hurricanes, fire, flood or earthquakes.

Inca Astronomy

Inca civilization is a civilization pre-Columbian Andean Group. It starts at the beginning of the 13th century in the basin of Cuzco in Peru and the current then grows along the Pacific Ocean and the Andes, covering the western part of South America. At its peak, it extends from Colombia to Argentina and Chile, across Ecuador, Peru and Bolivia.

The Incas considered their King, the Sapa Inca, to be the "child of the Sun". Its members identified various dark areas or dark nebulae in the Milky Way as animals, and associated their appearance with the seasonal rains. Its members identified various dark areas or dark nebulae in the Milky Way as animals, and associated their appearance with the seasonal rains

The Incas used a solar calendar for agriculture and a lunar calendar for the religious holidays. According to chronicles of the Spanish conquistadors, on the outskirts of Cuzco in present day Peru there was a big public schedule that consisted of 12 columns each 5 meters high that could be seen from afar. With it, people could set the date. They celebrated two major parties, the Inti Raymi and Capac Raymi, the summer and winter solstice respectively.

They had their own constellations: the Yutu (Partridge) was the dark zone in the Milky Way that we call the Coal Sack. They called the Pleiades cluster Qollqa. With the stars of the Lyra constellation they did a drawing of one of the most known animals to them, and named it Little Silver Llama or colored Llama, whose brightest star (Vega) was Urkuchillay, although according to others, that was the name of the whole constellation. Moreover there were the Machacuay (snake), the Hamp'atu (toad), the Atoq (Fox), the Kuntur, etc.

Major cities were drawn following celestial alignments and using the cardinal points.

On the outskirts of Cuzco there was an important temple dedicated to the Sun (Inti), from which came out some lines in radial shape that divided the valley in 328 Temples. That number is still a mystery, but one possible explanation relates it to the astronomy: it coincides with the days that contain twelve lunar months. And the 37 days that are missing until the 365 days of the solar year coincides with the days that the Pleiades cluster is not observable from Cuzco.

India

The earliest textual mention that is given in the religious literature of India (2nd millennium BCE) became an established tradition by the 1st millennium BCE, when different ancillary branches of learning began to take shape.

During the following centuries a number of Indian astronomers studied various aspects of astronomical sciences, and global discourse with other cultures followed. Gnomons and armillary spheres were common instruments.

The Hindu calendar used in ancient times has undergone many changes in the process of regionalization, and today there are several regional Indian calendars, as well as an Indian national calendar. In the Hindu calendar, the day starts with local sunrise. It is allotted five "properties," called angas.

The ecliptic is divided into 27 nakshatras, which are variously called lunar houses or asterisms. These reflect the moon's cycle against the fixed stars, 27 days and 72 hours, the fractional part being compensated by an intercalary 28th nakshatra. Nakshatra computation appears to have been well known at the time of the Rig Veda (2nd to 1st millennium BCE).

China

The Chinese were considered as the most persistent and accurate observers of celestial phenomena anywhere in the world before the Arabs. Detailed records of astronomical observations began during the Warring Sates period (4th century BCE) and flourished from the Han period onwards.

Some elements of Indian astronomy reached China with the expansion of Buddhism during the Later Han dynasty (25-220 CE), but the most detailed incorporation of Indian astronomical thought occurred during the Tang Dynasty (618-907).

Astronomy was revitalized under the stimulus of Western cosmology and technology after the Jesuits established their missions. The telescope was introduced in the 17th century. Equipment and innovation used by Chinese astronomy: armillary sphere, celestial globe, the water-powered armillary sphere and the celestial globe tower.

Chinese astronomy was focused more on the observations than on theory. According to writings of the Jesuits, who visited Beijing in the 17th century, the Chinese had data from the year 4,000 BCE, including the explosion of supernovae, eclipses and the appearance of comets.

In the year 2300 BCE, they developed the first known solar calendar, and in 2100 BCE recorded a solar eclipse. In 1200 BCE they described sunspots, calling them "specks dark" in the Sun. In 532 BCE, they left evidence of the emergence of a supernova star in the Aquila constellation, and in the 240 and 164 BCE passages of Halley comet. In 100 BCE Chinese invented the compass with which they marked the direction north.

And in more recent times, they determined the precession of the equinoxes as one degree every 50 years, recorded more supernovae and found that the tail of comets always points in the opposite direction to the Sun's position

In the year 1006 CE they noted the appearance of a supernova so bright that could be seen during the day. It is the brightest supernova that has been reported. And in 1054, they observed a supernova, the remnants of which would later be called the Crab Nebula.

Their celestial sphere differed from the Western one. The celestial equator was divided into 28 parts, called "houses", and there were a total of 284 constellations with names such as Dipper, Three Steps, Supreme Palace, Tripod, Spear or Harpoon. Chinese New Year starts on the day of the first new moon after the sun enters the constellation Aquarius.

The polymath Chinese scientist Shen Kuo (1031-1095 CE) was not only the first in history to describe the magnetic-needle compass, but also made a more accurate measurement of the distance between the Pole Star and true North that could be used for navigation. Shen Kuo and Wei Pu also established a project of nightly astronomical observation over a period of five successive years, an intensive work that would even rival the later work of Tycho Brahe in Europe. They also charted the exact coordinates of the planets on a star map for this project and created theories of planetary motion, including retrograde motion.

Europa Occidental

Following the fall of Rome, the knowledge complied by the Greeks was barely transmitted through the work of monks who often copied manuscripts that held no meaning for them. Eventually, with the rise of Cathedral schools and the first universities, scholars started to tackle the puzzles that science offers. Through trade (and pillaging), new manuscripts from the East came through the Crusades, and contact with Islamic scholars (especially in Spain) allowed translations to Latin to be made. Some scholars attempted to pull the information into an order that would fit it into their Christian viewpoint.

Mathematical genius: Nicholas Copernicus of Poland

In the early 1500s, Nicholas Copernicus (1473 – 1543) concluded that Universe would be simpler if the Sun, rather than the Earth, were at its center. Then the retrograde motion of the planets would occur even if all the planets merely orbited the Sun in circles. The backward motion would be an optical illusion that resulted when we passed another planet. Similarly, if you look at the car to your right while you are both stopped at a traffic light, if you start moving first, you might briefly think that the other car is moving backwards.

Copernicus shared his ideas with mathematicians, but did not publish them until a young scientist, Georg Rheticus, convinced him and arranged for the publication in another town. A printed copy of *De Revolutionibus Orbium Celestium* arrived just as Copernicus was dying in 1543. He may have never seen the unsigned preface written by the publisher that suggested that the book was a mathematical way to calculate positions, not the actual truth. Following Aristotle, Copernicus used circles and added some epicycles. His book followed the structure of Ptolemy's book, but his devotion to mathematical simplicity was influenced by Pythagorus.

Copernicus's book contains (figure 3) perhaps the most famous diagram in the history of science. It shows the Sun at the center of a series of circles. Copernicus calculated the speeds at which the planets went around the Sun, since he knew which went fastest in the sky. Thus he got the planets in the correct order: Mercury, Venus, Earth, Mars, Jupiter, Saturn, and he got the relative distances of the planets correct also. But, his calculations really didn't predict the positions of the planets much better than Ptolemy's method did.

In England, Leonard Digges wrote a book, in English, about the Earth and the Universe. In 1576, his son Thomas wrote an appendix in which he described

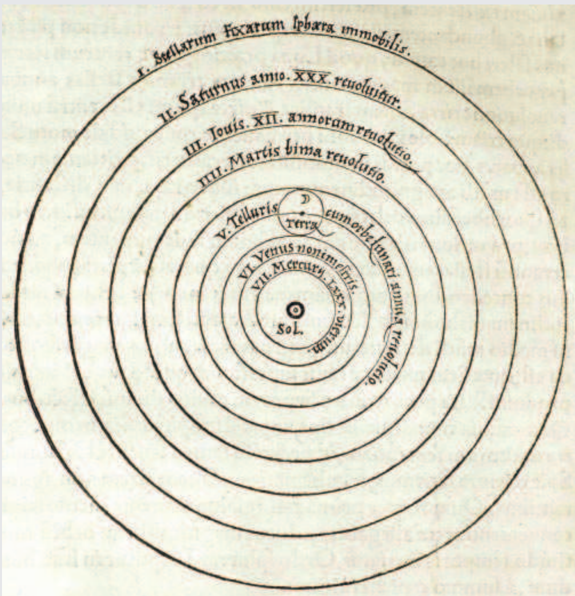

Fig. 3. Copernicus's diagram first showing the Sun at the center of what we therefore now call the Solar System. This diagram is from the first edition of De Revolutionibus Orbium Celestium (On the Revolutions of the Celestial Orbs), published in 1543.

Copernicus's new ideas. In the appendix, an English-language version of Copernicus's diagram appeared for the first time (figure 4). Digges also showed the stars at many different distances from the solar system, not just in one celestial sphere.

Observational genius: Tycho Brahe of Denmark

Fig. 4. The first Copernican diagram in English, from Thomas Digges's appendix to A prognostication everlasting, a book by his father first published in 1556. It contained only a Ptolemaic diagram. Thomas Digges's appendix first appeared in 1576; this diagram is from the 1596 printing.

The Danish aristocrat Tycho Brahe (1546 – 1601) took over an island off the coast of Copenhagen, and received rent from the people there. On this island, Hven, he used his wealth to build a great observatory with larger and better instruments. Though these were pre-telescopic instruments, they were notable for allowing more precise measurements of the positions of the stars and planets than had previously been possible.

Tycho ran his home as a forerunner of today's university, with visiting scientists coming to work with him. He made better and better observing devices to measure the positions of stars and planets, and kept accurate records.

But in his scientific zeal, he neglected some of his duties to his monarch, and when a new king and queen came in, he was forced out. He chose to move to Prague, on the continent of Europe, taking even his printing presses and pages that had already been printed, his records, and his moveable tools.

Tycho succeeded in improving the accuracy of scientific observations. His accurate observations of a comet at various distances showed him that the spheres did not have to be nested with the Earth at the center. So, he made his own model of the universe -a hybrid between Ptolemy's and Copernicus': the Sun and the Moon revolve around the Earth, while the other planets revolve around the Sun. Tycho still had circles, but unlike Aristotle, he allowed the circles to cross each other.

We value Tycho mainly for the trove of high-quality observations of the positions among the stars of the planet Mars. To join him in Prague, Tycho invited a young mathematician, Johannes Kepler. It is through Kepler that Tycho's fame largely remains.

Using Mathematics: Johannes Kepler of Germany

As a teacher in Graz, Austria, young Johannes Kepler (1571 – 1630) remembered his childhood interest in astronomy, fostered by a comet and the lunar eclipse that he had seen. He realized that there are five solid forms made of equally-shaped sides, and that if these solids were nested and separated by spheres, they could correspond to the six known planets. His book on the subject, *Mysterium Cosmographicum* (Mystery of the Cosmos), published in 1596, contained one of the most beautiful diagrams in the history of science (figure 5). In it, he nested an octahedron, icosahedron, dodecahedron, tetrahedron, and cube, with eight, twelve, twenty, four, and six sides, respectively, to show the spacing of the then-known planets. The diagram, though very beautiful, is completely wrong.

Fig. 5: Kepler's foldout diagram from his Mysterium Cosmographicum (Mystery of the Cosmos), published in 1596. His thinking of the geometric arrangement of the solar system was superseded in the following decade by his arrangements of the planets according to the first two of his three laws of planetary motion, a system we hold valid up to this day.

But Kepler's mathematical skill earned him an interview with Tycho. In 1600, he became one of several assistants to Tycho, and he made calculations using the data that Tycho had amassed. Then Tycho went to a formal dinner and drank liberally. As the story goes, etiquette prevented him from leaving the table, and he wound up with a burst bladder. His quick and painful death was carefully followed in a diary, and is well documented.

But Kepler didn't get the data right away. For one thing, the data was one of the few valuable things that Tycho's children could inherit, since Tycho had married a commoner and was not allowed to bequeath real property. But Kepler did eventually get access to Tycho's data for Mars, and he tried to make it fit his calculations. To make his precise calculations, Kepler even worked out his own table of logarithms.

The data Kepler had from Tycho was of the position of the Mars in the sky, against a background of stars. He tried to calculate what its real motion around the Sun must be. For a long while, he tried to fit a circle or an egg-shaped orbit, but he just couldn't match the observations accurately enough. Eventually, he tried a geometrical figure called an ellipse, a sort of squashed circle. It fit! The discovery is one of the greatest in the history of astronomy, and though Kepler first applied it to Mars and other planets in our solar system, we now apply it even to the hundreds of planets we have discovered around other stars.

Kepler's book of 1609, *Astronomia Nova* (The New Astronomy), contained the first two of his three laws of motion:

Kepler's first law: The planets orbit the Sun in ellipses, with the Sun at one focus.

Kepler's second law: A line joining a planet and the Sun sweeps out equal areas in equal times.

An ellipse is a closed curve that has two key points in it; they are known as the foci. To draw your own ellipse, put two dots on a piece of paper; each is a focus. Then take a piece of string longer than the distance between the foci. Tape them down on the foci. Next, put a pencil in the string, pulling it taut, and gently move it from side to side. The curve you generate will be one side of an ellipse; it is obvious how to move the pencil to draw the other side. This experiment with the string shows one of the key points defining an ellipse: the sum of the distances from a point on the ellipse to each focus remains constant. A circle is a special kind of ellipse where the two dots are on top of each other.

Kepler kept searching for harmonies in the motions of the planets. He associated the speeds of the planets with musical notes, the higher notes corresponding to the faster-moving planets, namely, Mercury and Venus. In 1619, he published his major work *Harmonices Mundi* (The Harmony of the Worlds). In it (figure 6), he included not only musical staffs with notes but

Fig. 6: From Kepler's Harmonices Mundi (The Harmony of the World), published in 1619.

also what we call his third law of planetary motion:

Kepler's Third Law of Planetary Motion: The square of the period of a planet's orbit around the sun is proportional to the cube of the size of its orbit.

Astronomers tend to measure distances between planets in terms of the Astronomical Units, which corresponds to the average distance between the Earth and the Sun, or 150 million kilometers.

Mercury	0.387 AU	0.240 years
Venus	0.723 AU	0.615 years
Earth	1 AU	1 year
Mars	1.523 AU	1.881 years
Jupiter	5.203 AU	11.857years
Saturn	9.537 AU	29.424 years

Table 1: Distances from the Sun and periods of the planets in Kepler's time.

Try squaring the first column and cubing the second column. You will see that they are pretty equal. Any differences come from the approximation, not from the real world, though with more decimal places the influences of the other planets could be detected.

Discoveries with the Telescope: Galileo Galilei of Italy

The year 2009 was the International Year of Astronomy, declared first by the International Astronomical Union, then by UNESCO, and finally by the General Assembly of the United Nations. Why? It commemorated the use of the telescope on the heavens by Galileo 400 years previously, in 1609.

Galileo (1564 - 1642) was a professor at Padua, part of the Republic of Venice. He heard of a Dutch invention that could make distant objects seem closer. Though he hadn't seen one, he figured out what lenses it must have contained and he put one together. He showed his device to the nobles of Venice as a military and commercial venture, allowing them to see ships farther out to sea than ever before. His invention was a great success.

Then he had the idea of turning the telescope upward. Though the telescope was hard to use, had a very narrow field of view, and was hard to point, he succeeded in seeing part of the Moon and realizing that there was a lot of structure on it. Because of his training in drawing in Renaissance Italy, he realized that the structure represented light and shadow, and that he was seeing mountains and craters. From the length of the shadows and how they changed with changing illumination from the Sun, he could even figure out how

Fig. 7a: One of Galileo's two surviving telescopes came to the Franklin Institute in Philadelphia in 2009, on its first visit to the United States. Note that the outer part of the lens is covered with a cardboard ring. By hiding the outer part of the lens, which was the least accurate part, Galileo improved the quality of his images. (Photo: Jay M. Pasachoff).

OBSERVAT. SIDEREAE

ctum daturam. Depreſſiores inſuper in Luna cernuntur magnæ maculæ, quàm clariores plagæ; in illa enim tam creſcente, quam decreſcente ſemper in lucis tenebrarumq́ue confinio, prominente hincindè circa ipſas magnas maculas contermini partis lucidioris; veluti in deſcribendis figuris obſeruauimus; neque depreſſiores tantummodo ſunt dictarum macularum termini, ſed æquabiliores, nec rugis, aut aſperitatibus interrupti. Lucidior verò pars maximè propè maculas eminet; adeò vt, & ante quadraturam primam, & in ipſa fermè ſecunda circa maculam quandam, ſuperiorem, borealem nempè Lunę plagam occupantem valdè attollantur tam ſupra illam, quàm infra ingentes quæda eminentiæ, veluti appoſitæ præſeferunt delineationes.

Hæc

Fig. 7b: A page from Galileo's *Sidereus Nuncius* (The Starry Messenger), published in 1610, showing an engraving of the Moon. The book was written in Latin, the language of European scholars. It included extensive coverage of the relative motion of the four major moons of Jupiter.

high they were. A few months earlier, the Englishmen Thomas Harriot had pointed a similar telescope at the Moon, but he had drawn only some hazy scribbles and sketches. But Harriot wasn't interested in publication or glory, and his work did not become known until after his death.

One lens Galileo used for his discoveries remains, cracked, in the Museum of the History of Science in Florence, Italy, and two full telescopes he made survive, also there (figure 7a).

Galileo started writing up his discoveries in late 1609. He found not only mountains and craters on the moon but also that the Milky Way was made out of many stars, as were certain asterisms. Then, in January 1610, he found four "stars" near Jupiter that moved with it and that changed position from night to night. That marked the discovery of the major moons of Jupiter, which we now call the Galilean satellites. He wrote up his discoveries in a slim book called Sidereus Nuncius (The Starry Messenger), which he published in 1610 (figure 7b). Since Aristotle and Ptolemy, it had been thought that the Earth was the only center of revolution. And Aristotle had been thought to be infallible. So the discovery of Jupiter's satellites by showing that Aristotle could have been wrong was a tremendous blow to the geocentric notion, and therefore a strong point in favor of Copernicus' heliocentric theory.

Galileo tried to name the moons after Cosmo de' Medici, his patron, to curry favor. But those names didn't stick. Within a few years, Simon Marius proposed the names we now use. (Marius may even have seen the moons slightly before Galileo, but he published much later.) From left to right, they are Io, Europa, Ganymede, and Callisto (figure 9). Even in a small, amateur telescope, you can see them on a clear night, and notice that over hours they change positions. They orbit Jupiter in periods up to a few days long.

Even in the biggest and best ground-based telescopes, astronomers could not get a clear view of structure on the surfaces of the Galilean satellites. Only when the NASA satellites Pioneer 10 and 11, and then Voyager 1 and 2, flew close to the Jupiter system did we see enough detail on the satellites to be able to characterize them and their surfaces. From ground-based and space-based observations, astronomers are still discovering moons of Jupiter, though the newly discovered ones are much smaller and fainter than the Galilean satellites.

Galileo used his discoveries to get a better job with a higher salary, in Florence. Unfortunately, Florence was closer to the Papal authority in Rome, serving as bankers to the Pope, and was less liberal than the Venetian Republic. He continued to write on a variety of science topics, such as sunspots, comets, floating bodies. Each one seemed to pinpoint an argument against some aspect of Aristotle's studies. He discovered that Venus had phases -which showed that Venus orbited the Sun.

This did not prove that Earth orbited the Sun, since Tycho's hybrid cosmology would explain these phases. But, Galileo saw it as support of Copernicus.

In 1616, he was told by Church officials in Rome not to teach Copernicanism, that the Sun rather than the Earth was at the center of the Universe. He managed to keep quiet for a long time, but in 1632 he published his *Dialogo* (Dialogue on Two Chief World Systems) that had three men discussing the heliocentric and geocentric systems. He had official permission to publish the book, but the book did make apparent his preference for the Copernican heliocentric system. He was tried for his disobedience and sentenced to house arrest, where he remained for the rest of his life.

Fig. 8. In 2009, to commemorate the 400th anniversary of Galileo's first use of the telescope on the heavens, a plaque was put on a column at the top of the Campanile, a 15th-century tower (re-erected in the early 20th century after it collapsed in 1902) in Venice. The commemoration here is of Galileo's demonstrating his telescope to the nobles of Venice by observing ships relatively far out at sea; it was before he turned his telescope upward. The writing on the plaque can be translated approximately as "Galileo Galilei, with his spyglass, on August 21, 2009, enlarged the horizons of man, 400 years ago."(Photo: Jay M. Pasachoff).

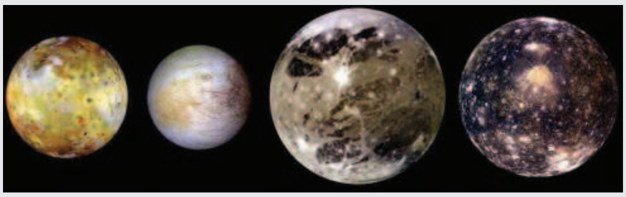

Fig. 9. Galileo himself would have been amazed to see what his namesake spacecraft and its predecessors showed from the "Medician satellites" that he discovered in 1609. Here they show in images at their true relative scale. From left to right, we see Io, newly resurfaced with two dozen continually erupting volcanoes. Second is Europa, a prime suspect for finding extraterrestrial life because of the ocean that is under the smooth ice layer that we see. Third is Ganymede, the largest moon in the solar system, showing especially a fascinatingly grooved part of its surface. And at right is Callisto, farther out than the others and covered with hard ice that retains the scarring from overlapping meteorite strikes that occurred over billions of years. (Photo:NASA, Galileo Mission, PIA01400).

The New Physics: Isaac Newton of England

Many believe that the three top physicists of all time are: Isaac Newton, James Clerk Maxwell, and Albert Einstein. A summary: Newton discovered the law of gravity, Clerk Maxwell unified electricity and magnetism, and Einstein discovered special and general relativity.

In a mostly true story, young Isaac Newton (1642 – 1727) was sent home from Cambridge University to Woolsthorpe, near Lincoln, in England, when the English universities were closed because of plaque. While there, he saw an apple fall off an apple tree, and he realized that the same force that controlled the apple's fall was, no doubt, the same force that controlled the motion of the Moon.

Eventually, Newton was back at Trinity College, Cambridge, on the faculty. In the meantime, a group of scientists in London got together in a coffeehouse to form a society (now the Royal Society), and young Edmond Halley was sent to Cambridge to confirm a story that a brilliant mathematician, Isaac Newton, could help them with an important scientific question. The trip from London to Cambridge by stagecoach was a lot longer and more difficult than the hour's train trip is nowadays.

Halley asked Newton if there were a force that fell off with the square of the distance, what shape would an orbit have? And Newton replied that it would be an ellipse. Excited, Halley asked if he had proved it, and Newton said it was on some papers he had. He said he couldn't find them, though perhaps he was merely waiting time to judge whether he really wanted to turn over his analysis. Anyway, Newton was moved to write out some of his mathematical conclusions. They led, within a few years, to his most famous book, the *Philosophiæ Naturalis Principia Mathematica* (the Mathematical Principles of Natural Philosophy), where what they then called Philosophy includes what we now call Science.

Newton's *Principia* came out in 1687, in Latin. Newton was still a college teacher then; it was long before he was knighted for his later work for England's mint. Halley had to pay for the printing of Newton's book, and he championed it, even writing a preface.

The *Principia* famously included Newton's law that showed how gravity diminishes by the square of the distance, and his proof of Kepler's laws of planetary orbits. The book also includes Newton's laws of motion, neatly shown as "laws," in Latin, whereas Kepler's laws are buried in his text.

Newton's laws of motions are:

Newton's first law of motion: A body in motion tends to remain in motion, and a body at rest tends to remain at rest.

Newton's second law of motion (modern version): force = mass times acceleration.

Newton's third law of motion: For every action, there is an equal and opposite reaction.

Newton laid the foundation though mathematical physics that led to the science of our modern day.

Astronomy Research Continues

Just as the ancient peoples were curious about the sky and wanted to find our place in the universe, astronomers of the present day have built on the discoveries of the past with the same motivation. Theoretical and observational discoveries moved our understanding of our place in the universe from Ptolemy's geocentric vision, to Copernicus's heliocentric hypothesis, to the discovery that the solar system was not in the center of our galaxy, to our understanding of galaxies distributed across the universe.

Contemporary astronomy grapples with the programs of finding the nature of dark matter and dark energy. Einstein's theory of relativity indicates that not only is our galaxy not in the center of the universe, but that the "center" is rather meaningless. More recent discoveries of hundreds of exoplanets orbiting other stars have shown how unusual our solar system may be. New theories of planet formation parallel new observations of unexpected planetary systems. The path of discovery lays before astronomers of the modern age just as it did for those from thousands or hundreds of years ago.

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