

## NOTES ON GALILEO

Galileo was born in Pisa of the famous leaning tower in 1564. Pisa is a medium-sized city in northern Italy (Tuscany). By tradition, Tuscans are a proud and independent lot. Galileo fit the bill. Galileo's father was a musician from a long time Florentine family with firm ideas of his own. He felt that the formal church music of the time had become sterile and needed to be infused with ancient Greek ideals as expressed by Homer. His work began the development that led to Italian opera. To understand something of Galileo's early upbringing, here is a quote from his father who represented the Renaissance spirit very well:

“It appears to me that those who rely simply on the weight of authority to prove any assertion, without searching out the arguments to support it, act absurdly. I wish to question freely and to answer freely without any sort of adulation. That well becomes any who are sincere in the search for truth.” Galileo absorbed this attitude thoroughly.

As a child Galileo's favorite pastime was the invention and construction of ingenious toy machines. In school he was equally conspicuous in literary studies. He was attracted to religion, and became a novitiate, but his father withdrew him from the care of the monks. Having had personal experience with the unremunerative aspects of both music and mathematics, his father wanted him to become a doctor. He was a talented musician and painter, and seemed capable of developing a career in nearly any field. He entered the University of Pisa in 1581 to study medicine.

In that same year, while watching a lamp set swinging in the cathedral of Pisa, he noticed that as the amplitude decreased, the time for one round trip (period) remained the same. This became the basis for the construction of all clocks for the next four centuries, and by itself is enough to have made him famous.

Galileo's father intentionally kept him ignorant of mathematics as a child, surmising, correctly, that his fascination with it would take him away from the study of medicine. Accident, however, frustrated this purpose. A lesson in geometry given by Ostilio Ricci for the pages of the grand ducal court chanced to have Galileo for an unseen listener. With Ricci's help he rapidly mastered the elements of the science, and extorted

his father's permission to exchange Galen for Euclid. He withdrew from the university before receiving a degree due to a lack of funds.

He conducted research on hydrostatics and the centers of gravity of solids, and was successful enough to be appointed lecturer in mathematics at Pisa at age 25, and Chair of Mathematics at Padua near Venice at age 28. He remained at Padua for 18 years and there conducted his most important work. The Venetian Republic was a lively place at this time. Venice, a city of 150,000 people, consumed 40 million bottles of wine each year (about 270 bottles per person), and there were more courtesans than in Rome. Galileo met Maria Gamba, and although they never married, they had two daughters and a son. One of Galileo's good friends was a young Venetian nobleman named Sagredo, who later was featured in his two major works, *Dialogue concerning the Two Chief World Systems*, and *Two New Sciences*. Both of these works are written in dialogue form and display Galileo's wit and sarcasm as well as polished writing style.

Galileo's most important work consisted of laying the foundation for the science of mechanics. He began by studying motion, showing that falling bodies exhibit uniform acceleration, i.e. that their speeds increase uniformly with time if friction is ignored. He also showed that the path of a projectile is parabolic. There is no factual basis for the story that he dropped weights from the leaning tower of Pisa to demonstrate that heavy and light objects fall at the same rates.

In 1611 Galileo visited Rome and demonstrated his telescope to high Church officials. Encouraged by their flattering response, he moved towards a more definite position on the Copernican system, which he supported. His great expository gifts, and his use of Italian, in which he was a master of style, made his thoughts known far beyond the universities, and created a powerful movement of opinion. Almost all the science professors of that time were Aristotelians, and, seeing their vested interests attacked, united against him. They attacked him through ecclesiastical authorities claiming there were contradictions between the Copernican model and the Scriptures.

Galileo agreed with one of his former students, B. Castelli, a Benedictine monk, that something should be done to forestall a crisis. He wrote letters to Castelli meant for the Grand Duke and Church authorities, emphasizing the Church's standing practice of interpreting the Scriptures allegorically whenever they came into conflict with scientific

fact, and saying “It would be a terrible detriment for the souls if people found themselves convinced by proof of something it was made then a sin to believe.” Cardinal Robert Bellarmine was the chief theologian of the Church, who took an instrumentalist view of the question, saying that mathematical hypotheses had nothing to do with physical reality. He was also concerned about raising an issue that might be used by Protestants against the Church. He decided the best thing to do was to have Copernicanism declared “false and erroneous” and to list Copernicus’ book on the Index of forbidden reading. Bellarmine met with Galileo to inform him of the coming decree, and told him that henceforth he must neither “hold nor defend” the Copernican model, but that it could be discussed as a “mathematical supposition.” The decree appeared in 1616.

In 1624 Galileo again went to Rome hoping to obtain a revocation of the decree of 1616. He failed in this attempt, but did get the Pope’s permission to teach “the systems of the world” as long as he discussed them noncommittally and came to the conclusion that man cannot presume to know how the world is really made because God could have brought about the same effects in ways unimagined by him.

Galileo returned to Florence and went to work on his great book *Dialogue concerning the Two Chief World Systems*. When it appeared in 1632, with the full approval of the censors, it was hailed as a literary and philosophical masterpiece. It was pointed out to the Pope, however, that despite its noncommittal title, and proper conclusion, the work was a compelling and unabashed plea for the Copernican system. The Pope was angry and ordered a prosecution. The problem was that the book had been approved by the censors, so it appeared there was nothing they could do. At that point a document was “discovered” in the file showing that during the 1616 Bellarmine interview Galileo had promised in writing not to teach or discuss Copernicanism in any way. The consensus of historians based on evidence made available when the file was published in 1877, is that this document had been planted, and that Galileo had not been so enjoined.

Galileo was tried, found guilty, and sentenced to life in prison. The Pope commuted the sentence to house arrest, which remained in effect for the eight remaining years of his life. Remarkably his spirit never flagged, and indeed his best work, *Two New Sciences* appeared in 1634, having been produced while he was under house arrest. The two sciences were the strength of materials and the science of motion.

The small book, *Siderius Nuncius*, or The Starry Messenger, is an announcement by Galileo of new observations made by him using telescopes he had made. Excerpts are quoted in Crowe's book. The telescope opened astronomy to a much wider group of practitioners than had been the case before. To compete with Tycho and Ptolemy, one needed to dedicate his life to the study. But with a simple telescope, anyone could look at the sky and make observations.

Galileo first heard about telescopes in the summer of 1609. They were at that time regarded as backyard toys for children, with a power (magnification) of about 3 or 4. Since about the 14<sup>th</sup> century, magnifying glasses had been used to aid the reading of older people who tend to become far-sighted (unable to focus on nearby objects) with age. By the end of that century, Italian craftsmen were constructing spectacles, much like today's eyeglasses only certainly less comfortable to wear. The lenses were shaped like lentils, the Latin word for which is lens, hence our noun for lenses in general. By the end of the 14<sup>th</sup> century, concave lenses were also being made to aid weak vision of young people who are short-sighted, i.e. myopic.

Lenses could then be purchased not only in all major cities of Europe, but in the rural regions as well, from itinerant peddlers at markets and fairs. Since a telescope could be made by combining two lenses, why did this not occur earlier than it did? It probably did, but the strengths of the lenses commonly available only permitted a telescope to be made that could magnify three or four times, so it did not stir up much interest. Finally in 1609, Lipperhey tried unsuccessfully to patent such a device in Holland, and word of it got around.

Galileo assembled a telescope using available lenses immediately upon hearing about it, and also, almost immediately, understood what was needed to make it stronger. He needed a stronger eyepiece (concave) lens. In order to supplement his income, Galileo regularly took in boarders and sold scientific instruments made by a craftsman in his employ. So he was in a position to build instruments, but he had never ground lenses before. He taught himself how to do so – no small accomplishment in itself – and by the end of that summer he had produced a telescope with a magnification of 8 or 9.

What does it mean to say that a telescope has a magnification of some amount, say 8? Does it mean that inside the telescope there is an image of the moon that is 8 times the size of the moon? Certainly not. Let us see how this works.

**SHOW** Elmo ray optics and powerpoint diagram for convex, concave lenses and Galilean telescope.

At this point Galileo had the most powerful telescope in the world in his hands. His first moves were to benefit financially from it. He had never been wealthy, and he had family responsibilities – three children, and two sisters whose doweries he was responsible for. So he approached the Senate of Venice addressing its leader as “Most Serene Prince” offering to give the telescope to the republic. Senators climbed the highest belltowers in Venice to look at sails of approaching ships. The ability to recognize an incoming ship as friend or foe from a greater distance was indeed of practical value. Galileo finished his letter by expressing the hope that “he, according to his desire will pass the rest of his life in your service.” In other words, he asked for tenure.

This public relations manouever worked. His salary was doubled and made permanent – however without any provisions for future raises.

Galileo then turned his attention and the telescope towards the skies to pursue what had been his principal motivation all along – to discover what could be learned about the celestial objects using the telescope. His first major discovery had to do with the moon.

#### MOUNTAINS ON THE MOON

At this time the Aristotelian view of celestial objects was nearly universally accepted. All things below the moon were made of fire, air, water, and earth, and were transient. All things from the moon up were made of aether – a perfect, eternal fifth element. The celestial bodies were perfect spheres.

In *Starry Messenger*, Galileo describes in detail, and embellishes with sketches, the irregular shapes he observed on the surface of the moon. His method was to observe carefully the dividing line between light and dark. This is where the Sun’s rays are incident nearly parallel to the moon’s surface, so mountains will cast long shadows, and valleys will appear dark. He saw shapes that looked to him like mountains and hills and

valleys, some regions reminding him of places on Earth. He then made a clever estimate of the heights of the tallest mountains on the moon.

SEE Powerpoint slide of mountain height calculation.

Galileo now turned his telescope to study Jupiter. SEE powerpoint slide of moons of Jupiter. Half a dozen years earlier, Galileo had been mathematics tutor to the young Cosimo de Medici, who in 1609 had become the Grand Duke of Tuscany, Galileo's native land. He had kept in touch with the Medici family, and now saw an opportunity to gain their patronage. So he sent a note to the Grand Duke's secretary saying "...and since it is up to me, the first discoverer, to name these new planets, I wish, in imitation of the ancient sages, who placed the most excellent heroes of that age among the stars, to inscribe these with the name of the Most Serene Grand Duke." He then asked whether he should name them after Cosimo only, or after the four Medici brothers together, and was told the latter was preferred, so they became the Medicean Stars (later moons).

During Easter vacation Galileo visited Florence to meet with Cosimo, who shortly after decided to offer Galileo a position at the Tuscan court. By September Galileo had come to Florence to take up his new position as Principal Mathematician of the University of Pisa (a position without duties), and mathematician and philosopher of the Grand Duke.

So just a year after he had doubled his salary at Padua and asked for an received a lifetime appointment, he had again increased his salary with a university position having no teaching duties, and in his old home territory. It was a good year for Galileo.

Through all this Galileo continued his observations. A very important observation, which is a smoking gun for the Ptolemaic model, is his sighting of a full set of phases of Venus. SEE powerpoint slides of phases of Venus.

#### OTHER RESULTS AND IMPLICATIONS

Galileo mentions almost casually that the moons of Jupiter might help solve the longitude problem on Earth. Here is the problem: A ship at sea exploring the globe is far from home port. How can the navigator determine its location? In the north-south direction the problem is straight forward. By sighting the angle of a known star, such as Polaris, off the northern horizon, the northern latitude can be determined. The problem is with the east-west location, or the determination of longitude.

Measuring the angular position of a star in the east-west direction is meaningless unless you know what time it is. If you sail from London westward, you want to know how far in longitude you have traveled. But that requires knowing what time it is back in London. If you measure the angular position of a known star from the ship, you need to know what time it is in London at the moment of your measurement in order to know the angular difference between your position and that of London. The Earth rotates 15 degrees per hour so an error of one hour amounts to a distance error of 1000 miles at the equator. The correct time must be known much better than this to be of use. Ships were often at sea for months or years and clocks in Galileo's time were nowhere near up to the task.

Galileo suggested that the moons of Jupiter were in effect an astronomical clock. For example, Io the moon nearest Jupiter, has a period of about 8 hours. That means it passes behind Jupiter once every 8 hours. Its moment of eclipse can be seen from anywhere on Earth that Jupiter is visible. With a book of predicted eclipse times, a navigator far from home could use the observed eclipses to reset his clock as often as needed, allowing him to determine his longitude.

This method worked fine for explorers on land, but not at sea. A ship rocks back and forth too much to get a steady view of Jupiter. The problem at sea grew worse as more ships were used for exploration and military work in the seas around the world. In 1714 Queen Anne of England approved the Longitude Act offering a prize of 20,000 pounds to anyone who could produce a method of determining longitude to within  $\frac{1}{2}$  degree accuracy. This corresponds to knowing the time back in the home port with an accuracy of two minutes. Eventually a lone mechanical genius named John Harrison developed a windup clock with an accuracy of  $\frac{1}{3}$  second per day and collected the prize. Such clocks were called ship's chronometers and were very carefully protected in the captain's cabin.

The precise orbits of Jupiter's moons served another valuable purpose. They provided the first method of determining the speed of light. SEE Speed of Light powerpoint slide. Because the diameter of the earth's orbit is so large, astronomical methods were able to determine the speed of light three centuries before this could be accomplished in the laboratory.

**Earthshine.** When Galileo looked at a new moon, or at the dark part of the moon when it is a slim crescent, he realized that something illuminated it. It was necessary for him to block out the bright crescent to see it, but it definitely was there. He described it as a faint white light that was quite uniform. This illumination can be seen by naked eye, and others had commented on it. Galileo dismissed the other proposed explanations he was aware of and proposed that it was due to light scattered back from the Earth towards the Moon. So this light starts from the Sun, goes to the Earth, is scattered from there towards the Moon, where it is scattered once again towards Earth. This explains its whiteness, since the Sun's light is somewhat yellow, and Earth is mainly blue.

Galileo distinguished this light from that seen during a lunar eclipse. When this occurs once again the Moon is not completely darkened. The light that is seen from the Moon in this case however is reddish, and brighter towards the outer rim, so he said it must have a different origin. He was right. We know today that this light is due to refraction in the Earth's atmosphere. This light is focused inward slightly as with a weak convex lens. It is red for the same reason that sunsets and sunrises are redder than the noonday sun. Blue light is scattered more strongly and more of it is removed from the forward rays which then become reddish.

Galileo observed the **Milky Way** with his telescope and said he could resolve it into thousands of individual stars. Since prehistory it was regarded as a continuous structure of some kind – hence the name. It appears as a faint white cloud on very clear nights. Indeed it is difficult to distinguish it from a cloud so the night must be very clear and dark.

Galileo's comments about the **fixed stars** were that his telescope did not magnify them as it did the planets. The planets became disks or crescent shapes with definite finite size. The stars still looked like points as they do by naked eye. This result although qualitative, reinforced the lack of observation of a stellar parallax, providing evidence that the stars were indeed very far away compared with the size of the solar system.

At the beginning of *Starry Messenger* is a statement of approval from the Council of Ten. This was a committee whose approval was needed in order to publish any book whatsoever. The Council dealt with all criminal and moral matters and had been in existence for three centuries. We should not be surprised at the slavish language Galileo



uses in the opening pages as he addresses the “Most Serene Cosimo II De Medici”. Not only was it customary, since all science then was supported by wealthy patrons, but as we know, Galileo was applying to Cosimo for just such patronage, which he received.