Astronomy Through the Ages 3:
Galileo Galilei:
Telescopic Astronomy
and the nature of motion

ASTR 101

10/3/2018

Assignment:

Watch the movie "**Galileo's Battle for the Heavens"**

can be viewed online at:

http://www.pbs.org/wgbh/nova/ancient/galileo-battle-for-the-heavens.html
or
https://www.youtube.com/watch?v=XCxkdR092c4

(no commercial breaks)

Galileo Galilei

- Italian astronomer, physicist, mathematician, and natural philosopher. Often referred to as the "father of modern astronomy and physics".
- Born in Pisa in 1564.
- In 1581, enrolled at the University of Pisa for a medical degree.
- It was during that time (1583) he made his famous discovery on pendulums.

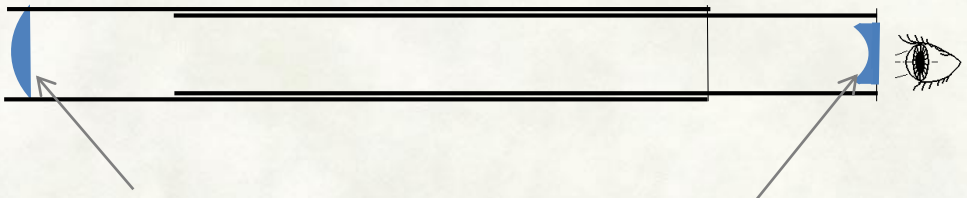
  While watching a chandelier swing back and forth at the Cathedral of Pisa, Galileo noticed that regardless how far it swung, the time it took to swing back and forth was always the same.

  This principle was later used to build pendulum clocks.

Galileo used his pulse to time the duration of swing

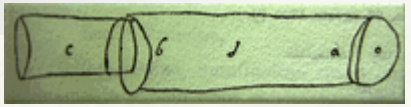
- While at the University of Pisa, he became interested in mathematics, and began self-studying mathematics .
- He dropped out of the University in 1585, but continued self-studying Mathematics.
- Became a professor of Mathematics at Pisa in 1589.
- Became the Chair of Mathematics at the University of Padua in 1592. He remained at Padua for the next 18 years and made most of his discoveries in physics and astronomy.

The Telescope



convex lens
(objective)

concave lens
(eyepiece)



- In 1608 Hans Lipperhey, a Dutch spectacle-maker found out that distant objects could be seen closer when looked through a combination of lenses. Based on this he built a small telescope.
- In 1609 Galileo learned about it. He figured out how it worked and set about building one of his own.
- He was able to build better quality telescopes, using lenses he ground himself. (with magnifications 8-30, and apertures about 1 inch).
- In August that year, Galileo demonstrated his telescope to the Venetian Senate.
- They were impressed, and understood the military potential of the invention.
- His professorship at Padua was confirmed for life and salary was doubled (as Galileo requested.)

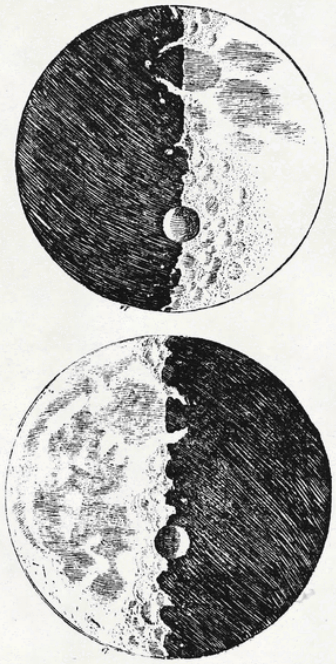
Galileo Galilei, a most humble servant of Your Serene Highness, being diligently attentive, with all his spirit, not only to discharging the duties pertaining to the lecturing of mathematics at the University of Padua, but also to bringing extraordinary benefit to Your Serene Highness with some useful and remarkable invention, now appear before You with a new contrivance of glasses, drawn from the most recondite speculations of perspective, which render visible objects so close to the eye and represent them so distinctly that those that are distant, for example, nine miles appear as though they were only one mile distant. This is a thing of inestimable benefit for all transactions and undertakings, maritime or terrestrial, allowing us at sea to discover at a much greater distance than usual the hulls and sails of the enemy, so that for two hours or more we can detect him before he detects us...

....(the telescope is) one of the fruits of the science which he has professed for the past 17 years at the University of Padua, with the hope of carrying on his work in order to present You greater ones, if it shall please the Good Lord and Your Serene Highness that he, according to his desire, will pass the rest of his life in Your service.

from Galileo's letter to the Doge (leader) of Venice

Galileo demonstrating his telescope to the Doge of Venice and the members of Senate

Telescopic Observations of the Sky

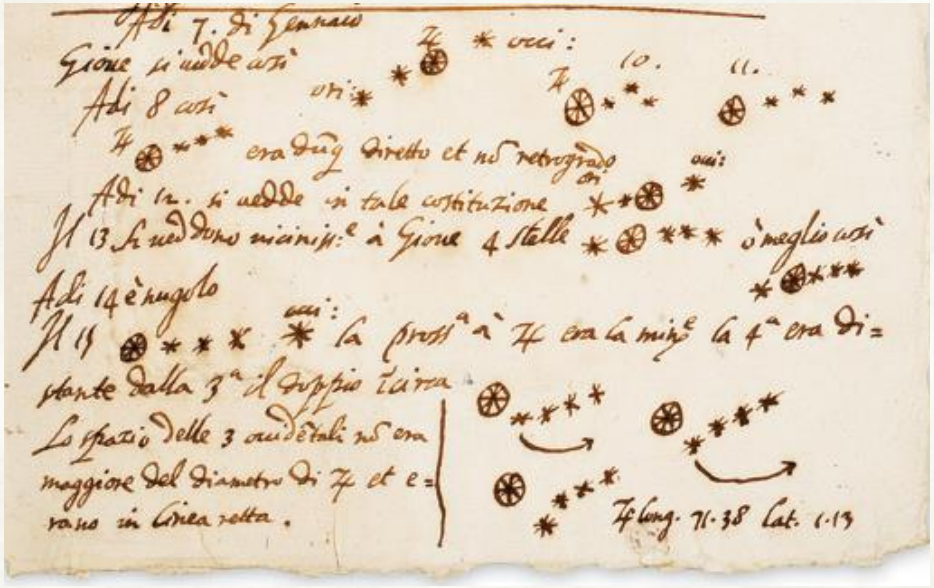


From National Geographic - August 25, 2009
400 year anniversary of Galileo's telescopic observations

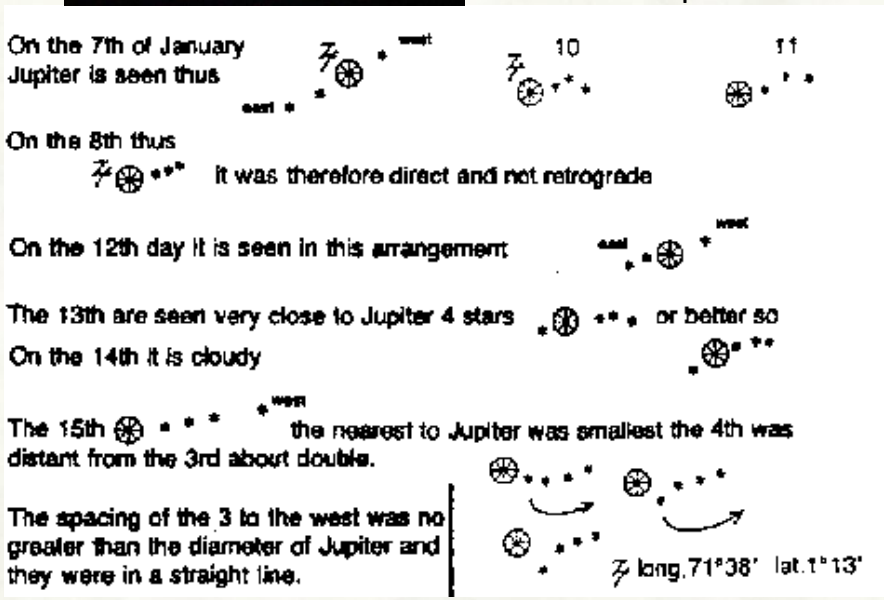
- Soon Galileo turned his telescope to sky, his first target was the Moon.
- Contrary to the prevailing belief that the Moon was a perfect sphere, what he saw was a rugged mountainous surface.
  - He estimated the height of mountains from the length of their shadows.
  - The thought dark areas on the moon were oceans, named them "maria/mare"
- Galileo's observations of rugged mountainous, Earth like moon surface directly contradicted Aristotle's cosmological descriptions of perfect and unchanging heavenly bodies.

Moons of Jupiter

Galilean moons: **Io, Europa, Ganymede,** and **Callisto** as visible through a small telescope



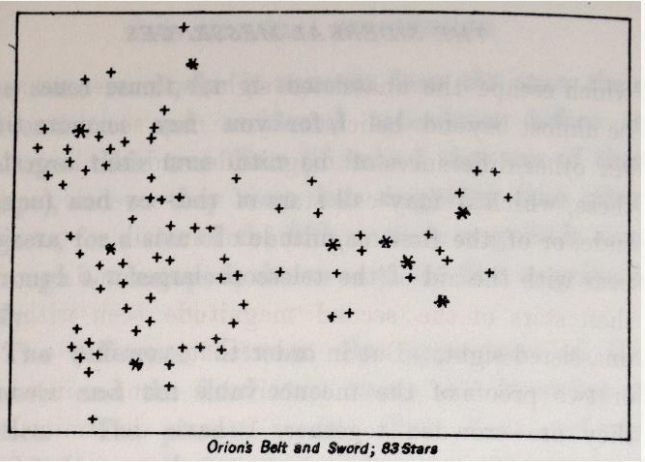
Galileo's notes on first observations of Jupiter in 1610.

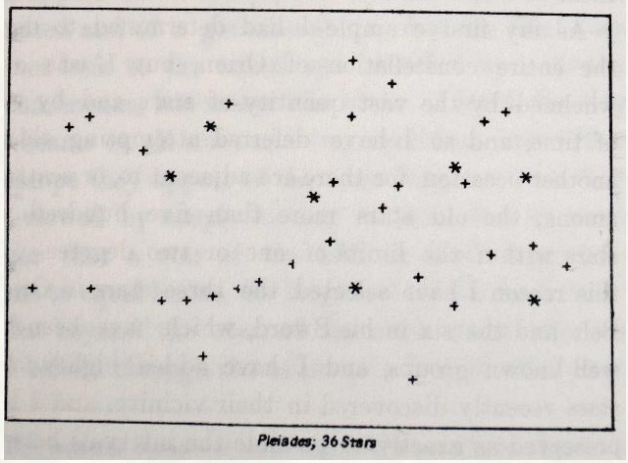


- on January 7, 1610 when Galileo pointed his telescope at Jupiter He saw three tiny stars very close to it, strung out in a line.
  - When he observed again next day he saw the same stars, but their positions had changed.
  - He continued to observe Jupiter and the stars. On January 13, a fourth star appeared.
  - After a few weeks, Galileo noticed that the stars were moving along with Jupiter across the sky, while changing their positions with respect to Jupiter.
- Soon, he realized those were not stars, but planetary bodies that were orbiting around Jupiter.
- Thus Galileo discovered the four largest satellites (moons) of Jupiter.

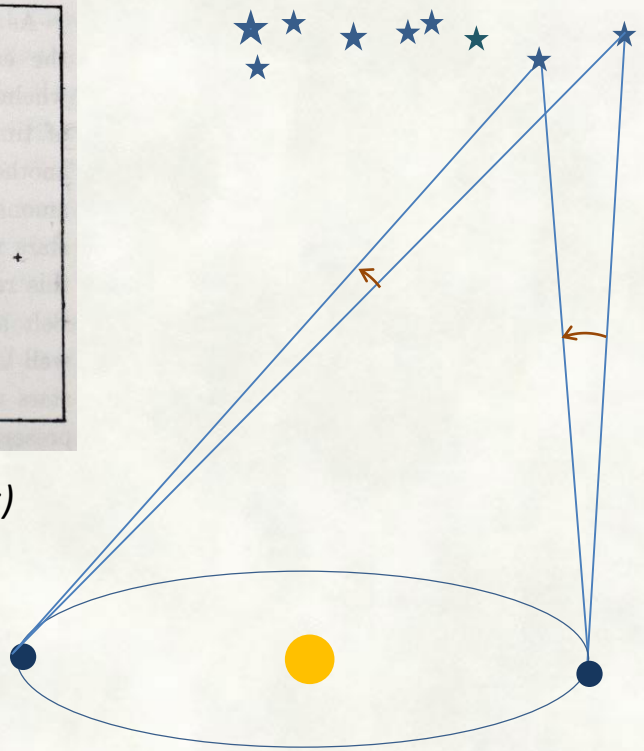
video: Galileo discovering Jupiter’s moons

www.pbslearningmedia.org/resource/ess05.sci.ess.eiu.galileomoon/galileo-discovering-jupiters-moons/





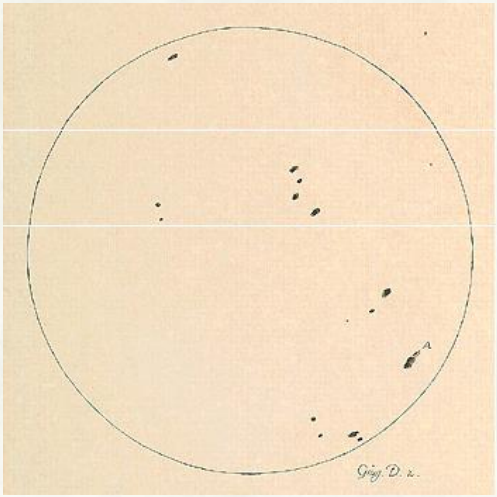
Galileo's sketches of stars in Orion and Pleiades (from *Sidereus Nuncius)*



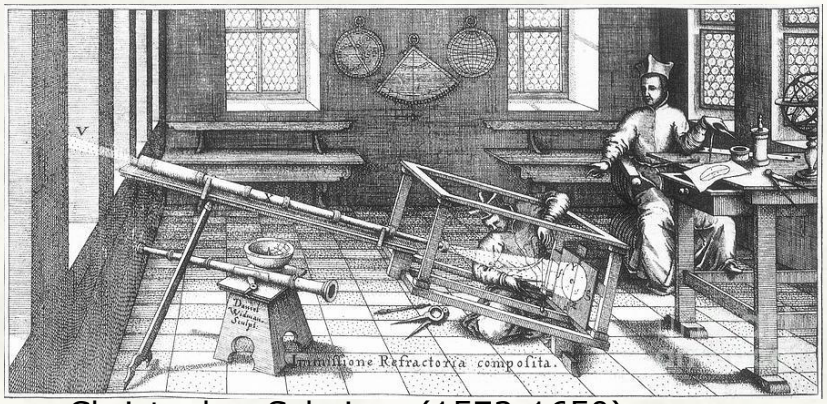
- Galileo observed the Milky Way through his telescope:
  - He saw that the Milky Way was made up of countless stars.
  - He explanted that the Milky way looked nebulous to the naked eye because there were so many stars, far away than anyone previously imagined.
- This eliminated a main argument against heliocentric theory since Greek times:
  - non observability of stellar parallax.

    Stars do not show parallax as the Earth goes around the Sun because stars are very far away. The earth's orbit is vey small in comparison to their distances.

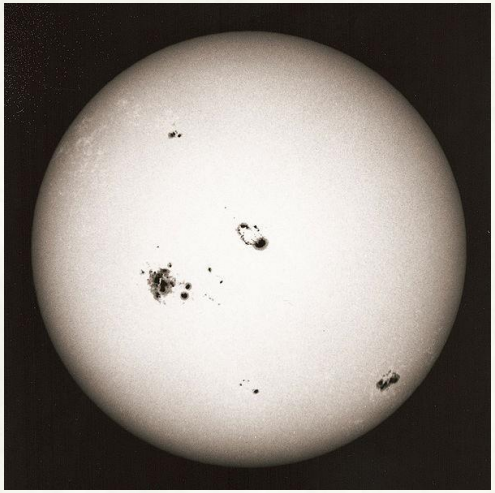
Sunspots



Galileo's drawings of sunspots



Christopher Scheiner (1573-1650) observing sunspots



A modern telescopic view of sunspots

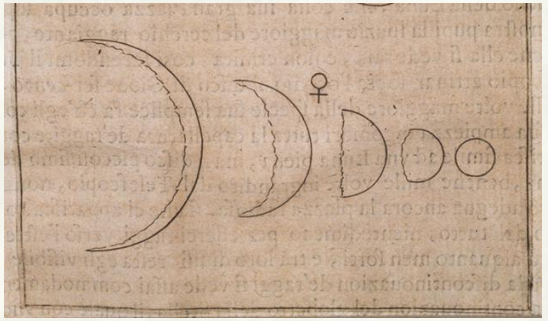
- In 1612 Galileo (and many others) observed sunspots, dark patches on the surface of the Sun.
  - Those "blemishes" on the Sun refuted the basic principles of Aristotelian doctrine of an unchanging perfect nature of the heavenly objects.
- Furthermore, Galileo observed motion of the sunspots indicating that the Sun was rotating.
  - This made it less strange that the Earth might rotate on an axis too, as required in the Copernican model.
- Christopher Scheiner, an astronomer and a priest who supported the geo-centrism, also observed sunspots.
  - But he refused to believe those were spots on the Sun. Instead he claimed they must be tiny undiscovered planets circling close to the Sun, which would occasionally pass in front of its disk.
  - Galileo showered that it was wrong, since spots were not permanent and their shape changed.

Galileo on sunspots

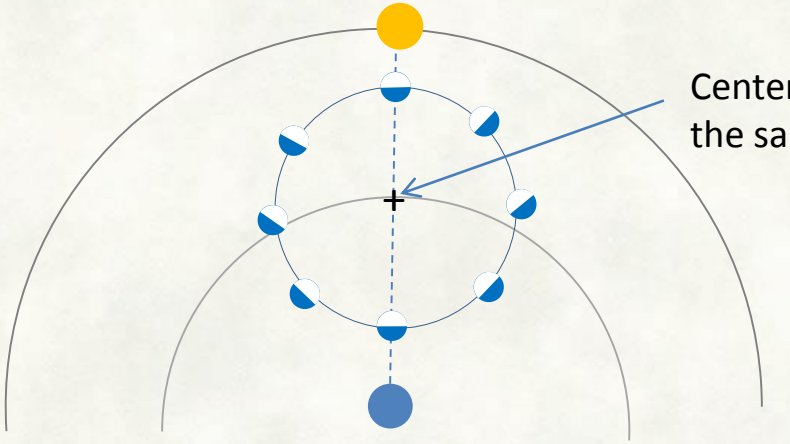
- http://mpb.pbslearningmedia.org/resource/ess05.sci.ess.eiu.galileosun/galileo-sunspots/

Phases of Venus

- In December 1610 Galileo observed Venus with his telescope.
- After few months of observations, he was able to observe that Venus was going through a full cycle of phases.
- This was not allowed in the Ptolemaic system.



Galileo's illustrations of Venus



Center of Venus' epicycle always in the same direction as the Sun

According to Ptolemaic system only crescent phase is visible

- Angular separation between Venus and the Sun never exceeds ~48°.
  - Ptolemaic geocentric system explained this by putting Venus on an epicycle, that goes around the earth at the same rate as the Sun. (center of epicycle is always in the same direction as the Sun).
- But if that was true, Venus would never be in full phase, only crescent phase would be visible from the Earth.

Phases of Venus

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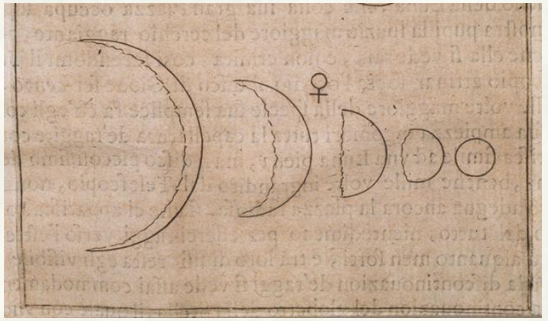
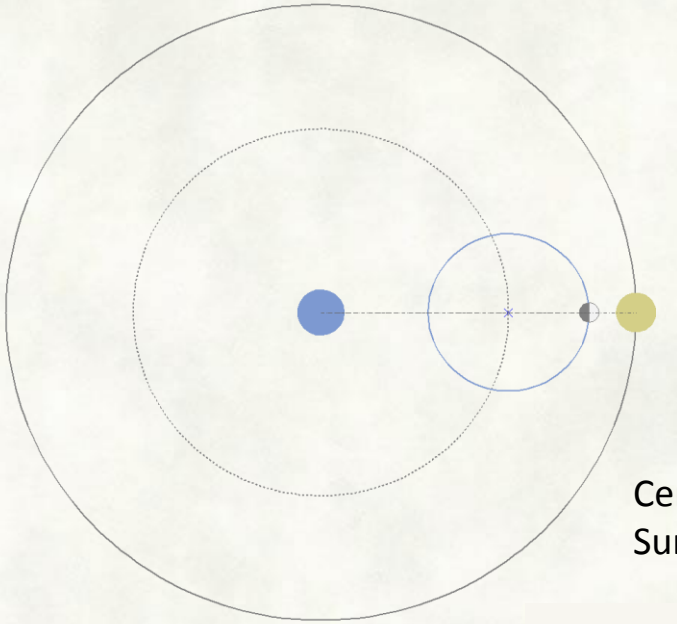
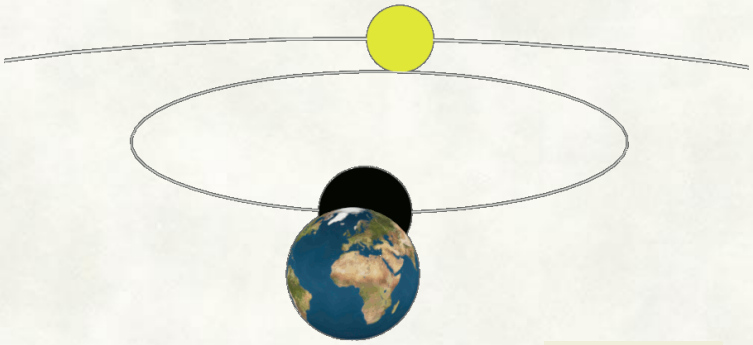


Galileo's drawings of Venus





Center of Venus' epicycle always in the same direction as the Sun, only the crescent phase would be visible

www.phy.olemiss.edu/~perera/animations/venus_phases.html

- Angular separation between Venus and the Sun never exceeds ~48°.
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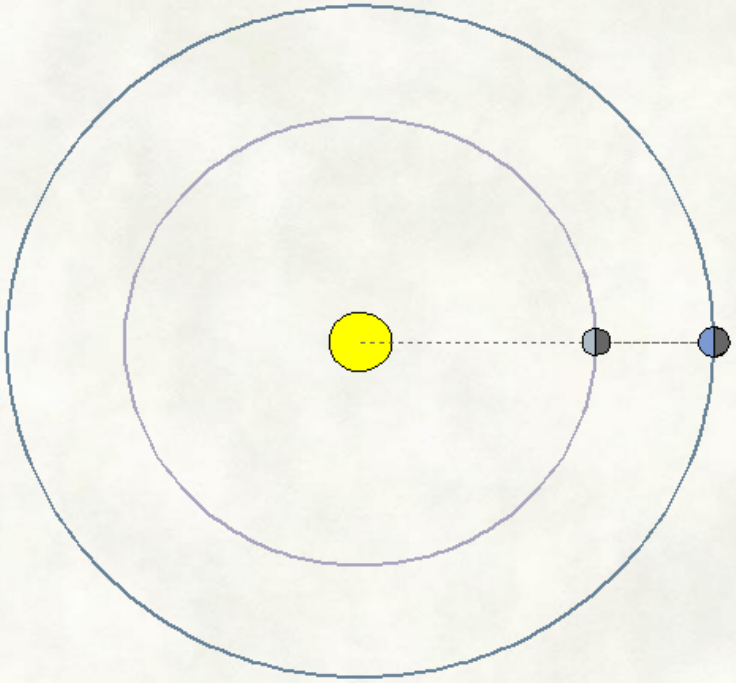
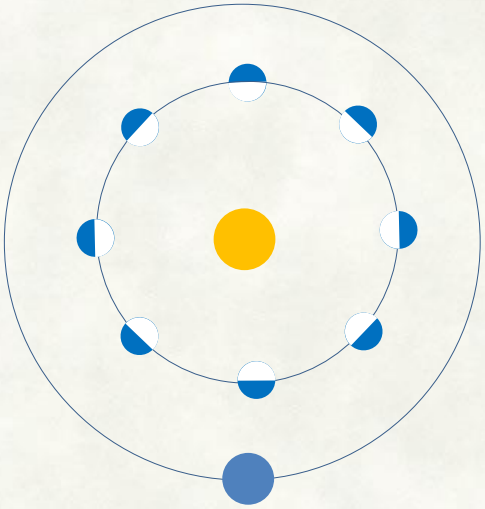
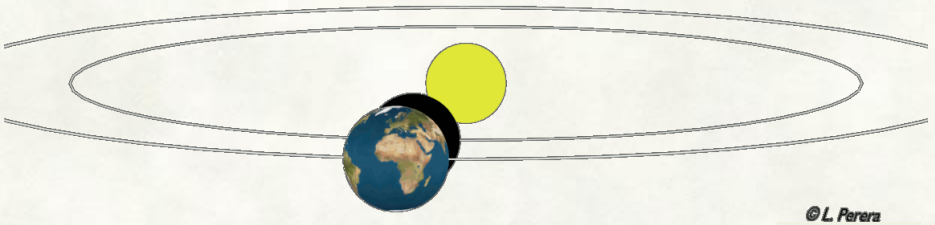
- But if that was true, Venus would never be in full phase, only crescent phase would be visible from Earth.

Phases of Venus







www.phy.olemiss.edu/~perera/animations/venus_phases.html

According to Copernican system all phases are possible

- Copernicus' heliocentric system allowed all phases of Venus visible from Earth.
- **Galileo's observation of phase cycle of Venus thus ruled out the Ptolemaic geocentric system.**

Phases of Venus:

http://mpb.pbslearningmedia.org/resource/ess05.sci.ess.eiu.galileosys/galileo-sun-centered-system/

- The Church that time, which embraced the geocentric view and Aristotelian doctrine, viewed the Copernican idea only as a hypothesis.
  - A mathematical device to calculate positions of planets, not as the real picture and a threat to the views of the church.
- But Galileo was gathering more and more evidence in favor of the Copernican view through his telescopic observations.

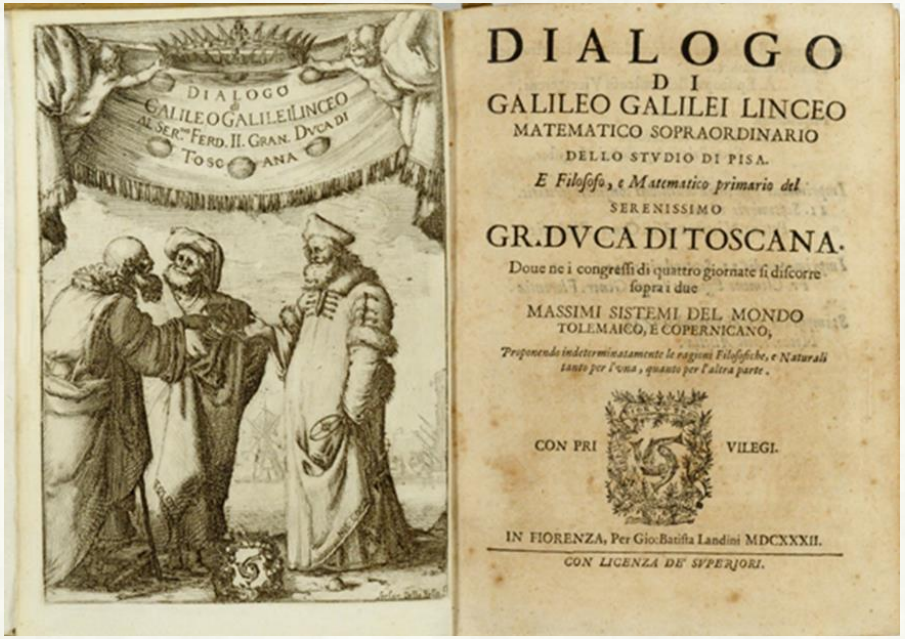
- But Galileo was gathering more and more evidence in favor of the Copernican view through his telescopic observations:
  - Craters and mountains on the Moon, and sunspots refuted the Aristotelian view of unchanging perfect nature of the heavens.
  - Phases of Venus could not be explained in terms of the Ptolemaic/Aristotelian system.
  - Moons of Jupiter showed that planetary bodies could move around objects other than the Earth.
  - Rotation of the Sun showed planetary objects could rotate as required in the Copernican model.
  - Resolution of the Milky way to stars proved that stars were at a greater distance than earlier thought thus ruling out the parallax argument.

- Still many rejected the heliocentric theory, and refused to believe what was seen though telescopes were real. They considered them as just artifacts due to optical defects in his telescope, some even refused to looked through his telescope.
- Frustrated by this, Galileo began openly expressing his ideas in supportive of the Copernican system.

Galileo was being questioned by the Church authorities in 1616. (19th century Painting)

- Alarmed by the growing activism, in 1616 Galileo was summoned to Rome
  - He was cautioned against speaking out on behalf of the Copernican claim and was forbidden to discuss the theory orally or in writing.
  - Copernicus' book "The Revolutions" was banned as the Sun centered system was contrary to the teachings of Scripture, a heresy.

Dialogues



- In 1623 a Galileo's supporter and friend, Cardinal Maffeo Barberini was elected Pope Urban VIII. He generally held a favorable view on the art and science.
- Soon Galileo met with Pope Urban III, during which they discussed the Copernican theory.
- Pope gave permission to Galileo to write about the Copernican theory as long as:
  - he gives a balanced view for and against the heliocentrism.
  - treats Copernican theory only as a mathematical hypothesis.
- Galileo completed the book '*Dialogues"* in 1629. It was published in Florence in 1632. All 1000 copies were sold out within months.

Dialogues

- It was a witty and brilliant work. The book was presented as a series of Dialogues over a span of four days among two philosophers and a layman- Salviati, Simplicio and Sagredo :
  - Salviati: An intellectual, with keen insights who seems to speak for Galileo and argues for the Copernican theory.
  - Sagredo: An intelligent layman who is seeking truth. Initially impartial, gradually comes to accept Salviati's arguments.
  - Simplicio: A follower of Aristotelian ideas, presents arguments against the Copernican theory. Speaks for Galileo's opponents, who puts up ineffectual, simplistic arguments for Salviati to knock down, often contradicting himself.
    - A nice summary is at: web.calstatela.edu/faculty/kaniol/a360/galileo_dialogue.htm

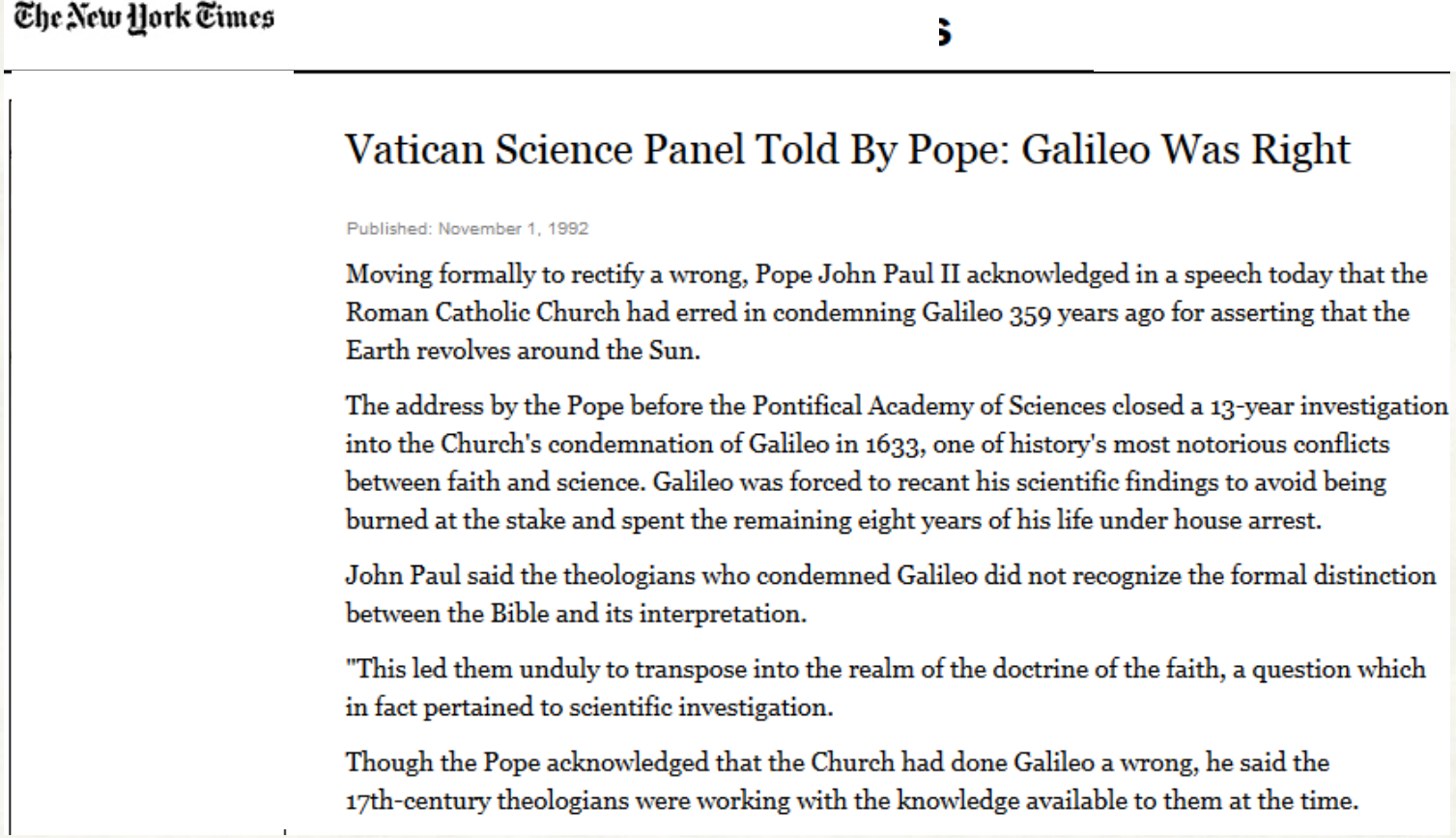
Dialogues

Galileo facing the Roman inquisition, (a 19th-century painting)

- In spite of scrutiny by the Church officials, book was biased and strongly supported Copernican ideas.
- Shortly afterwards the sale of the book was banned, Galileo was summoned by the Roman Inquisition.

- After a two week trial he was condemned.
  - Galileo agreed to plead guilty to a lesser charge in exchange for a lenient sentence.
  - He had to confess that the Copernican case was made too strongly in his book *Dialogue* and agreed to modify his opinions in his next work, and he believed and always will believe that what church recognizes and teaches was true.
- Galileo was sentenced to prison for an indefinite term, later was allowed to return to his house in Florence, where he lived under house arrest until his death in 1642.

Statue of Giordano Bruno, a Dominican priest and a philosopher. Erected at the place he was executed in 1600 CE by the Roman Inquisition for spreading heretic views (among were sun centered system and plurality of worlds, infinite universe)



The New York Times

Vatican Science Panel Told By Pope: Galileo Was Right

Published: November 1, 1992

Moving formally to rectify a wrong, Pope John Paul II acknowledged in a speech today that the Roman Catholic Church had erred in condemning Galileo 359 years ago for asserting that the Earth revolves around the Sun.

The address by the Pope before the Pontifical Academy of Sciences closed a 13-year investigation into the Church's condemnation of Galileo in 1633, one of history's most notorious conflicts between faith and science. Galileo was forced to recant his scientific findings to avoid being burned at the stake and spent the remaining eight years of his life under house arrest.

John Paul said the theologians who condemned Galileo did not recognize the formal distinction between the Bible and its interpretation.

"This led them unduly to transpose into the realm of the doctrine of the faith, a question which in fact pertained to scientific investigation.

Though the Pope acknowledged that the Church had done Galileo a wrong, he said the 17th-century theologians were working with the knowledge available to them at the time.

- Papal Inquisition was abolished in 1822.
- In 1835 Galileo's book *Dialogue* was taken off the Vatican's list of banned books. *(*later published as *Dialogue Concerning the Two Chief World Systems)*
- Heliocentrism gradually gained acceptance:
  - But still there were many accepted geocentric theory on religious grounds.
  - In the US both Yale and Harvard had taught the geocentric theory until early eighteenth century.
- In 1992 Vatican formally admitted that Galileo's views on the solar system were correct.

MR. RUGGLES AT NEW HAVEN.

On the 27th of July a semi-centennial address was delivered before the alumni of Yale College, by Samuel B. Ruggles, LL.D., and it has been published by D. Appleton & Co. in a neat pamphlet. We find it filled with interesting statements, some of which we extract:—

THE PTOLEMAIC THEORY ONCE TAUGHT AT YALE.

The fact is strange and curious, that even here in emancipated America, the Ptolemaic or geocentric theory, enforced by Papal assumption on the dark ages, was actually taught for several years, within these very walls. It was not until 1718, that the light of the heliocentric system was first let in, through the efforts of the clear-sighted Doctor Samuel Johnson, then a tutor in the College, and who in due season would have become its President, but for his ill-timed doubts of the validity of Presbyterian ordination. A copy of the "Principia," sent out from Europe, had reached the little college library, upon which the youthful Johnson entered with great avidity, after studying the higher mathematics for the purpose. "Till then," says his biographer, "the Ptolemaic system of the world was as strongly believed as the Holy Scriptures; but Johnson was soon able to overthrow it, and establish on its ruins the doctrine of Copernicus." The heliocentric system at once illuminated the College, and here it will continue to pour forth its magnificent light until the College, and the earth, and the sun, and the stars, shall be no more. Poor old Copernicus, who in his dying hours had sought, by a letter of dedication, to disarm the opposition of the Pope, was lying in his grave on the Baltic, carefully covered by the Papal excommunication, which was not formally annulled by the Vatican until the year 1821, seven years after our class left college. Since that time, the Church of Rome, claiming to be the chosen keeper and interpreter of Holy Writ, together with the residue of the Christian world, have permitted the students of the Pentateuch to read the Genesis by the light of Copernicus and Newton.

THE FIRST NOTIONS OF GEOLOGY.

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but still

NEWSFEED SCIENCE

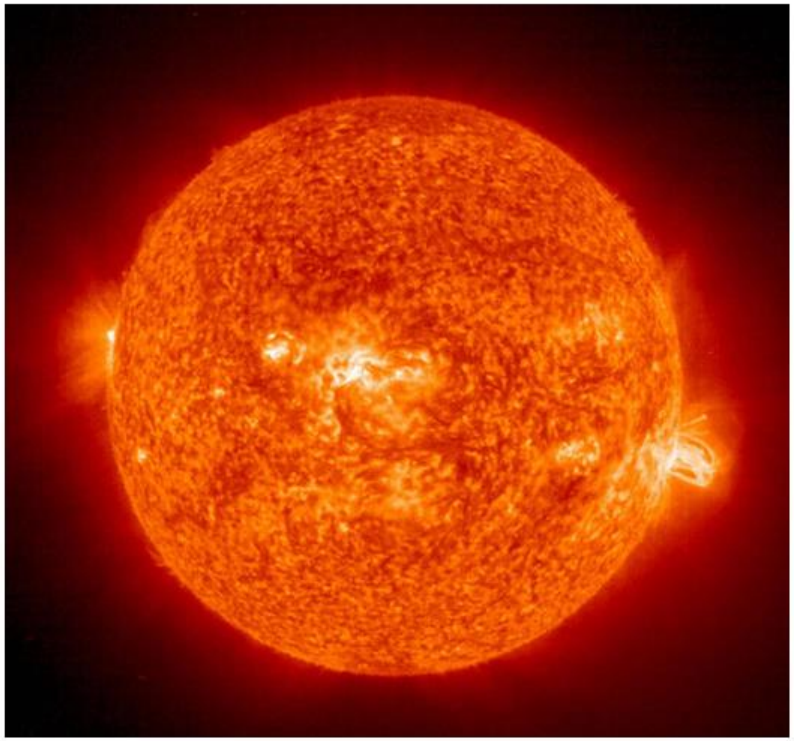
1 in 4 Americans Apparently Unaware the Earth Orbits the Sun

Samantha Grossman @sam_grossman | Feb. 16, 2014

A National Science Foundation study involving 2,200 participants find that about 25 percent of Americans got this question wrong: 'Does the Earth go around the sun, or does the sun go around the Earth?'

Does the Earth go around the sun, or does the sun go around the Earth?

When asked that question, 1 in 4 Americans surveyed answered incorrectly. Yes, 1 in 4. In other words, a quarter of Americans do not understand one of the most fundamental principles of basic science. So that's where we are as a society right now.


Getty Images

Galileo on the laws of Motion

Galileo made extensive contributions to the understanding of the laws governing the motion of objects.

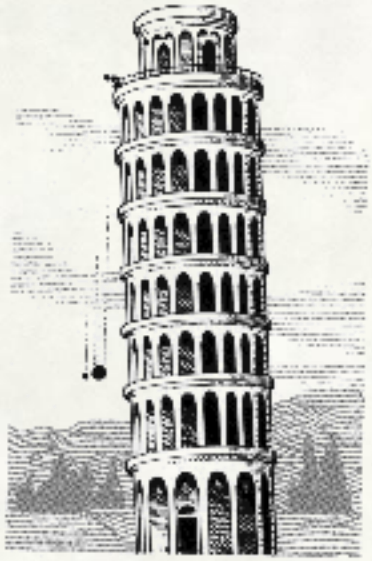
- He published those finding in '*Dialogues Concerning Two New Sciences', the book* he wrote during the final years of his life while under house arrest.


DISCORSI
E
DIMOSTRAZIONI
MATEMATICHE,
intorno à due nuoue ſcienze
Attenenti alla
MECANICA & i MOVIMENTI LOCALI;
del Signor
GALILEO GALILEI LINCEO,
Filoſofo e Matematico primario del Sereniſſimo
Grand Duca di Toſcana.
Con vna Appendice del centro di grauità d'alcuni Solidi.
NON SOLIS
IN LEIDA,
Appreſſo gli Elſevirii. M. D. C. XXXVIII.

Prevailing ideas of the time on motion were mainly Aristotle's ideas:

- According to Aristotle, all bodies *by their very nature*, have a natural way of moving toward their natural place with a speed decided by its nature.
  - Earthly objects fall because they move towards the center of the Earth (universe), their natural place.
  - Air and fire move (rise) linearly upward.

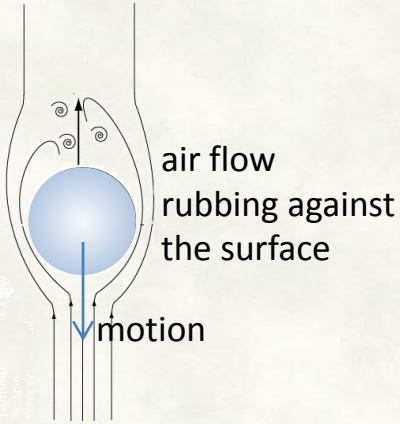
Galileo on falling objects

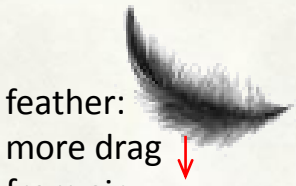


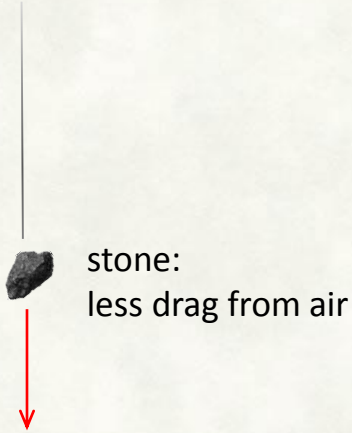
- This implied if an object is dropped it would instantly acquire a speed determined by its weight and nature and falls at a constant speed.
  - **Heavier objects fall faster, lighter objects slower,** according to Aristotelian view.

- Galileo showed that it was wrong. He showed that all objects falls at the same rate regardless of the weight.
  - Contrary to the popular belief, it is unlikely that he showed this by dropping two different sized objects off the tower of Pisa. (Not mentioned in his writings).
- Galileo did a number of experiments to study the nature of motion of falling bodies.
- **He came to the conclusion that a freely falling body has a uniform accelerated motion regardless of its nature.**
  - Speed of a falling object increases at a uniform rate, regardless of the weight of the object.

Galileo on falling objects- Friction







- In real life this is not exactly true (a stone falls faster than a feather).

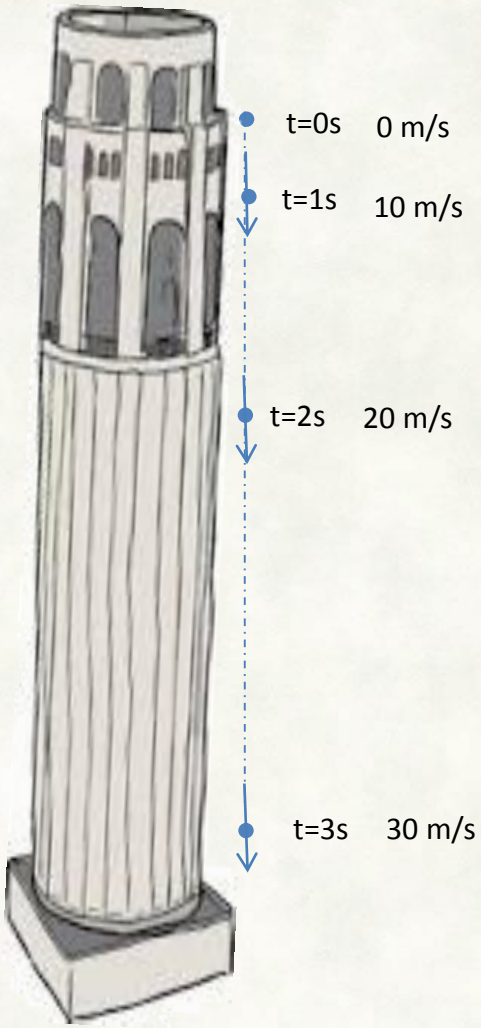
- Galileo correctly identified that such differences were due to (air) friction.
  - When an object moves it rubs against a surface, and rub against air. The force due to rubbing action acts against the motion is called the **friction.**
- This is what makes the difference in motion for different types of objects.
  - When a stone and a feather are dropped, feather falls slower because due to its shape it is subjected to more drag(friction) from air.
  - If a stone and a feather are dropped in a vacuum, they would fall at the same rate.

It was done on the Moon by Apollo 15 astronauts:

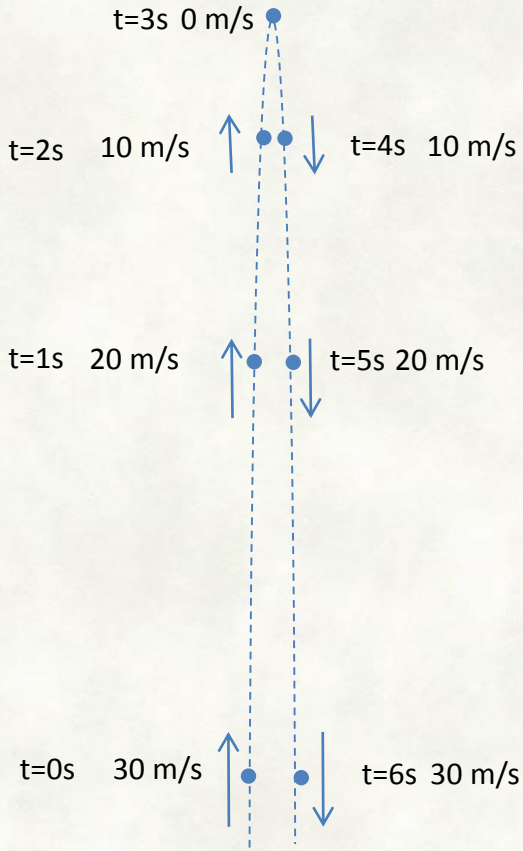
http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo_15_feather_drop.html

And in vacuum chambers: https://www.youtube.com/watch?v=E43-CfukEgs

Galileo on falling objects



speed of an object falling freely



Speed of an object thrown vertically upward

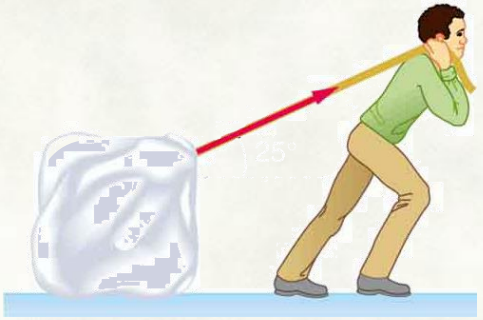
- Speed of a freely falling object increases at a rate 10 m/s each second (9.8 m/s more accurately).
  - ie. an object accelerates 9.8 m/s per second when they fall freely (without air resistance)

Galileo on Motion

- In addition to vertical motions(falls and rises), Aristotle described another type of motion, *Forced Motions*.
  - Produced by external forces (pushes and pulls) on objects.
  - In such motions objects only moved as long as a force is applied according to Aristole.

A rock won't move without a cause

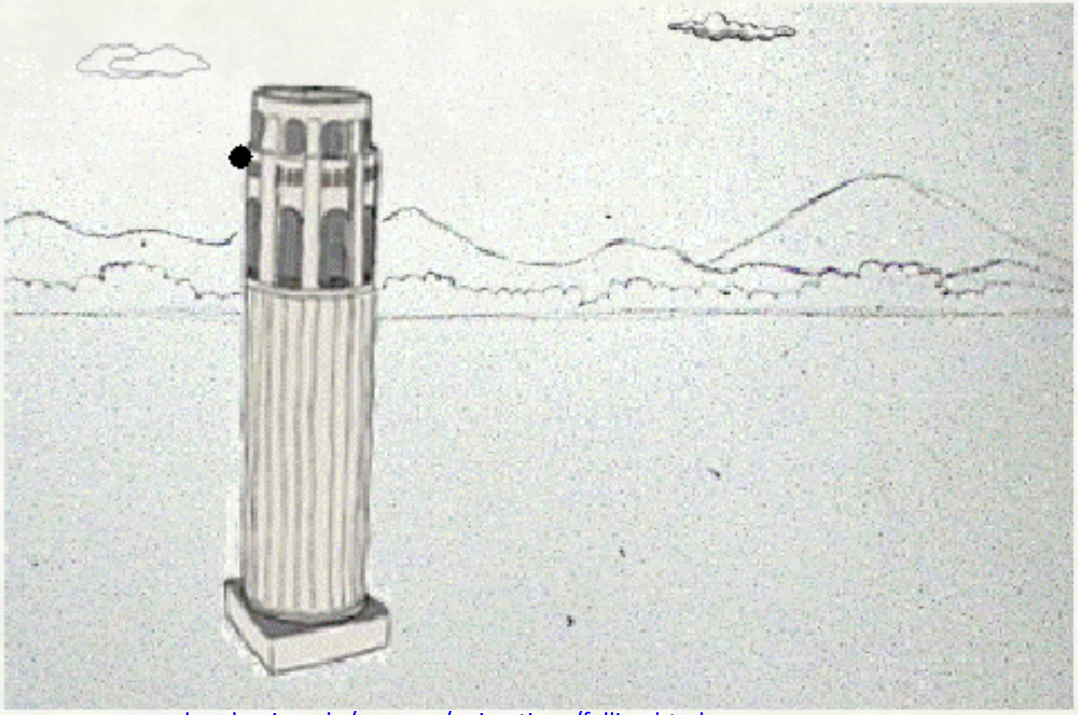
has to be pushed



or pulled

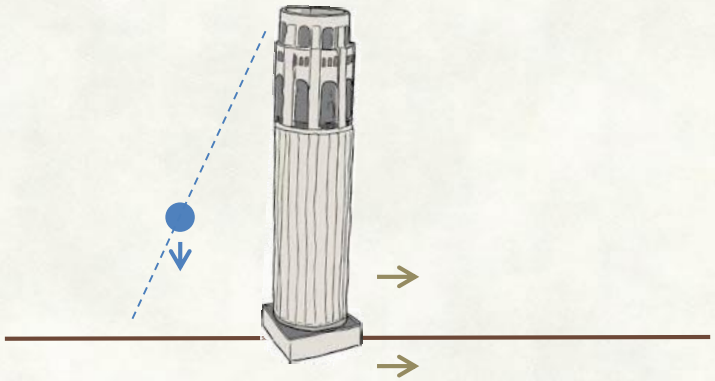
According to Aristotle a force is needed to keep objects moving

- It was on this ground that Aristotelians rejected the idea that the Earth was rotating or moving around the Sun.
- Again Galileo pointed out that it was wrong. Moving objects stop because of friction.
  - according to Galileo, if there is no friction a moving object would keep moving at the same speed.
  - no other force is needed to keep it moving as Aristotle envisioned.



www.phy.olemiss.edu/~perera/animations/falling.html

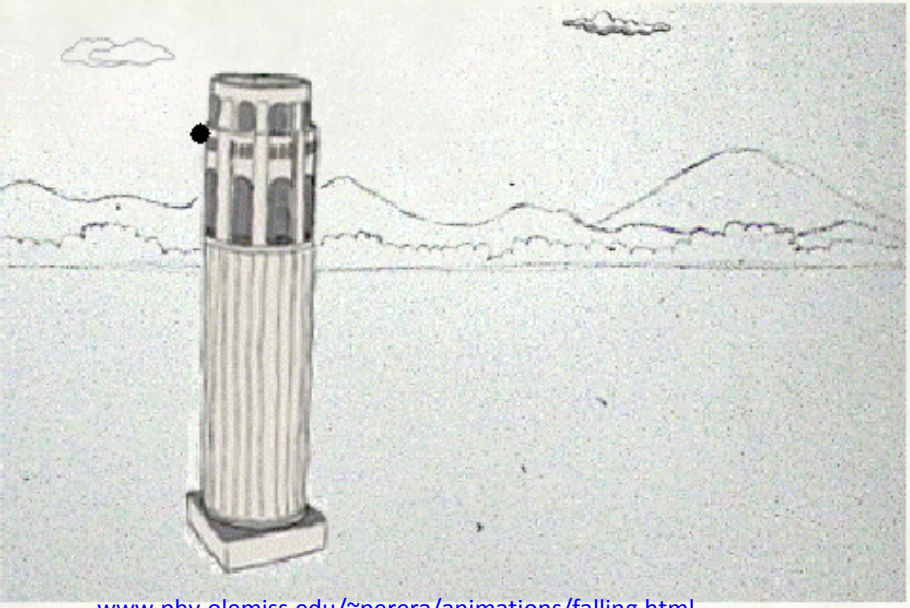
Falling Objects on the Moving Earth according to Aristotle



Appearance of a ball dropoped from a tower According to Aristotle

Suppose a ball is dropped from a tall tower (on the moving Earth)

- <u>According to Aristotle:</u>
  - Before the ball is dropped everything was moving with the Earth.
  - When the ball is dropped, its horizontal movement ceases (no horizontal force)
  - Ball moves vertically down while the tower moves with the Earth.
  - So if the earth is moving the ball has to strike the ground away from the tower.



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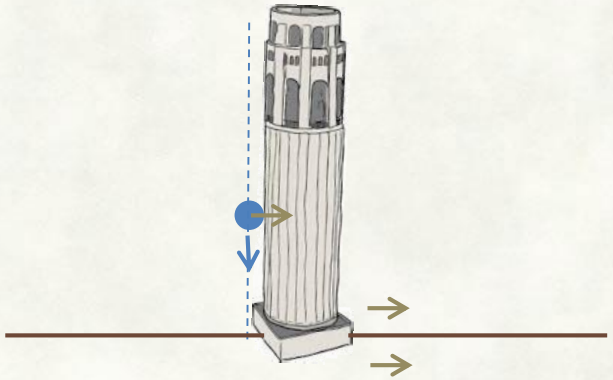
Falling Objects on the Moving Earth According to Galileo



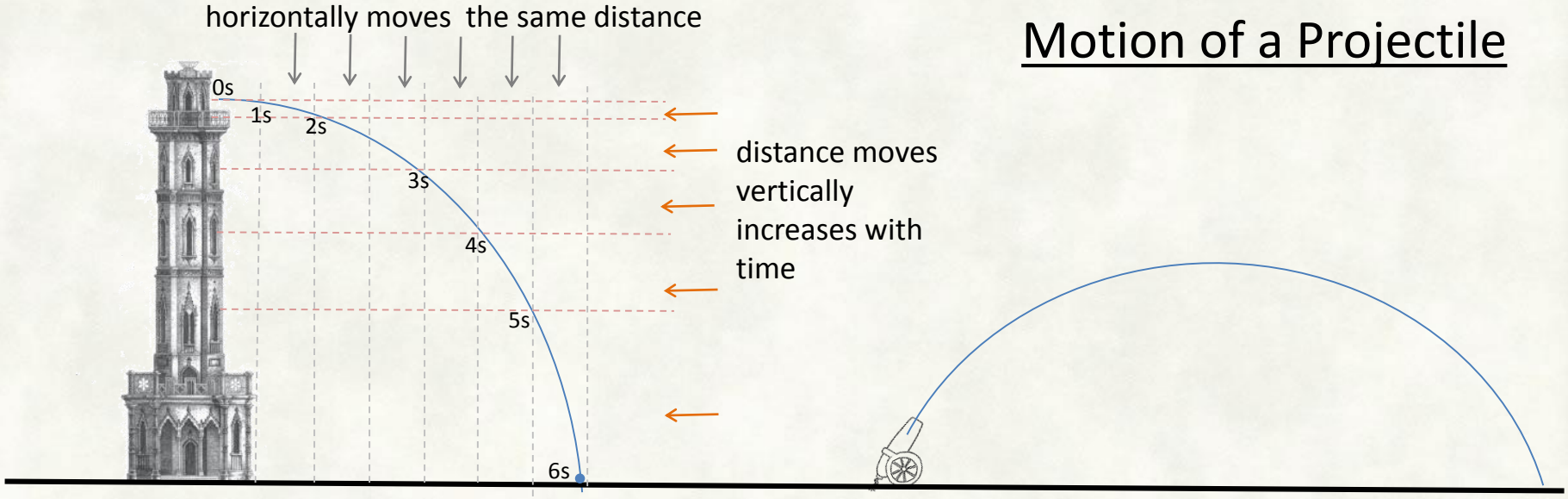
Appearance of a ball dropped from a tower According to Galileo

Suppose a ball is dropped from a tall tower (on the moving Earth)

- <u>According to Galileo:</u>
  - Both ball and the tower are moving horizontally with the same speed.
  - When the ball is dropped, while it is moving downward, it continues to move horizontally with the same speed with the Earth as before.
    - (since there is no force acting horizontally to stop it)
  - Ball falls vertically and strike ground right bellow where it was dropped.
  - An observer in the tower does not see any horizontal movement of the ball.


NOVA
JULIAN BARBOUR
Theoretical Physicist

Motion of a Projectile



Galileo concluded that the path of a cannon ball was a parabola (ignoring drag from air)

- Suppose a ball is thrown horizontally (ignore air friction for now):
  - According to Galileo, vertically it has a uniformly accelerated motion so the vertical speed and the distance it moves vertically in a given time interval increases with time.
  - since there is no force acting horizontally on the ball, it will move at a uniform speed horizontally, moving a same distance in a given time interval.
  - Combining those two motions Galileo came to the conclusion that path of a projectile would be a parabolic curve.

Review Questions

- Who invented the telescope?
- What did Galileo's observations of the Moon reveal?
- What was the significance of Galileo observing phases of Venus?
- What was the significance of Galileo observing satellites of Jupiter?
- How did Galileo's observations help undermine the prevailing views of the Ptolemaic model of the Universe and Aristotle's physics?
- Why is it not possible to see phases other than a crescent of Venus according to the Ptolemaic model?
- What was the strongest telescopic evidence against the Ptolemaic model?
- How did the Galileo’s observation of the Milky way helped to resolve the failure of astronomers to detect stellar parallax.
- Copernicus’ book “The Revolutions” did not made much controversy when it was published. Why was it banned in 1616, more than 80 years later?
- Why did supporters of the geo-centric system were reluctant to believe that sunspots were real?
- Why is the argument against the motion of the Earth by Aristotle that falling objects would fall at an angle wrong?
- According to Galileo what is the natural state of motion of an object?
- Why does a feather fall slower than a stone on Earth even though according to Galileo they should fall at the same rate.

Review Questions

- Suppose somebody is throwing a baseball vertically upward from a pickup truck moving at a uniform speed. What is the path of the ball
  - As seen from the truck?
  - As seen by somebody on ground?
- In the example of the falling ball from a tower, according to Galileo ball continue moving horizontally after it was released. What about the friction from air? Isn't the horizontal motion of the ball slows down due to drag from air?