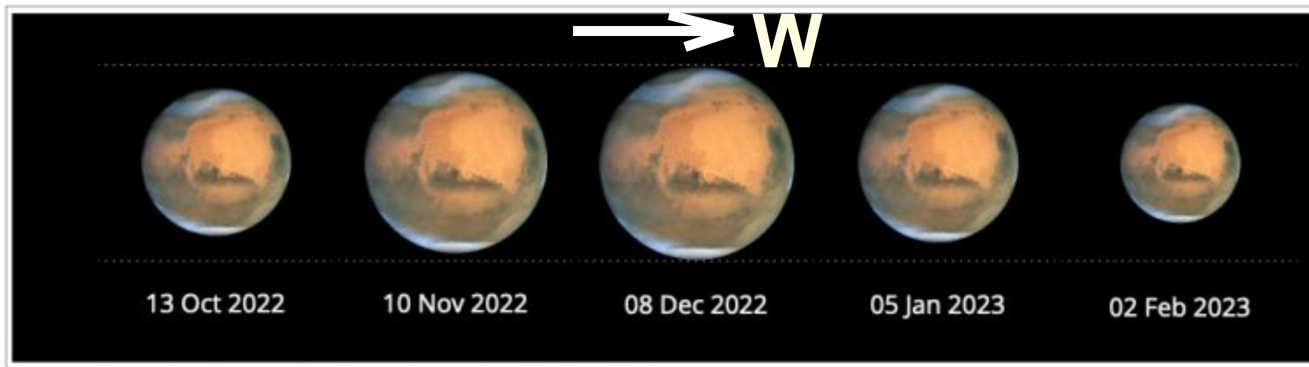
Copernicus and the sky in 2022:

We have discussed in L8 the retrograde loops Mars does in the sky. Geocentric system encountered big problems and was abandoned by Mikołaj Kopernik (Nicolaus Copernicus). Among the reasons were:
(i) Greek theories had planets moving while attached to spheres of aether/quintessentia; but Mars would crash into sun's *crystal sphere*.
(ii) For unexplained reasons, geocentric model requires Mars to always be at *perigeum* (closest approach to Earth) at the time of *opposition* with Sun, i.e. while 180^{o} away from the Sun.
On 17 October, Mars rises at 21:35 in Toronto, earlier a few min. every day, because it moves westward along a loop (retrogradation).
Soon after ASTB03 2022 ends, on 8 Dec. Mars will be closest, brightest, AND will rise at sunset, 16:41 (in Toronto). This happens every 26 mo.

For Kopernik, when Earth overtakes Mars, Sun is *automatically* opposite to Mars, which then rises at sunset.



ASTB03 Lecture 9

16th to 17th centuries AD: Brahe and Kepler

- Observer **Tycho Brahe**
  [pron.: TEE-koh BRA-heh]

- **Johannes Kepler**
  Theorist

Tycho Brahe – astronomer, but also astrologer and alchemist

Danish astronomer born as Tyge Ottesen Brahe, better known as Tycho Brahe (1546-1601), provided 10x more accurate data than anyone before. Born in Knudstrup borg (today: Knutstorps borg).

- Born in a wealthy family of nobles close to king & parliament
- Abducted as an infant by childless uncle & aunt.
- Lived in uncle's castles. Had a tamed moose for a pet. The moose died, having drunk alcohol at a party in Landskrona castle & fallen down a flight of stairs☹.
- A colorful figure with artificial nose of metal, a result of a duel at Rostock University with another student (his 3rd cousin) over astrological math problem.

Brahe observed by naked eye using giant angle-measuring quadrants and compasses. Here, he holds such device:

Tycho Brahe & castle-observatory Uraniborg on the Danish island of Hven (now Ven, Sweden), in Øresund sound.

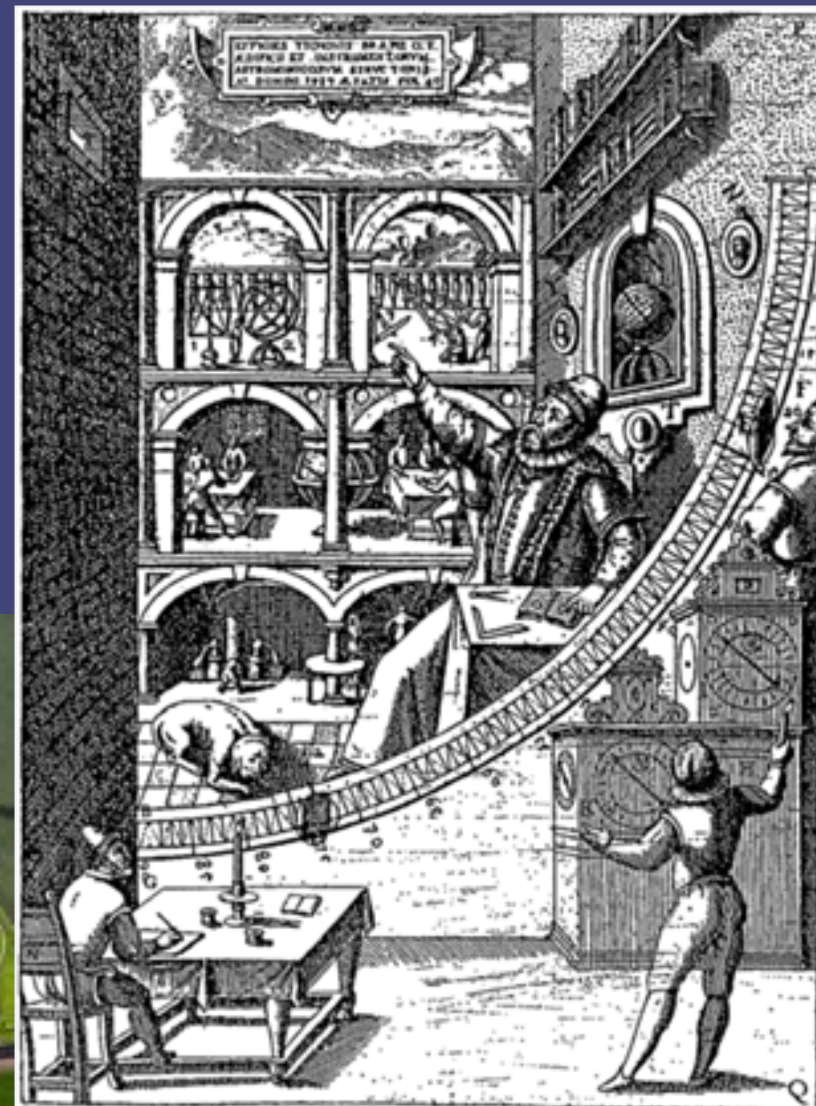
King Leopold II as a royal favor gave Brahe the island of Hven & money to built a castle-observatory Uraniborg.

The island was named after Lady Hvenild, a figure in a lore of Lady Grimmel who killed her own brothers and in retribution was later starved to death in a dungeon. Then in 1288 Viking Erik the Priest-Hater stopped by to burn down 4 castles (manor houses, really) and kill some inhabitants.

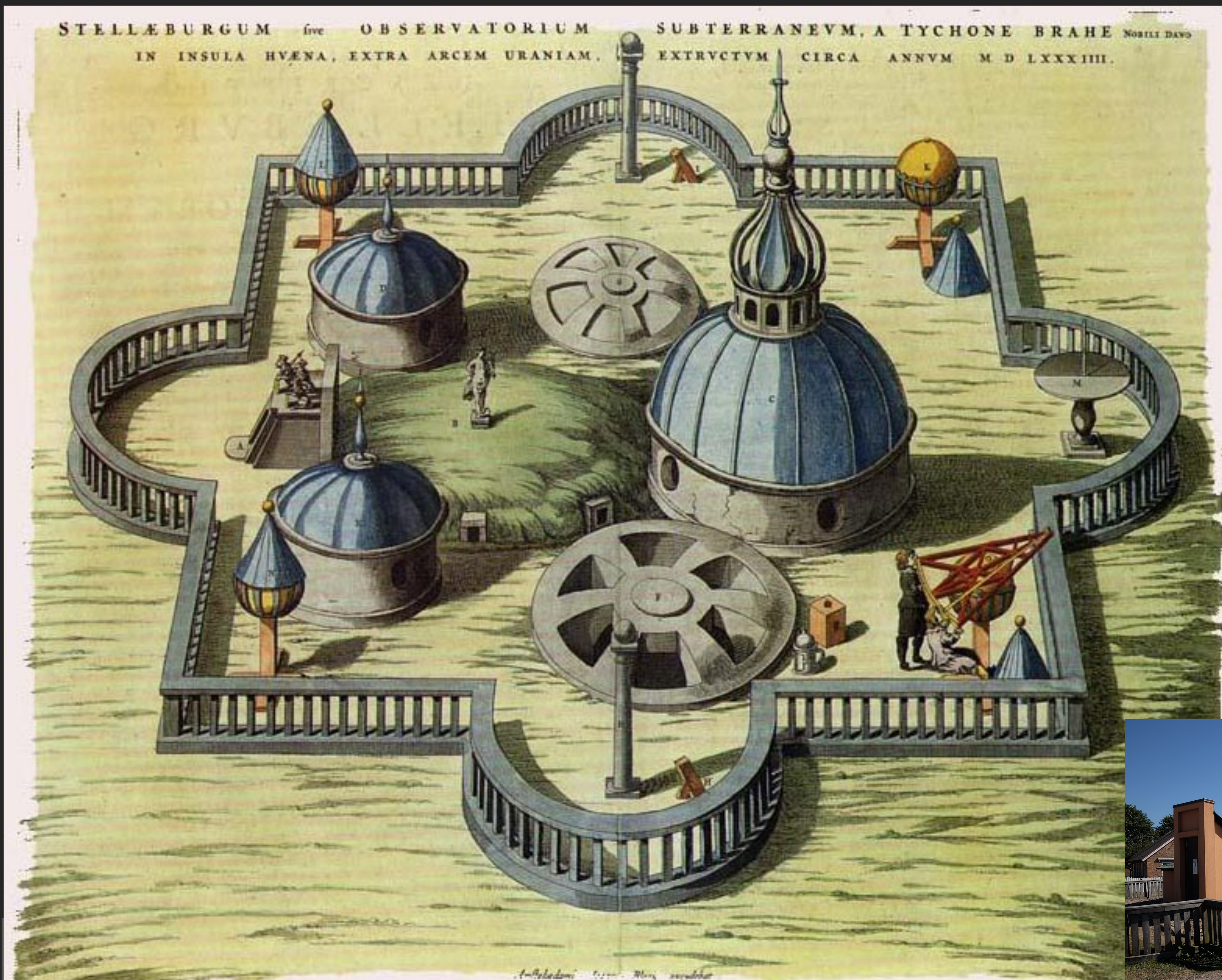
Brahe's treatment of peasants was felt by them as awful. They started leaving the island! But his long-term observations with the huge, precise, naked-eye instruments were exquisite!

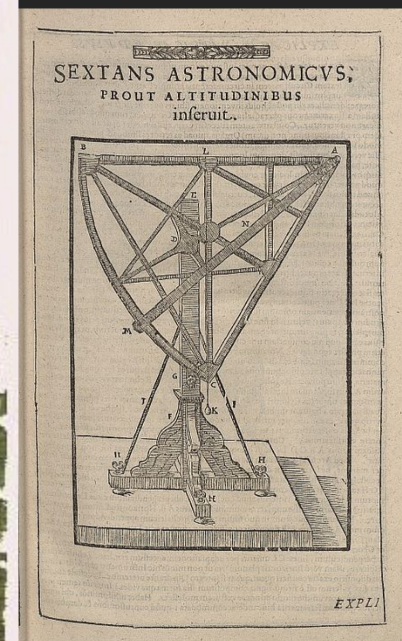
Brahe's observations were long-term. Positional errors reached the physical minimum: resolving limit of the eye (~1' = arcminute)

Uraniborg observatory and alchemy lab on island Hven



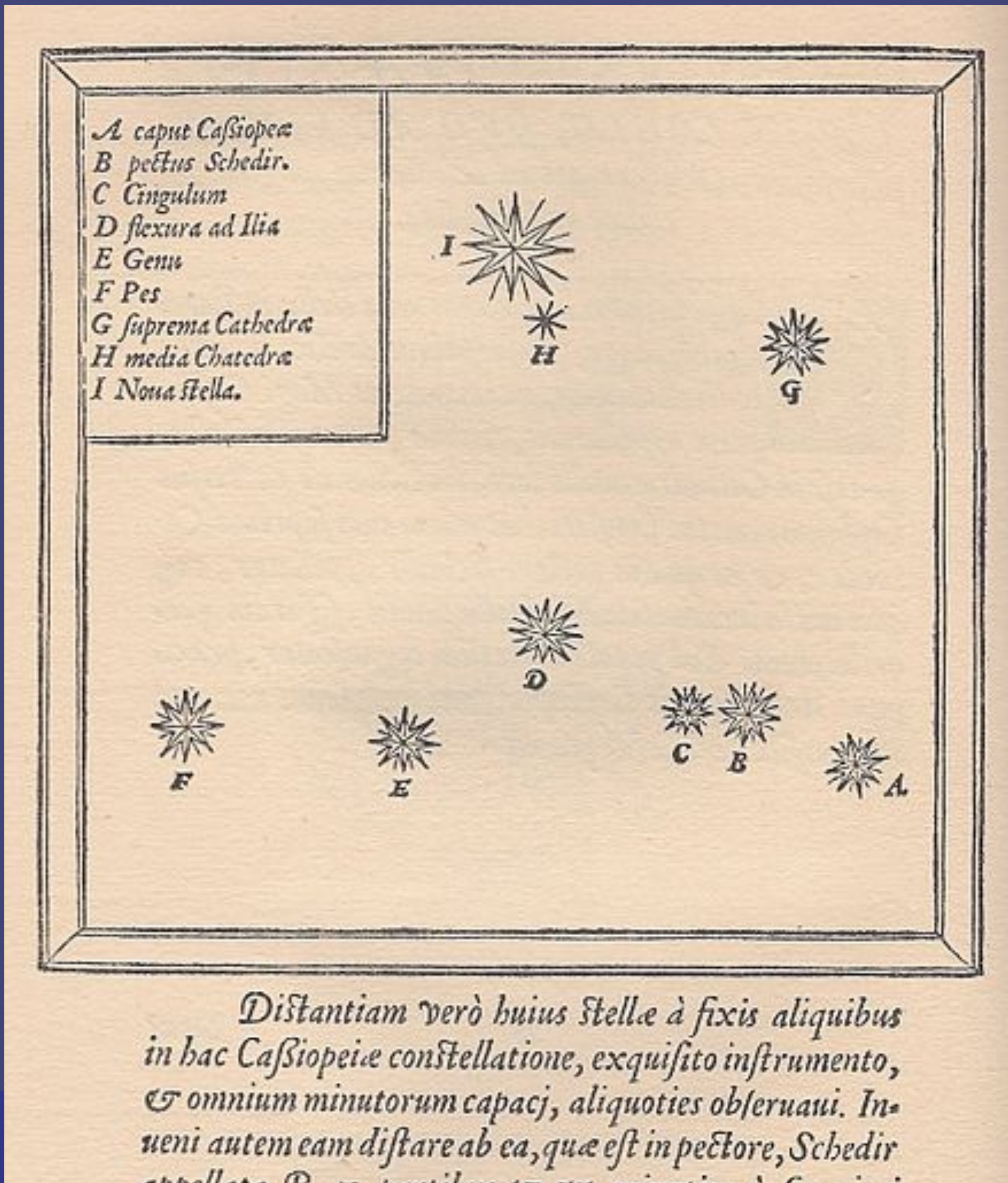
Tycho Brahe's second, subterranean observatory Stjerneborg on Hven. Hand-colored copper plate engraving by Joan Blaeu from 1595.





Quelle: Deutsche Fotothek

450 years ago, on 11 November 1572, Tycho Brahe discovered something extremely unusual



A new star (I) that faded away to invisibility only after more than a month

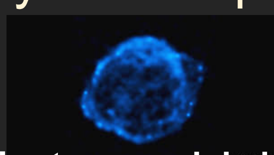
Peak brightness larger than Venus, the brightest planet.

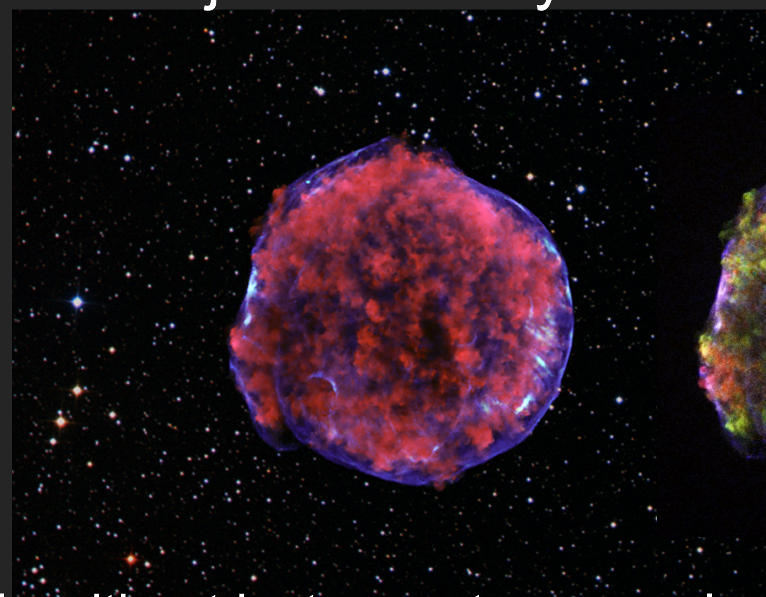
Tycho saw no parallax and concluded that the object is much further than the Moon.

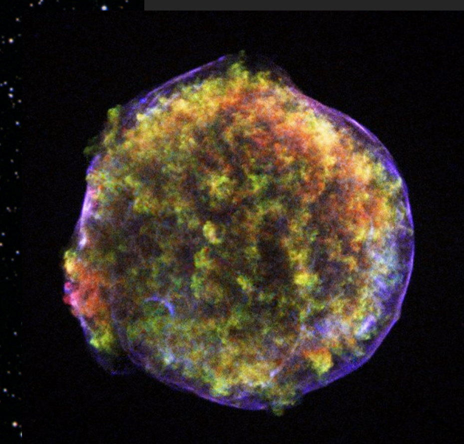
Tycho Brahe & SN 1572

- In 1573 Tycho described the new star in a little book we now call "De Stella Nova" (*"De nova a nullis aevi memoria prius visa stella"*).
- Stella Nova (a new star), which was in fact what we now call supernova, showed that Aristotle's unchanging heavens are changing after all. This was a major discovery.

Two views in optical and X-ray electromagnetic waves of the supernova type I remnant, now called SN 1572 = B Cas = B Cassiopeiae = 3C 10 or simply "Tycho's supernova remnant".

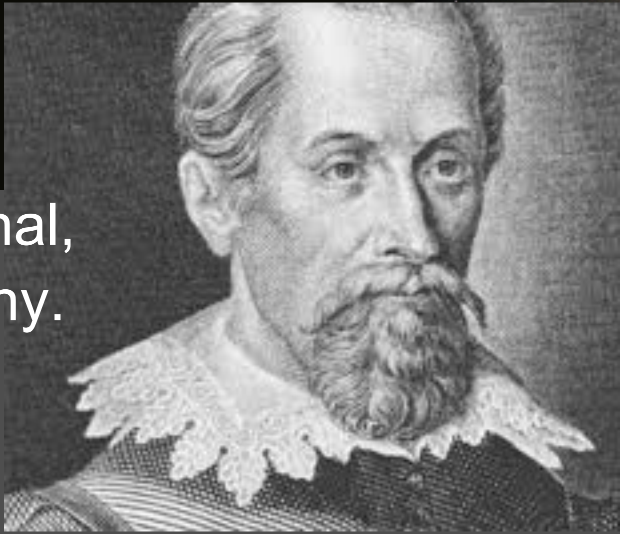






Such "new" stars which are visible without instruments are explosions of the so-called white dwarfs & happen several times per millenium in the Milky Way (the previous was in 1006, the next already in 1604 but then none until now).

Johannes Kepler (1571-1630)



- The oldest of six children in a poor, disfunctional, once noble family from Weil der Stadt, Germany.
- His father was an uneducated, cruel man, became mercenary soldier, and in the end disappeared somewhere in the Netherlands
- Kepler's mother Katharina was a healer & herbalist, reportedly a rather quarrelsome, nasty person. As an old women she was accused of witchcraft by the townspeople (causing pain without touching, casting evil eye, boiling magic potions, causing women to miscarry & animals to die mysteriously, etc.)
- Johannes defended her (successfully) in a trial that dragged on for years.

Johannes Kepler (1571-1630)

Mother led a 6-yr old Johann to a hill, to observe the Great Comet of 1577 (a long-period comet; Brahe used its simultaneous observations in Hven & Prague to prove that its distance from Earth was >> distance to the Moon).

As a student of Tübingen University in Germany, Kepler became a believer in the Copernican hypothesis.

This was because his astronomy professor Michael Mästlin was an advocate of Copernicus, and a thorough and knowledgeable mathematician, one of those who left very pertinent comments on their copies of *De Revolutionibus.*

Johannes Kepler – reading the mind of God

Kepler's eyesight was poor. He never attempted to be a leading observer. He decided to be a theorist and to decipher God's design for the world through the study of numerology, astrology, astronomy, physics and metaphysics, even the occult (magic). Whatever it takes!

- Kepler was a Pythagorean in his philosophy of nature, and Protestant Christian as regards religion, but did not care much about religion or inter-denominational wars.

After studies in German university of Tübingen, Kepler had to accept a high-school teaching job in Graz, (Styria, Austria) that allowed him to continue his studies in math and astronomy.

This job was disappointing for Kepler, who at that time still aspired to become a Lutheran theologian and priest.

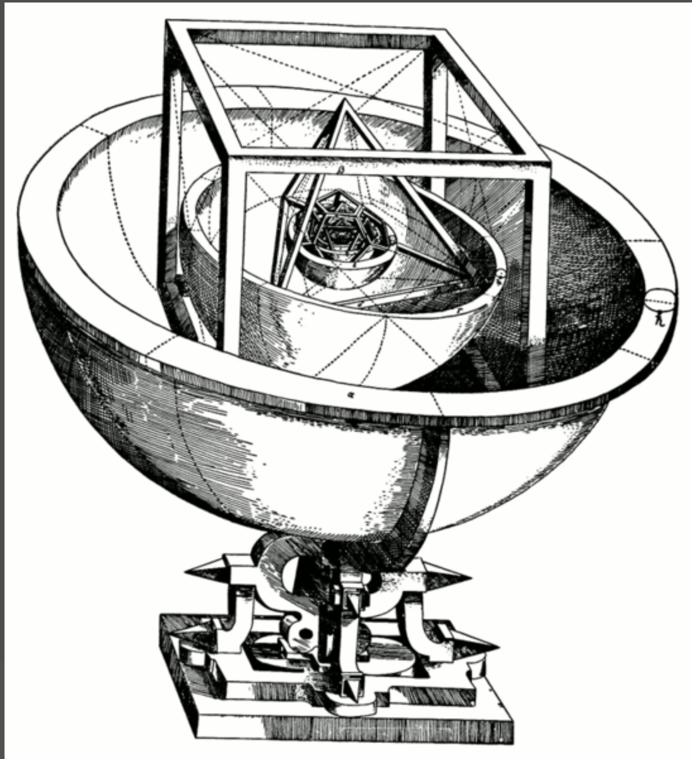
But it left time for astronomy!

Kepler's polyhedral universe & other early ideas

- His first and probably the greatest personal "great moment" was when he discovered a law of planetary distances. Kepler used Plato's ideal figures – 5 regular polyhedra (4,6,10,12,20-sideded) for 5 known planets. They were inscribed one into another, their sizes were supposed to express the sizes of planetary orbits. (We now know it's all incorrect!)
- He believed that Earth naturally makes 360 rotations every year not 365.25, and that the 5.25 rotations are due to sunlight striking Earth (wrong!)

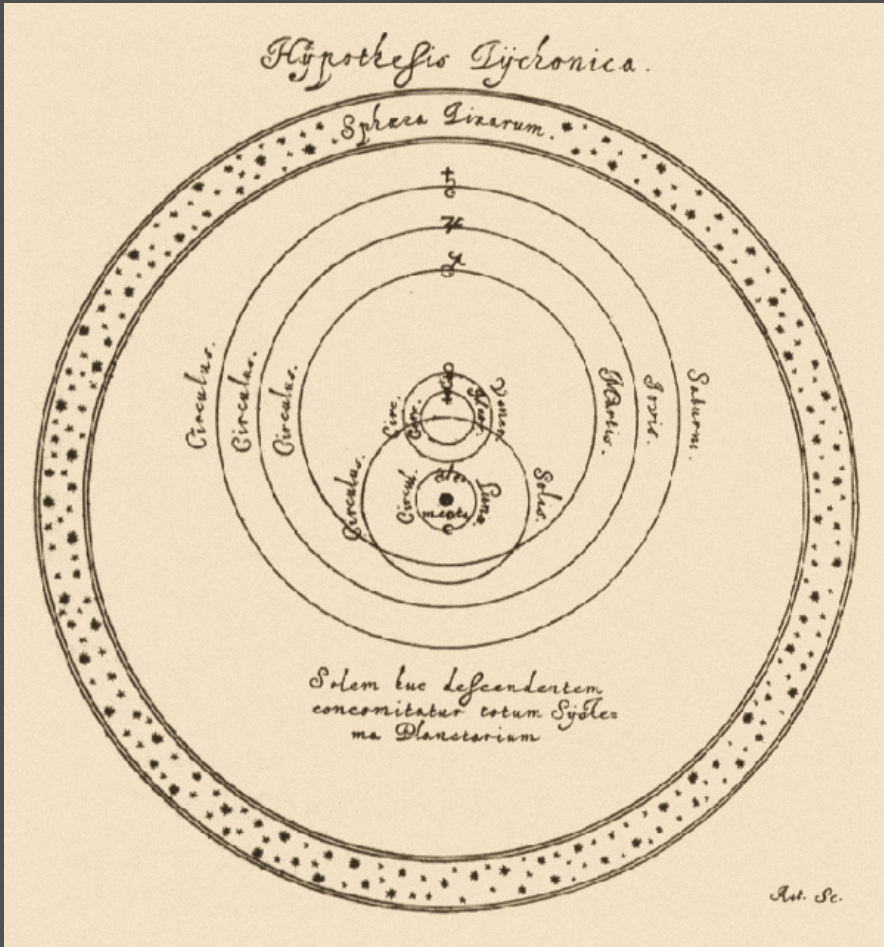
On the other hand,

- Kepler published a book about optics introducing 'light rays' method, and symmetry of snowflakes. He was the 1st crystallographer.



The mixed system of Tycho Brahe needed a theoretical proof. Kepler gets a job offer.

Tycho believed in a mixed *geoheliocentric* scheme (previously discussed by Heraclitus Pontius in 4th c. BC, and Johannes Scotus Eriugena in the Middle Ages): a system with Earth in the center & Sun orbiting it, but planets orbiting around the Sun, not Earth (incorrect but explaining why Earth seemingly rests)



To verify the scheme by detailed calculations, Brahe in 1599 invited Johannes Kepler as an assistant to move from the Graz to Prague, capital of Czechia (Benatky nad Jizerou castle).

Kepler moves from Graz to Prague

- The offer from Brahe was very timely!
- Life was intellectually a bit boring, but also unsettled for Kepler in Graz, because of the persecution of Protestants in that mostly Catholic region (although Kepler, a Lutheran, tried his whole life not to get involved in religion or politics, and even naively thought that his astronomical discoveries will help the warring parties to reconcile)
- So when Tycho Brahe invited him to Prague, Kepler accepted eagerly, ready to work with the famous astronomer as a theorist.
- Besides, right then times became very difficult at Graz for all Protestants (mainly Lutherans) so Kepler actually *had to leave* or convert to Catholicism. He tried to use the excuse that he was originally christened as a Catholic to no avail. Counterreformation was in full swing in the Austrian province of Styria. He would risk the family's well-being or worse by staying there.
- Religious wars in Kepler's lifetime killed a noticeable percentage (up to 30%) of population of some German-language regions.

Movie time

You may want to take a look at these videos about Kepler – not a required material, but very interesting...

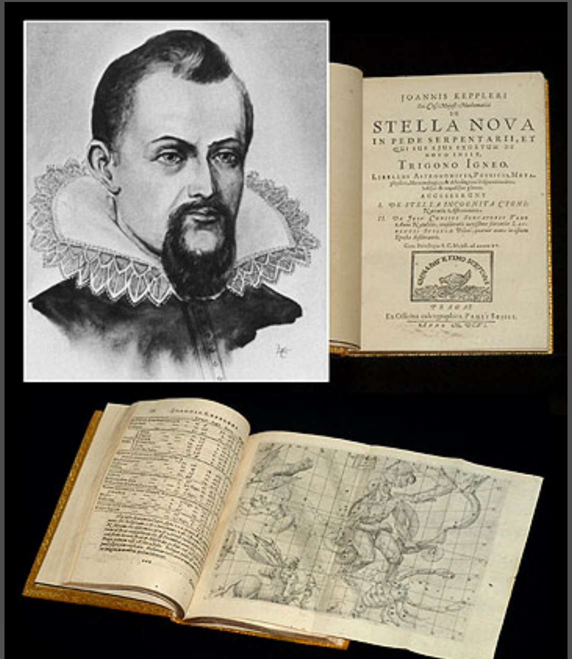
https://www.youtube.com/watch?v=XFqM0IreJYw

Carl Sagan's in his old TV series "Cosmos" discusses Kepler's laws

https://www.youtube.com/watch?v=--Tqp9nwCNk

A recent & almost perfect biography of Kepler.

To find out more you may read a detailed, well researched book *"Tycho and Kepler – the unlikely partnership that forever changed our understanding of the heavens"* by Kitty Ferguson.



Johannis Kepler & *De Stella Nova* (published 1604)

Did Kepler steal his data & murder Tycho Brahe??

- Tycho several times declined Kepler's request for a complete access to his data. He divided the analysis between his assistants, some of whom where his relatives. Johannes negotiated, insulted Brahe & in the end left Benatky and Tycho.

Benatky castle

- But Brahe needed Kepler. He showed a lot of patience in trying to arrange a work contract for his assistant & convince him to come back, with or without family.
- Tycho's sudden death in 1601, supposedly from bladder infection caused by sitting at duke's dining table for too long, left Kepler in a position to finally use Tycho's extensive records of observations to analyze the motions of all the planets.

Did Kepler steal his data & murder Tycho Brahe??

Kepler came into possession of the data illegally. The rightful owners, family of Brahe, sued him & won in court.

"I confess that when Tycho died, I quickly took advantage of the absence, or lack of circumspection, of the heirs, by taking the observations under my care, or perhaps usurping them."

J. Kepler

Tycho was protective of data and his priority rights (details of his system having been stolen by a German acquaintance named Baer, or Ursus in Latin) but, in fact, remained patient and fair with Johannes. Just before he died, Tycho asked king Rudolph II to make Kepler the Imperial Mathematician/Astrologer, which took place with some negotiations and delay.

Johannes Kepler – thieve & murderer?!

- Poisonous mercury found in the hair of Tycho Brahe added some mistery of his death… some suspected a foul play by Kepler. The amount was however too small to poison a person, as a recent exhumation showed. (His body was exhumed twice, in 1901 and in 2010.)

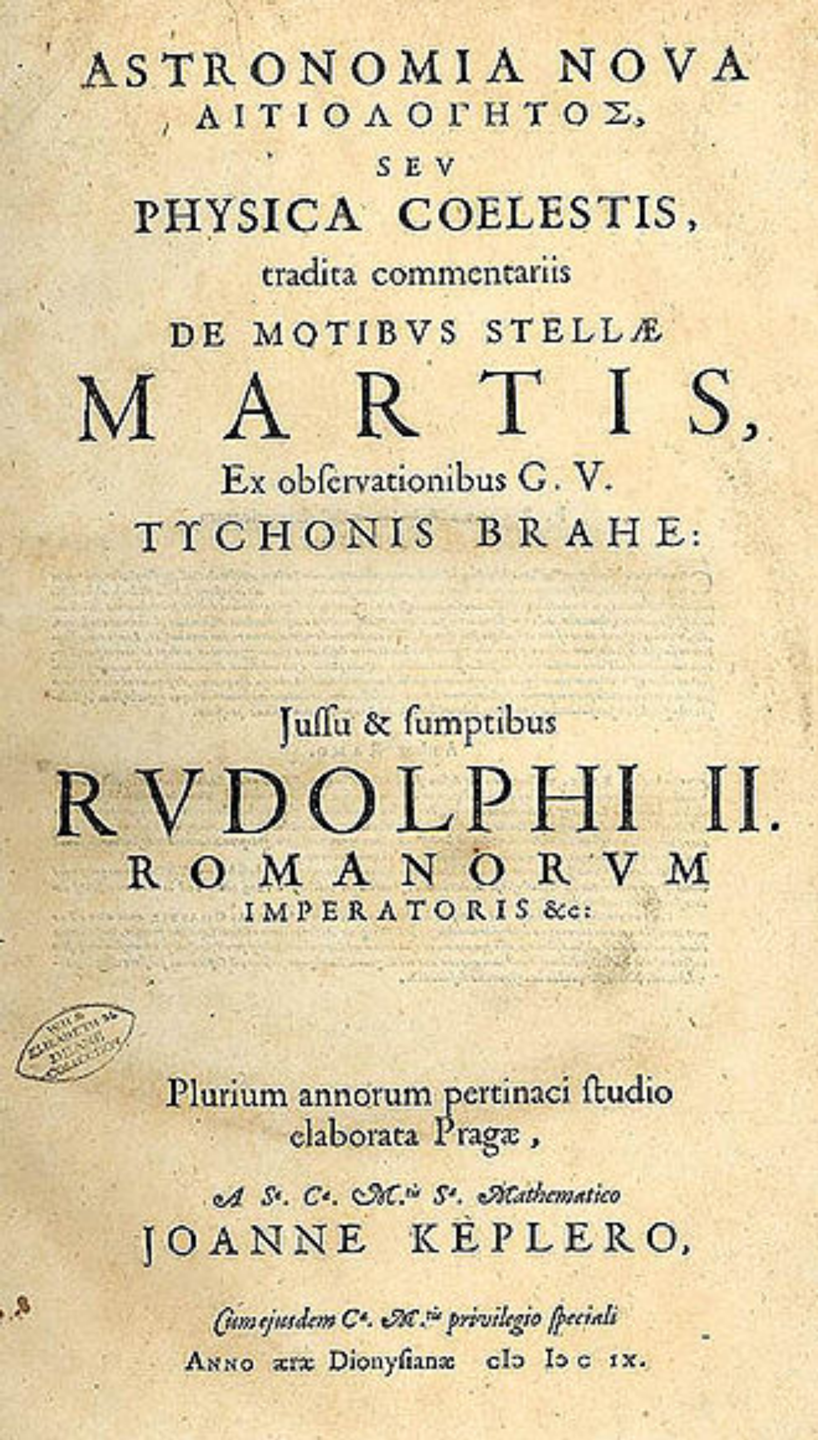
- Mercury, arsenic, gold (all found in fairly large concentrations in his body) were common alchemical ingredients and Tycho, like most researchers of his epoch and later even I. Newton, was active in his alchemical laboratory.

- Kepler technically speaking stole the data, but did not murder Brahe (despite what a popular book *Heavenly Intrigue* published in 2004 claims).

Great Moment of overturning ancient astronomy

Kepler began by studying the motion of Mars – trying to deduce from the observations how the planet actually moved.

- In the course of his intense work, he had to abandon everything he deeply believed in.
- According to Plato only the circle is a pure figure worthy of heavens. So initially he was calling the idea of oval or elliptic orbits “a heap of horse dung” and rejecting them
- However, through his correct conviction that very small (8’ = 8/60 of degree) deviations of theoretical predictions vs. Brahe’s precise observations of Mars are not to be dismissed, but are crucially important, Kepler came to believe in the reality of elliptic orbits. Such orbits repeatedly reproduced the observations, while other theories were too inaccurate. In modern science – that settles it.



ASTRONOMIA NOVA
ΑΙΤΙΟΛΟΓΗΤΟΣ,
SEV
PHYSICA COELESTIS,
tradita commentariis
DE MOTIBVS STELLÆ
MARTIS,
Ex obſervationibus G. V.
TYCHONIS BRAHE:

Juſſu & ſumptibus
RVDOLPHI II.
ROMANORVM
IMPERATORIS &c:

Plurium annorum pertinaci ſtudio
elaborata Pragæ,
A Ss. Cs. M.tis Ss. Mathematico
JOANNE KEPLERO,

Cum ejusdem Cs. M.tis privilegio ſpeciali
ANNO æræ Dionyſianæ cIↄ Iↄ c IX.

Johannes Kepler

By 1606, he had solved the mystery of Mars' movement. In 1609 he published the book *Astronomia Nova (The New Astronomy). We'll discuss how he did it below.*

As we see, Kepler acknowledged that the discovery was made based on Brahe's observations,

and named his approach "Physica Ceolestis" (Physics of the heaven)

De motibus stellae Martis = On the motion of star of Mars

Johannes Kepler & the non-uniform orbital motion

Planets do not move at uniform speed along an elliptic orbit.

- Kepler recognized that they move faster when close to the Sun and slower when farther away. The angular speed, i.e. speed in degrees/day, with which a pointer from the sun to the planet turns around the sun, is in fact inversely proportional to the momentary sun-planet distance squared.
- There was no such correlation with the distance to Earth!
- Kepler understood that the body that governs the motion of planets is the Sun, not Earth. This was a proof that Copernicus was right.

- Sun had to exert some kind of remote force, like magnetic attraction. Descartes and Kepler incorrectly believed that there is a big vortex (most likely, of aether) propelling the planets along their paths.

Johannes Kepler's *Harmonices Mundi* – a mixed bag

Later, Kepler discovered how the radii of the planets' orbits are related to the planets' orbital periods. He published these result in 1619 in the 5th chapter of a book called *Harmonices Mundi* (*The Harmonies of the World*).

- The other chapters were devoted to the idea of musical intervals characterizing frequencies in our planetary system (but today we know that planets don't strictly obey such intervals)
- The writing was partly a *mystical nonsense*: the unequal motion of the Earth, for instance, was said to correspond to a musical interval of half-tone between Mi and Fa. Kepler pointed out the design beside this:

The tones were supposedly indicating: Misery & Famine

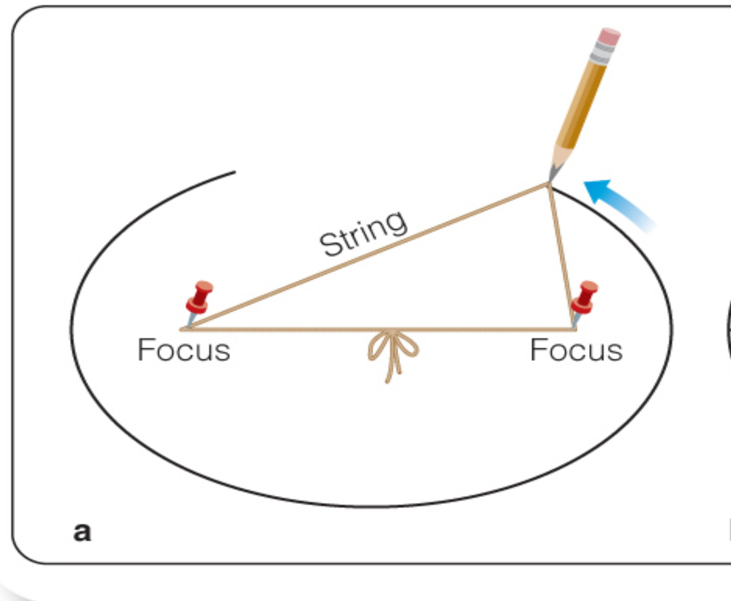
Kepler's Three Laws of Planetary Motion

- Although Kepler often dabbled in the metaphysical and mystical writings, he was primarily a mathematical astronomer. His stated motivation was to find physical causes of everything, though this was too grand a task in his time.
- Nevertheless, Kepler was convinced that physics and astronomy need each other, and need to develop jointly to study the mutual interactions of celestial bodies.
- His triumph was the solution of the problem of the motion of planets. The key to his solution was an ellipse, as he realized in 1598(?)
  - Ellipse is a figure drawn around two points – called the foci (i.e., focal points) – in such a way that the distance from one focus to any point on the ellipse and back to the other focus equals a constant.

Kepler's ellipses

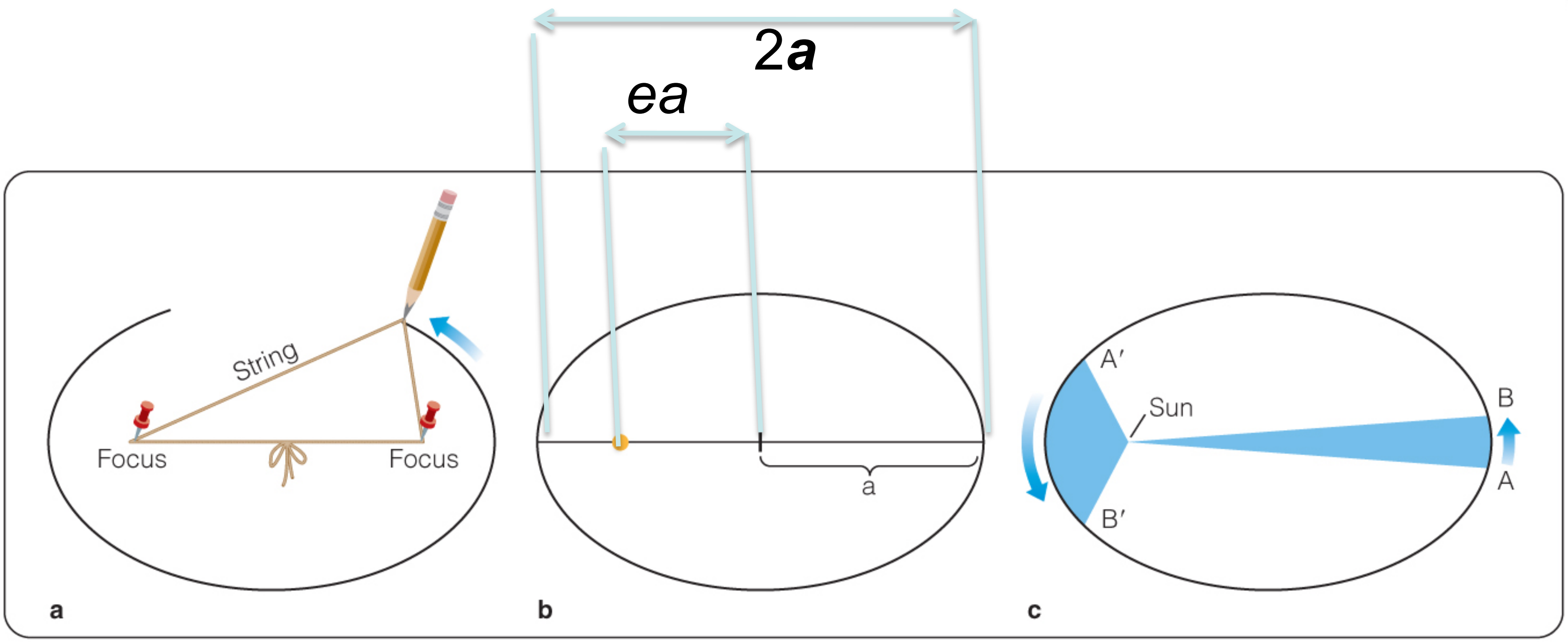
- This makes it easy to draw ellipses with two thumbtacks and a loop of string:
  - First, press the thumbtacks into a board.
  - Then, loop the string about the tacks.
  - Next, place a pencil in the loop.
  - If you keep the string taut as you

  move the pencil, it traces out an ellipse.



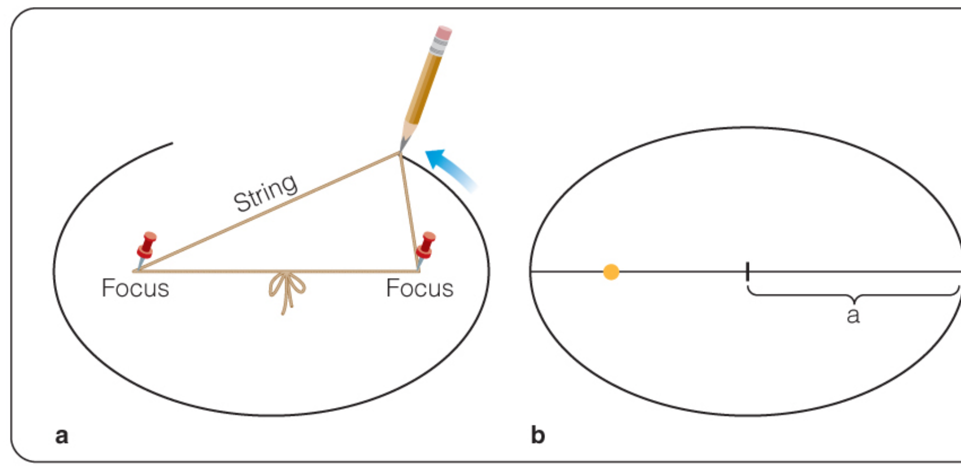
Kepler's ellipses

- The shape of an ellipse is described by only two numbers (3 additional numbers are needed to fully specify its orientation in space, and 1 more the moment of time of perihelion, the closes approach point)
  - The semi-major axis, ***a***, is half of the longest diameter.
  - The eccentricity, **e,** is half the distance between the foci divided by the semi-major axis.



Kepler's ellipses

- The eccentricity of an ellipse gives you its shape (elongation) and varies from 0 to 1:
  - If e is nearly equal to one, the ellipse is very elongated.
  - If e is close to zero, the ellipse is nearly circular.
  - In the picture, e ~ 0.5



Kepler's results are described by 3 fundamental rules that have been tested empirically and confirmed so many times that we refer to them as 'natural laws.'

- They are called Kepler's laws of planetary motion.

Kepler's 1st Law (1605)

- Kepler's first law states that the orbits of the planets around the Sun are ellipses with the Sun at one focus.

  - Thanks to the high precision of Tycho's observations, persistence, and the sophistication of his mathematics, Kepler was able to recognize the elliptical shape of the orbit of Mars, even though the shape is very nearly circular, visibly shifted into eccentric position w.r.t. the sun
  - As to the shape parameter (eccentricity e), currently we have:

  $e < 0.02$ for Earth, $e=0.09$ for Mars, and

  $e=0.04$ for Jupiter, but with time these numbers do change in time... bodies mutually interact.

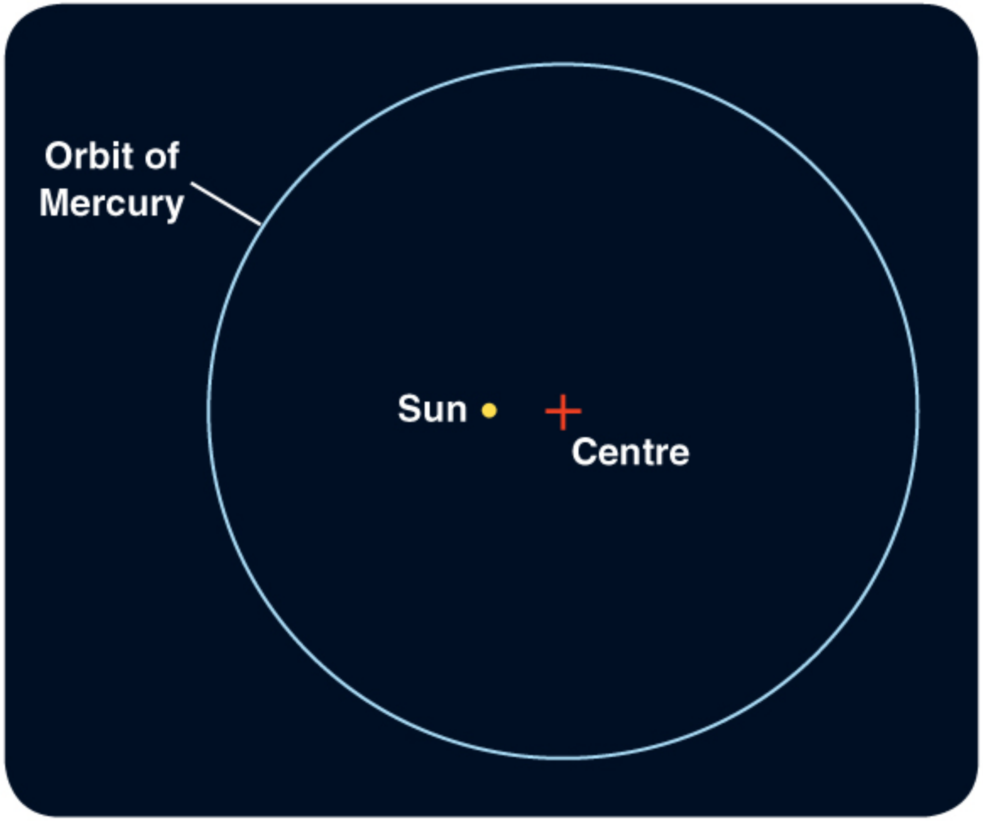
Kepler's 1st law

- Of the planets known to Kepler, Mercury has the most elliptical orbit.
  - However, even Mercury deviates only moderately from a circle:

    $e = 0.206$

    More visible is the eccentric position of the sun

Figure 3.4



Kepler's 2nd law (areal speed law, 1601)

- Kepler's second law states that a line from the planet to the Sun sweeps over equal areas in equal intervals of time.
  - This means that, when the planet is closer to the Sun and the line connecting it to the Sun is shorter, the planet moves more rapidly to sweep over the same area that is swept over when the planet is farther from the Sun

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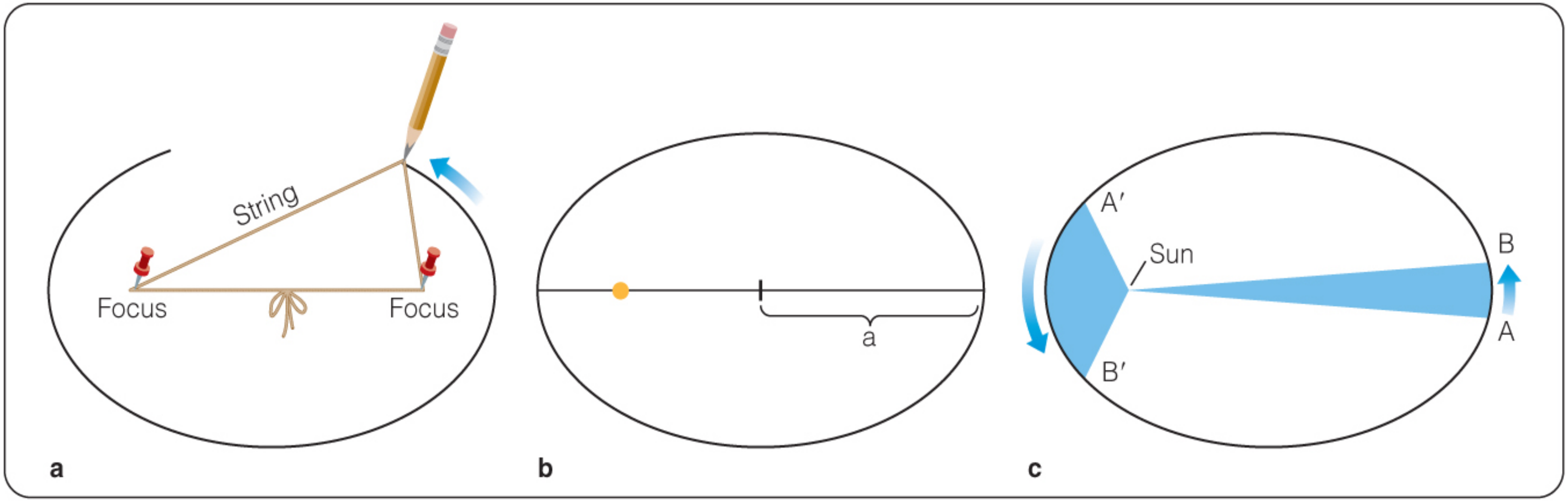
Digression: Using language of modern physics

For very slim sections, having small angles, the area equals ½ r dx, where dx is the linear distance travelled in time dt perpendicular to radius r. Constancy of the rate of area creation (½ r dx/dt = const.) implies that the velocity component in the direction perpendicular to radius, which equals $v_{perp} = dx/dt$, is inversely proportional to distance r from the focus: $r\, v_{perp} = \text{const.}$ (Law of conservation of angular momentum)

Kepler's 2nd law

- The planet in the figure would move from point A' to B' e.g. in one month – sweeping over the blue area shown.
  - When the planet is farther from the Sun, the blue area stays the same, but one month's worth of distance is shorter – from A to B.

Figure 3.3



Kepler's 3rd law in the Solar System (1609)

- Let's call the time that a planet takes to travel around the Sun once the *orbital period*, P. Its average distance from the Sun equals the semi-major axis of its orbit, a.
- Kepler's third law states that the two quantities, P and a, are closely related as follows:
- Orbital period squared is proportional to the semi-major axis cubed.
  - Different but equivalent forms

$P^2 \sim a^3$	(a proportionality)
$P \sim a^{3/2}$	(a proportionality)
$(P/1yr)^2 = (a/1AU)^3$	(exact equality for planets in sol. sys.)
$P = (a/1AU)^{3/2}\ yr$	(exact equality for planets in sol. sys.)

Notice: numbers 1 AU and 1 yr do not necessarily apply to exo-planetary systems, as they would depend on how massive the star is.

Kepler's 3rd law for the planets: $P^2 \sim a^3$

- E.g. Jupiter's average distance from the Sun (which equals the semi-major axis of its orbit) is 5.2 AU.
  - The semi-major axis cubed is about 140.6.
    - So, the period must be the square root of 140.6 – roughly 11.8 years. And it is!
    - The $P^2 = (a/\mathrm{AU})^3$ yr law that we used is for the Sun as a central body. For other central bodies, Kepler's laws also hold, but other units must be used. E.g. for the motion around the Earth the distance should be measured in Earth-Moon distances and the orbital period in units of a sidereal* moon-month, like so:
    - $P^2 = 27.3^2 \, (a \, / \, 384400 \text{ km})^3 \text{ days}^2$

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*) *Sidereal* means: with respect to stars

On Kepler's Three Laws of Planetary Motion

Kepler's laws are empirical (or *phenomenological*).

That they are expresses through mathematical formulae is unimportant; all modern physical laws are. What is important, is that these laws follow directly from observations. Kepler derived them from Tycho's extensive observations without referring to any first principles, fundamental assumptions, or physical theory. There was NO explanation of ***why*** the laws hold.

Kepler knew that planets travel in orbits determined by force from the sun. He would gladly have connected the orbits with underlying force field, but the time for that has not yet come. There was no clarity about the force field. But Kepler found that the force decreases with distance.

Johannes Kepler never knew *what* held the planets in their orbits or why they continued to move around the Sun in the ways he discovered. He speculated that the Sun emits some 'vortex matter', maybe a vortex in aether, which pushes planets *along* their orbits. This was similar to ancient Greek ideas that some kind of angels constantly push planets *along* their orbs, and to some ideas of Rene DesCartes (or: Descartes).

Kepler's Three Laws are phenomenological

  - One can say that the idea of vortices pushing planets along orbits was wrong by about 90 degrees. In fact, the force acts not *along* the orbit but precisely *toward the sun's center*, but the dynamics of that was not yet understood for another 50+ years or so, well after Kepler's death in 1630.
- Does this mean Kepler's laws are not important? On the contrary. They still apply, while the Ptolemaic, Tychonian and Copernican *models* are out of date (contradict facts or at least are shown to be inaccurate)
- Kepler's laws were groundbreaking modern science, demonstrating the tight symbiosis of what we now call mathematical physics and empirical, quantitative observations.

Peter Goldreich (Caltech theoretical astrophysicist) jokingly observed:

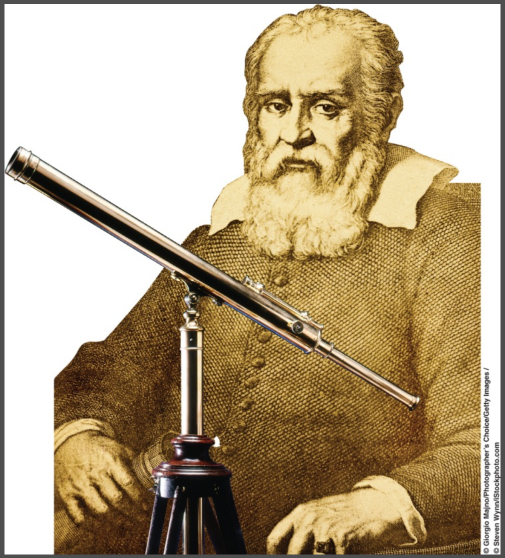
"Observations are much better than theories: only ½ of all observations will be proven wrong, compared with 100% of theories."

Jupiter as a miniature solar system

- Galileo discovered the 4 main moons of Jupiter.
- Kepler has checked* whether the periods of orbital motions around that planet satisfy some kind of 3rd law regarding orbital periods.They did, although due to the inaccuracy of period & distance determination the correlation was not as tight as among planets.
- Kepler correctly proposed that Jupiter's family illustrates the norm: smaller objects are swirling around massive ones. It's not an exception among planets. Outer planets have many dozens of small moons (written with lowercase m). However, our Moon is fairly big & massive relative to our planet. This is not so common.
- Curiously, in the 17th century very little attention was given to the 3rd law of Kepler ($P \sim a^{3/2}$), even by its discoverer!

- *– J. Kepler, Epitome Astronomiae Copernicanae (1618-1621)*

No full translation into English exists of this widely read book, in which all 3 laws were formulated.



Galileo Galilei (1564-1642)

Italian physicist, astronomer, and mathematician

The life of Galileo overlapped that of both Tycho Brahe and Johannes Kepler (with whom he corresponded by mail, but only once or twice).

Galileo Galilei

the leaning tower of Pisa

- Galileo was born in the Tuscan city of Pisa, and studied medicine there but later convinced his father that he should study mathematics and natural science (=Physics).

- Galileo discovered that the pendulum swings with a period independent of how far it is deflected, constructed thermometer, water pump power by a horse etc. He studied accelerated motion by rolling objects on slopes & found that *$s = a\, t^2/2$ (distance-time-acceleration eq.)*
- He established that bodies freely fall (neglecting air drag) in a way independent of their mass ($a = g = const.$)

Galileo became a professor of mathematics at the university in Padua in the Venetian Republic. There he remained for 18 years, during which he adopted the Copernican views.

Telescopic Observations

- Galileo did not invent the telescope.
- Invention in ~1608 belonged to lens maker Lippershey from Holland.
- Galileo, hearing the descriptions in the Fall of 1609, was able to build somewhat better telescopes in his workshop, magnifying 9x, then 30x

(now in Galileo's museum in Florence, Italy)

- Neither was Galileo the first person to look at the sky through a telescope.

However, he was the first to observe the sky carefully and apply his observations to the main theoretical problem of the day: the place and nature of Earth among planets


Courtesy Yerkes Observatory

Telescopic Observations

- It was the telescope that was used by Galileo to publicly defend the heliocentric model. But against what?

  Strangely, he was attacking a Ptolemaic system which was no longer popular among top scientists: the question of the day was whether Tychonian geo-heliocentric or Copernican heliocentric system was right

  Galileo never believed in elliptic orbits of Kepler (!)

- Still, what Galileo saw through his telescopes was so amazing that in 1610 he rushed a small book into print,

  Sidereus Nuncius (*The Starry Messenger*).

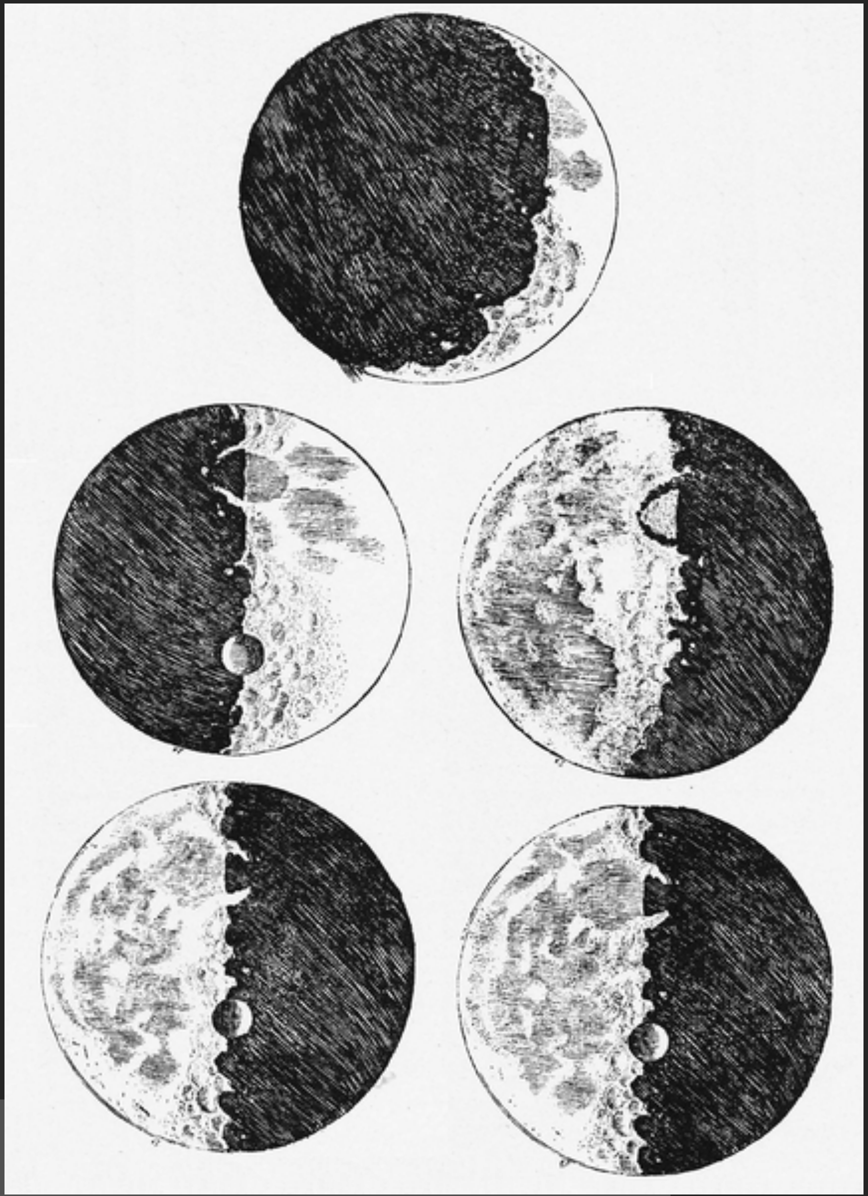
In the book, he reported three major discoveries.

Telescopic Observations - 1

First, the Moon was not perfect. (Aristotle's philosophy held that the Moon & planets were perfect)

- It had mountains and valleys on its surface. Galileo used the shadows to calculate the height of the mountains.
- Galileo showed that it was a rocky world, like parts of Earth.
- This put a division of the world into heaven and earth, two completely different realms, into question. The boundary between Earth and Heaven had to move outward, beyond the Moon, or better yet – disappear.
- Galileo wanted very much to prove Copernicus system. He presented a lot of arguments as proofs. Among them many 'not-really-proofs' such as the mountains on the Moon. This might prove Ptolemy wrong, but it's different than showing heliocentric system to be right.

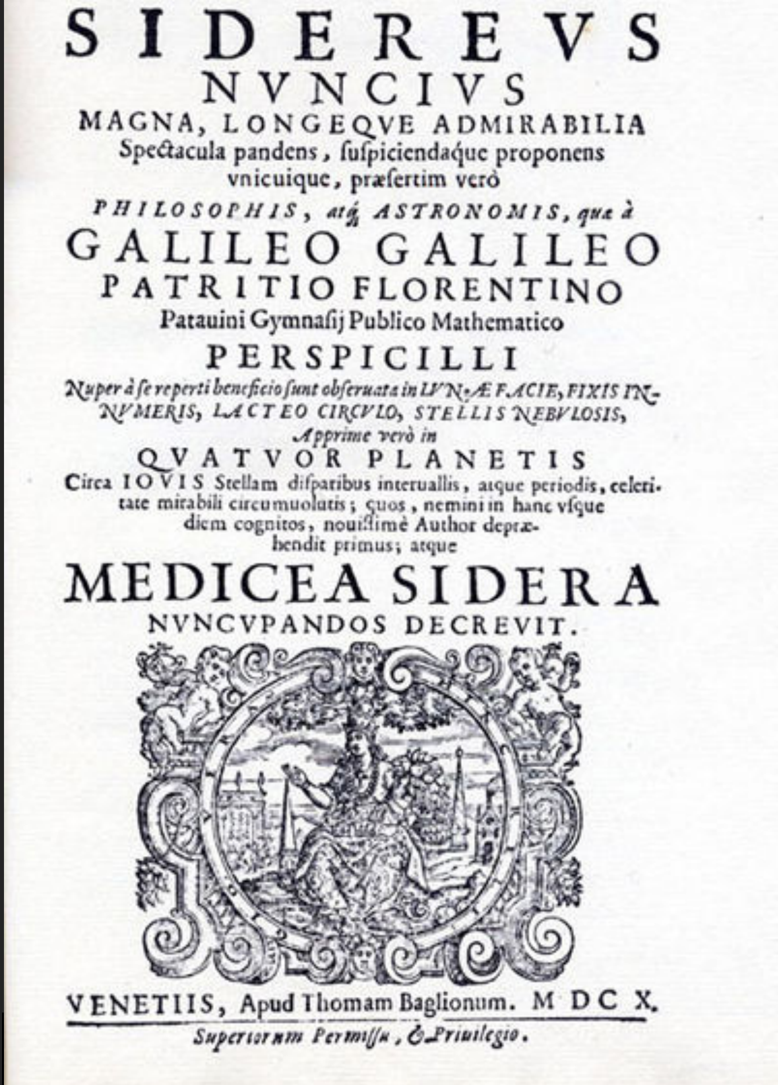
Our Moon and Galileo's drawings of it 400 years ago



Second, Galileo's telescope revealed 4 stars or planets circling Jupiter. Today, they are known as the Galilean moons of Jupiter

Sidereus Nuncius (1610)

= Starry Messenger


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

Medicean 'stars' (Medicea Sidera, the stars of Medici*)

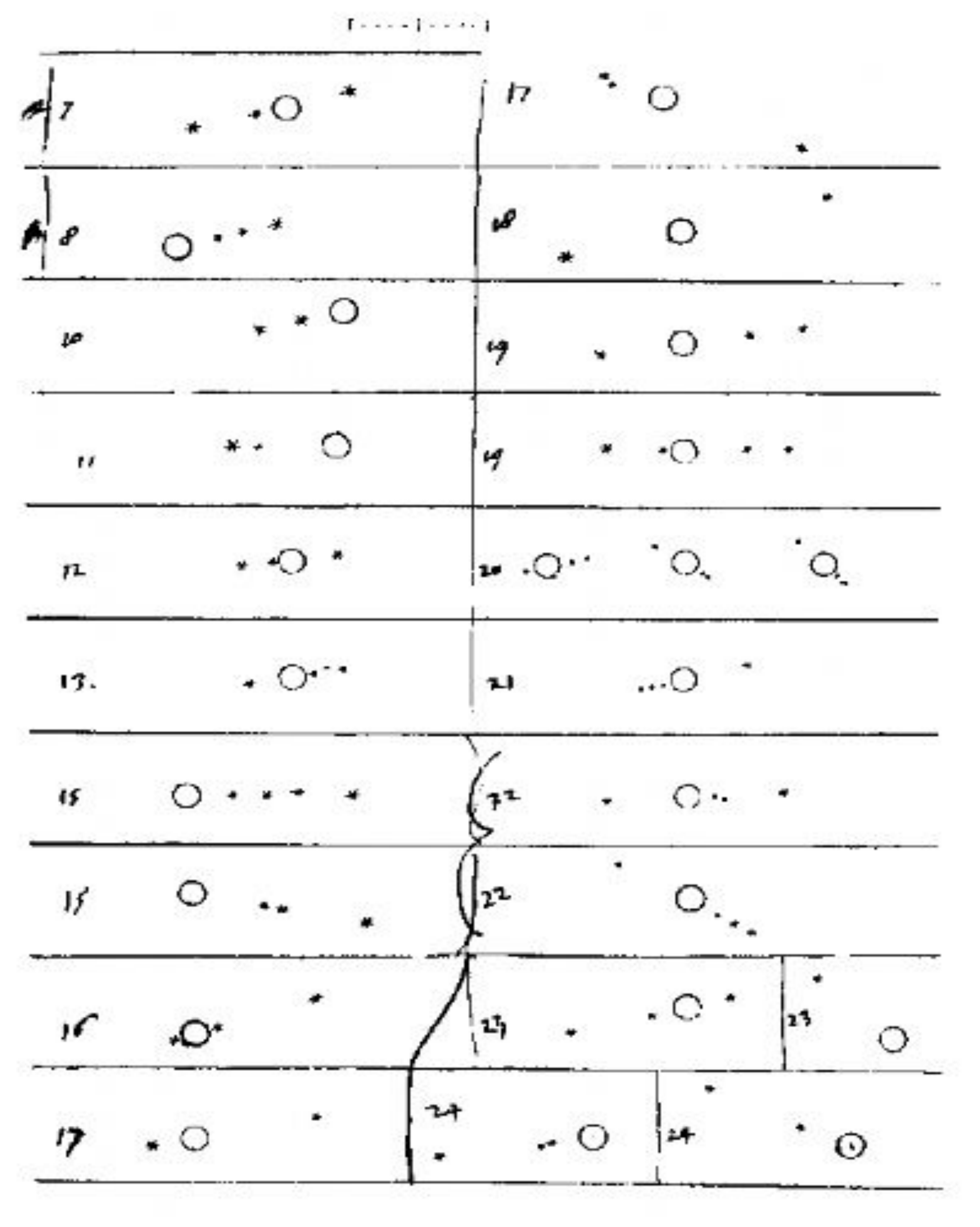
In fact they are neither stars nor planets: Io, Europa, Ganymede and Callisto are the four largest moons of Jupiter:

*) - Medici family from Florence held political power in Tuscany, sponsoring arts and sciences. But later astronomers dropped that naming of Jovian moons. Astronomers keep sponsor's names in the heavens only for as long as necessary!

Telescopic Observations of Jupiter & moons

- Ganymede indeed is larger than planet Mercury!
- three have underground oceans of water, and one extremely active volcanoes (Io).

..but that required 3 more centuries to become known.



observations by Galileo, Jan 7-24, 1610

First telescopic observations

- The moons of Jupiter supported (but not “proved”) the Copernican model over the Ptolemaic model.

  - Critics of Copernicus had said Earth could not move – because the Moon would be left behind.
  - However, Jupiter moved *and* kept its satellites. Galileo's discovery suggested that Earth, too, could move and keep its Moon.

- Also, Aristotle’s philosophy included the belief that all heavenly motion was centered on one object only: the Earth.

Now, it was evidently wrong!

Galileo showed that there could be multiple centers of motion.

Telescopic Observations

- Galileo noticed qualitatively the *P* vs. *a* relation (period vs. distance) : Jupiter's innermost moon had the shortest orbital period and the moons further from Jupiter had longer periods.
  - In this way, Jupiter’s moons made up a harmonious system ruled by Jupiter – just as the planets in the Copernican universe were a harmonious system ruled by the Sun.

- This similarity again did not constitute a *proof of heliocentric system*
  - Nevertheless, Galileo presented it as such, or at least a very strong indication that the solar system is Sun-centered and not Earth-centered

First telescopic observations of the Galaxy

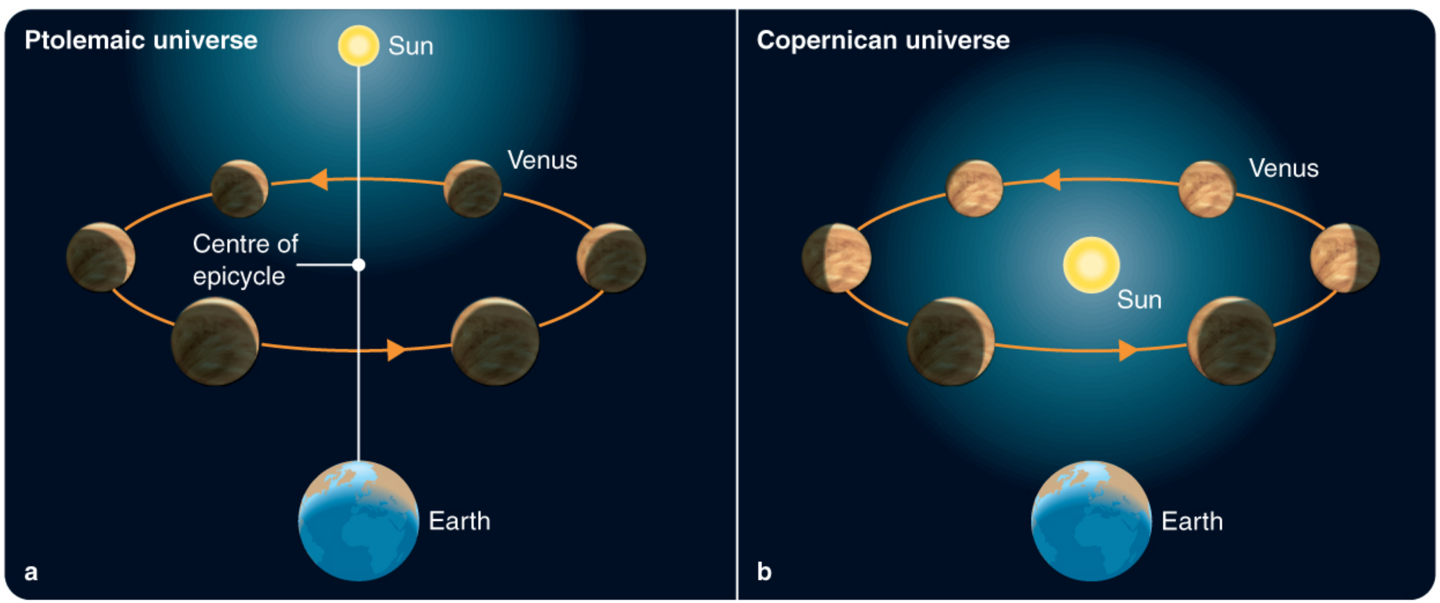
- The third discovery followed when Galileo turned the telescope on the Milky Way.
- He could see thousands of previously unknown stars, which led him to the correct conclusion that the Milky Way is made of separate stars (now we know about dusty interstellar gas as well).

In the years of further exploration with his telescope, Galileo made additional fundamental discoveries.

Further Telescopic Observations that began in 1610 but were reported later

- When Galileo observed Venus, he saw that it was going through phases like those of the Moon. In the Ptolemaic model, Venus moves around an epicycle centered on a line between Earth and the Sun – it never gets very far from the sun on the sky. Why does Venus pay so much attention to sun was not explained. And Ptolemy's model predicts that Venus would always be seen as a crescent (left-hand illustration). Galileo disproved that.

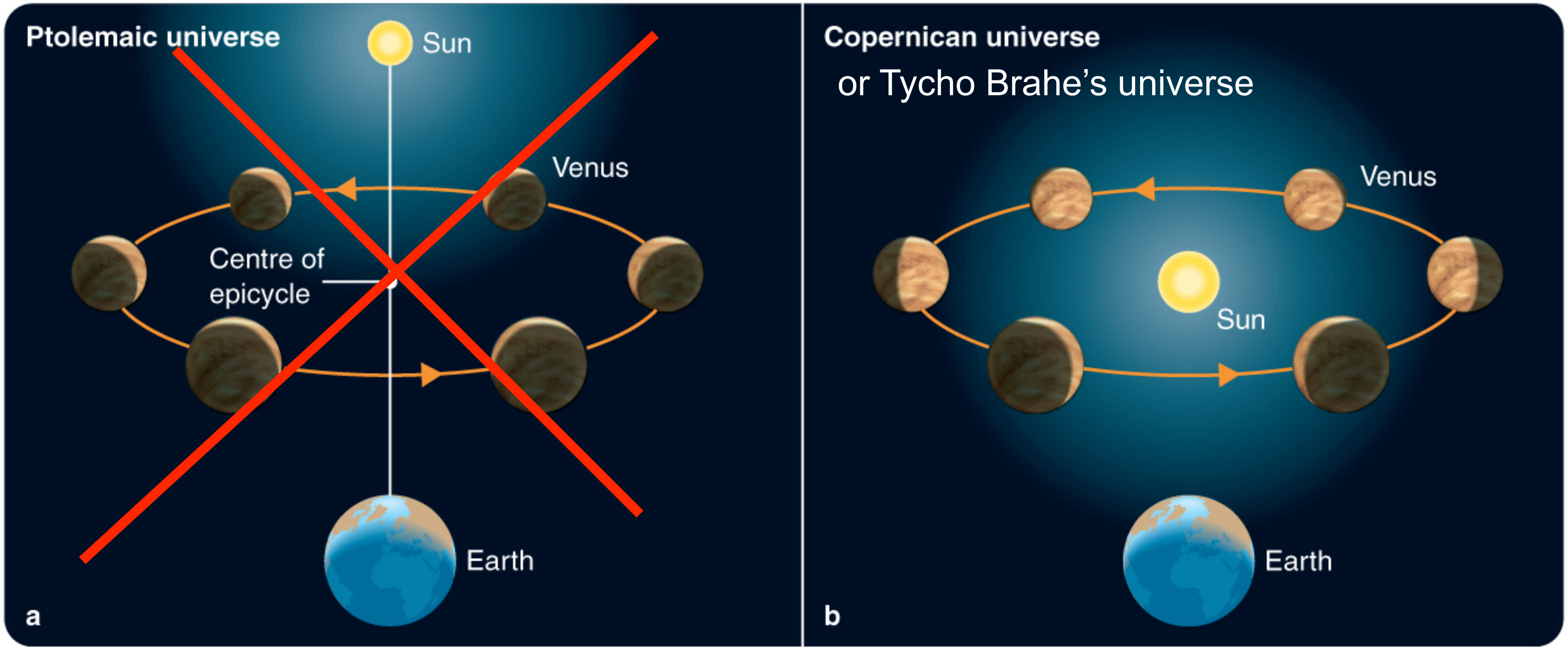
Figure 3.6



Telescopic Observations

- Galileo saw Venus go through a complete set of phases, including full and gibbous. This proved that it did indeed revolve around the Sun. Galileo claimed Copernicus was right.
- But that's a proof of *either* Copernican *or* Tychonian system!

Figure 3.6



Telescopic observations

Sidereus Nuncius (1610) was popular and made Galileo famous.

He got a job as mathematician and philosopher of grand duke of Tuscany in Florence. In 1611, Galileo visited Rome and was treated with great respect.

- He had friendly discussions with his childhood friend, the powerful Cardinal Barberini, supporter of arts and sciences, who later became pope Urban VIII
- Church officials and Jesuit priests

supported him. Civil authorities likewise.

The largest opposition was offered by Academia = university professors. There was no problem with Holy Office at Vatican or Inquisition in 1611. But all has changed in several years.

Galileo applies for another grant(?)

1st trial of Galileo

Galileo being outspoken, forceful, and often tactless, offended many important people who questioned his telescopic discoveries.

- Some critics said he was wrong, others said he was lying
- Some refused to look through a telescope lest it mislead them
- Others looked and claimed to see nothing – actually that's hardly surprising given the awkwardness and optical errors of the first telescopes 😐

- When Galileo visited Rome again in 1616, Cardinal Bellarmine interviewed him privately and ordered him to cease public debate about models of the universe.

- Galileo appears to have mostly followed the order but could not stay silent for long.

Censorship as a way to cancel freedom of speech, expression and thought

- *De Revolutionibus* was only suspended for a few years pending revision of places where strong but unsupported claim were made and/or it went too much into religious perspective. It was recognized as useful for its predictions of planet positions and allowed into circulation after modifications.

  Everyone who owned a copy of the book was required to cross out certain statements and add handwritten corrections that stated the Earth's motion and the central location of the Sun were only theories and not facts.
- The Inquisition (through the Congregation of the Index) banned books relevant to the Copernican hypothesis. That came 76 years after Copernicus died, and was a direct response to the challenge by Galileo, after he published *Letters on Sunspots* in 1613, exposing his Copernican views.

In the 1500s and 1600s the censorship and control over printing presses was a common phenomenon in European secular and church domains.

In whole England, only 2 universities and 21 printing offices were approved and licensed by the crown, with a total of 53 presses. In 1535 in France, king Francis I decreed that anyone who printed anything would be hanged.

Censorship today remains a thorny issue. The role of Inquisition is played by similarly efficient, though *mostly* less murderous governments & businesses.

Dialogo and the Trial

- In 1623 Galileo's childhood friend Cardinal Maffeo Barberini became Pope, taking the name Urban VIII.
- Galileo went to Rome in an attempt to have the 1616 order to cease debate lifted. The attempt was unsuccessful, but at least Galileo was told that as long as he said that Copernican system was a hypothesis and did not insist that it is truth, he'll be fine. (Here we see how prescient Osiander's forgery of the preface to Copernicus De Revolutionibus was: it said Copernican system was just a mathematical hypothesis.)
    - Galileo began to write a massive defense of Copernican model, completing it in 1629.
    - After some delay, Galileo's book was *approved* by both the local censor in Florence and the head censor of the Vatican in Rome, and was printed in 1632.

Dialogo and Trial

- The book was titled *Dialogo Dei Due Massimi Sistemi* (1632) or *Dialogue Concerning the Two Chief World Systems*.
  - It confronted the ancient astronomy of Aristotle and Ptolemy with the Copernican model.
  - As mentioned, at this point in time, the attacked Ptolemaic system was already depreciated by leading scientists, so the thrust of the Italian-language book was to be fighting popular misconceptions among non-scientists.

Galileo wrote the book as a debate among three friends

- Salviati is a swift-tongued defender of Copernicus.
- Sagredo is intelligent but largely uninformed.
- Simplicio is a dim-witted defender of Ptolemy.

DIALOGO
DI
GALILEO GALILEI LINCEO

MATEMATICO SOPRAORDINARIO

DELLO STVDIO DI PISA.

E Filosofo, e Matematico primario del

SERENISSIMO

GR. DVCA DI TOSCANA.

Doue ne i congressi di quattro giornate si discorre sopra i due

MASSIMI SISTEMI DEL MONDO TOLEMAICO, E COPERNICANO;

Proponendo indeterminatamente le ragioni Filosofiche, e Naturali tanto per l'vna, quanto per l'altra parte.

CON PRIVILEGI.

IN FIORENZA, Per Gio: Batista Landini MDCXXXII.

CON LICENZA DE' SVPERIORI.

Dialogo and Trial

The Dialogue book was a clear defense of Copernicus.

- Some claims were weakly supported by evidence, although presented as proofs. For instance the sunspots, or tides. A few things were mistakes.
- Also, Galileo exposed the Pope's authority to ridicule and provoked the church authorities.
- Prior to this the Pope privately asked Galileo to keep a balanced discussion of two world systems and also to mention his own arguments.
- Galileo placed the Pope's argument in the mouth of the ignorant Simplicio. The Church took offense and ordered Galileo to face the Inquisition.
- Galileo was interrogated by the Inquisition. 4 *private meetings* were held. 3 out of 10 judges declined to sign the mild sentence.

Galileo's Trial

The Inquisition condemned Galileo, not primarily for heresy but for disobeying the orders given him in 1616. The church authorities felt they must react to Galileo. They placed *Dialogo* on the Index of prohibited works.

In 1633, at the age of 70, kneeling before the Inquisition,

Galileo read a long recantation admitting his errors. A myth has it that as he rose, Galileo whispered about the Earth "E pur si muove"

("Still it moves")

In our modern science myths, these events are painted as a brutal trial complete with torture or threats* of torture. In fact, the controversy and trial were mild and were caused mostly by Galileo's rebellious personality.

* - Yet it is true that when Galileo initially refused to come to Rome for trial, he was threatened with being brought there in chains.

Galileo before the Inquisition – an artist's vision, not factual!

Modern myth of Galileo as a science martyr

- Although Galileo was formally sentenced to life-long home arrest, he was actually confined to luxurious homes, like home of Archbishop of Siena, former pupil of Galileo, who permitted and even encouraged the scientist to resume writing books. Another home included a suite with a view toward Vatican gardens, the villa of the ambassador of Tuscany and his own villa, where Galileo received numerous visitors, and had an active social and scientific life.

- His daughter Virginia was a nun. At a convent she took the name Maria Celesta (because of father’s interests in things celestial). She overtook the second part of the sentence: once per week to say 4 psalms.

The final years of Galileo

Not being allowed to write much about theoretical astronomy (to which, unlike Kepler, Galileo did not contribute anyway; he did not even appreciate Kepler's laws!), the old scientist focused on Physics. This was a very good decision. He famously described kinematics, dynamics (motion & forces) and strength of materials.

For the last 10 years of his life, Galileo wrote a book on the nature of motion, especially the accelerated motion of falling bodies. It was smuggled & published as *Dialogues Concerning Two New Sciences* by publisher Louis Elsevier into Protestant Holland. Congregation of the Index outlawed its publication in Italy!

- Galileo died in 1642, 99 years after the death of Copernicus.
- The next year, Isaac Newton was born. He provided a number of (more) solid proofs supporting Copernican system.
- 350 years later, in 1992, Pope John Paul II made a formal statement acknowledging the unjust condemnation of Galileo by the Catholic Church, saying that both sides made mistakes.