the Scientific Revolution:

the Cosmos Mechanized



Ptolemaeus to Copernicus

One school in history of astronomy:

minor imperfections in the original Ptolemaic system were discovered through observations accumulated over time.

It was mistakenly believed that more levels of epicycles (circles within circles) were added to the models to match more accurately the observed planetary motions.

The multiplication of epicycles is believed to have led to a nearly unworkable system by the 16th century.

Copernicus created his heliocentric system in order to simplify the Ptolemaic astronomy of his day, thus succeeding in drastically reducing the number of circles.

With better observations additional epicycles and eccentrics were used to represent the newly observed phenomena till in the later Middle Ages the universe became a 'Sphere/With Centric and Eccentric scribbled o'er,/Cycle and Epicycle, Orb in Orb'

Alfonsine Tables

- Tables of solar, lunar and planetary positions wrt. fixed stars
- Called after Alfons X of Castile the Wise (el Sabio) (1221-1284)
- composed in 1252, in Toledo
- assembled by translators of Toledo
- based on observations an studies of Islamic scholars
- most popular astronomical tables for 300 years (incl. Copernicus)

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Ptolemaeus to Copernicus

• As a measure of complexity:

- the number of circles is given as 80 for Ptolemy,
- versus a mere 34 for Copernicus
- By this time each planet had been provided with from 40 to 60 epicycles to represent after a fashion its complex movement among the stars. Amazed at the difficulty of the project, Alfonso is credited with the remark that had he been present at the Creation he might have given excellent advice.

1543

Nicolaus Copernicus

- publishes heliocentric universe in De Revolutionibus Orbium Coelestium

- implicit introduction Copernican principle: Earth/Sun is not special

1609-1632

Galileo Galilei

- by means of (telescopic) observations, proves the validity of the heliocentric Universe.

• 1609/1619

Johannes Kepler

- the 3 Kepler laws, describing the elliptical orbits of the planets around the Sun

• 1687

Isaac Newton

- discovers Gravitational Force as agent behind cosmic motions
- publishes his Principia (Philosophiae Naturalis Principia Mathematica), which establishes the natural laws of motion and gravity (the latter only to be replaced by Einstein's theory of GR)

1755

Immanuel Kant

- asserts that nebulae are really galaxies separate from and outside from the Milky Way,
- calling these Island Universes

• 1785

William Herschel

- proposes theory that our Sun is at or near the center of ou Galaxy (Milky Way)

Nikolaus Copepnicus (1473-1543)

Nicolaus Copernicus

Birthhouse Copernicus, Torun

- 1473 born in Torun (Poland)
- 1491-1495 study Univ. Krakow
- 1496-1501 3 years Univ. Bologna canon law
- 1503- Warmia
- 1514 Frombork
- Languages: Latin , German
- **1514 Commentariolus** Nicolai Copernici de hypothesibus motuum coelestium a se constitutis commentariolus
 - + theoretical treatise on heliocentric mechanism
 - + 40 pages, 7 basic assumptions

Tower (living) Copernicus, Frombork

Frombork Cathedral









Commentariolus

. There is no one center of all the celestial circles or spheres.

6.

- 2. The center of the earth is not the center of the universe, but only of gravity and of the lunar sphere.
 - All the spheres revolve about the sun as their midpoint, and therefore the sun is the center of the universe.
 - The ratio of the earth's distance from the sun to the height of the firmament (outermost celestial sphere containing the stars) is so much smaller than the ratio of the earth's radius to its distance from the sun that the distance from the earth to the sun is imperceptible in comparison with the height of the firmament.
 - Whatever motion appears in the firmament arises not from any motion of the firmament, but from the earth's motion. The earth together with its circumjacent elements performs a complete rotation on its fixed poles in a daily motion, while the firmament and highest heaven abide unchanged.
 - What appear to us as motions of the sun arise not from its motion but from the motion of the earth and our sphere, with which we revolve about the sun like any other planet. The earth has, then, more than one motion.
 - The apparent retrograde and direct motion of the planets arises not from their motion but from the earth's. The motion of the earth alone, therefore, suffices to explain so many apparent inequalities in the heavens.

De Revolutionibus

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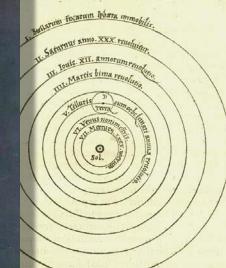
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Cum Gratia & Privilegio Carl Maieft. BASILEAE, EX OFFICINA HENRICPETRINA

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Orbium Coelestium



Nicolaus Copernicus

1543 - publication
De Revolutionibus Orbium Coelestium
(On the Revolution of the Celestial Spheres)

1514- **Commentariolus (Little Commentary)** 1532 – finished work on Revolutionibus

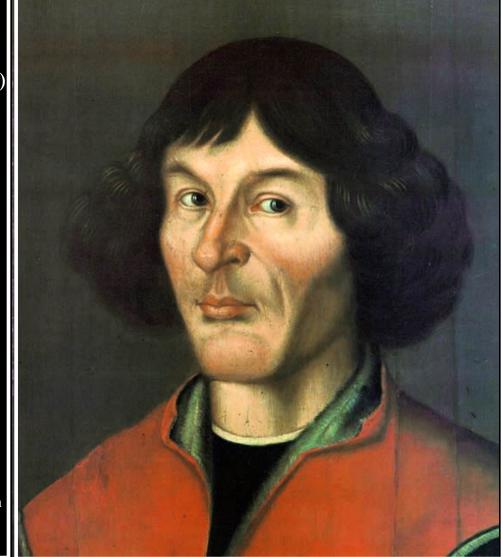
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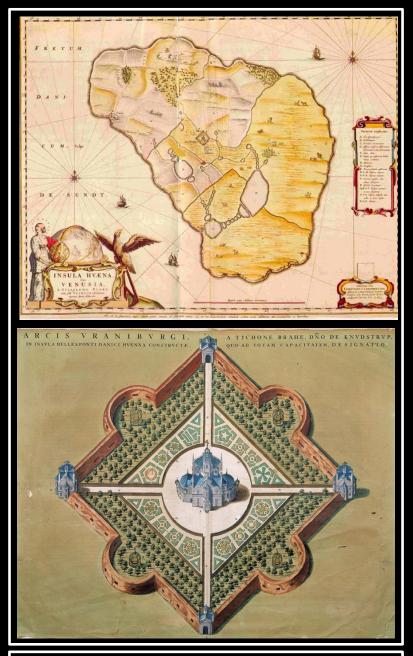
- printed by Johannes Petreius, Nuremburg

May 24, 1543 - death Copernicus - legend: presentation last pages printed Revolutionibus

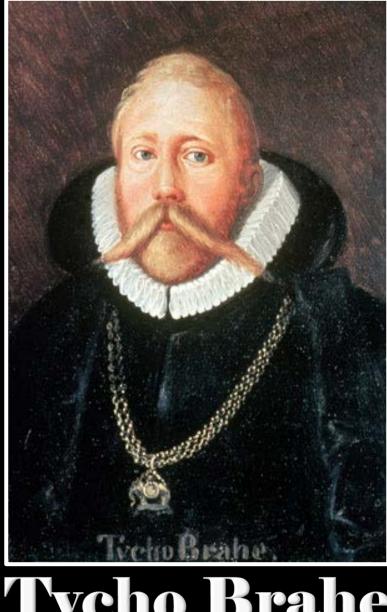
Note:

Copernicus cited Aristarchus of Samos in an early (unpublished) manuscript of De Revolutionibus (which still survives), though he removed the reference from his final published manuscript.





Observatory Uranienborg on island Hven (nowadays between Sweden-Denmark)



Tycho Brahe (1546-1601)



Tycho Brahe (1546-1601)

- Danish nobleman
- astronomer, astrologer, alchemist
- Observatory Uraniborg on island Hven
- Hven was his fiefdom
- entire island Hven devoted to exploitation for observatory
- Brahe famous for high
 + acccuracy
 + quantity
 astronomical and
 planetary observations
- before telescope
- Key to Scientific Revolution







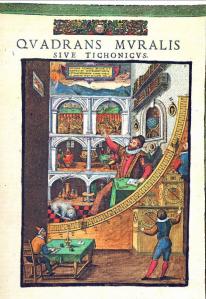


Uraniborg

Uraniborg

- Island Hven given to Tycho by Danish king Frederik II
- 1576: building of Uraniborg
- 1581: building of annex, Stjerneborg
- cellar Uraniborg: alchemy experiments
- 1576-1597 ~ 100 students & assistants
- research community in Research Center & Institution of Education





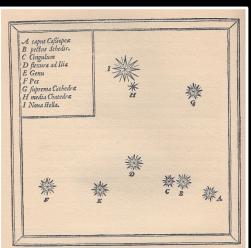
EXPLI-



De Nova Stella (1572)

End of the Aristoteleian cosmological view that - the world beyond the Moon is eternally unchanging

- 11 Nov. 1572 Tycho observed a new star
- Constellation Cassiopeia
- At hindisight it has been 1 of the 5 visible supernovae that have exploded in the Galaxy over the past 1000 years
- distance: 7500 lightyears
- Tycho published this in De Nova Stella

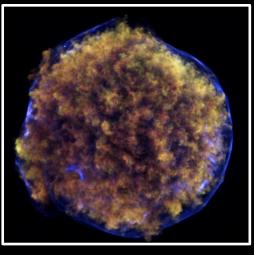


Distantiam verò huius Stelle à fixis aliquibus in hac Cassiopeie constellatione, exquisito instrumento, & omnium minutorum capaci, aliquoties observaui. Inueni autem eam distare ab ea, quæ est in pectore, Schedir appellata B, 7. partibus & 55. minutis : à superiori verò

Supernova remnant

SN1572 Tycho's SNR (1572)

Exploding star

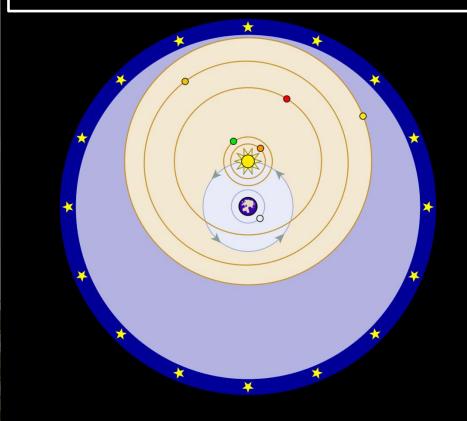




Geo-Heliocentric Model

Tycho's Geo-Heliocentric Model:

- Sun circles the Earth
- Planets circle the Sun

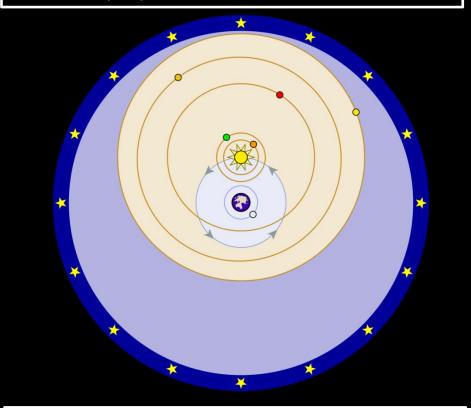




Geo-Heliocentric Model

Tycho did not accept the heliocentric view of Copernicus:

- Observational data in 16th century were not good enough to prove it.
- No stellar parallax could be measured:
- would imply stars to be so distant they would be larger than Sun
- Completely eliminited the ancient (Aristotelean) idea of heavely spheres
- "Earth is a lazy body":



"such a fast motion could not belong to the earth, a body very heavy and dense and opaque, but rather belongs to the sky itself whose form and subtle and constant matter are better suited to a perpetual motion, however fast"

Brahe & Kepler

Arguably, the most significant step in Tycho's career:

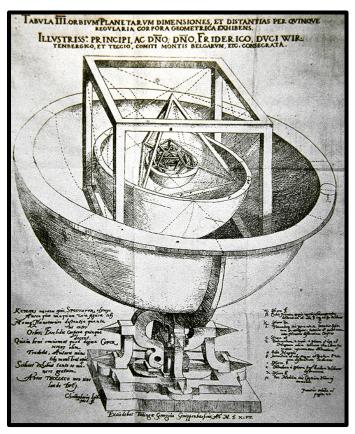
- move to the German imperial court in Prague (following tensions with new Danish king Christian IV)
- meeting up with (young) Johannes Kepler



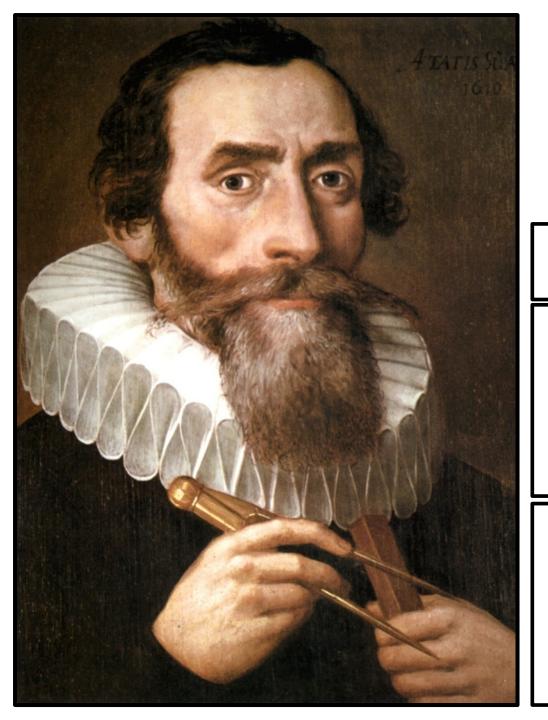
The analytical genius of Kepler gained access to the state of the art accurate observations of Tycho Brahe, opening up the path towards unravelling the laws of motion in the solar system.



Johannes Kepler (1571-1630)



Mysterium Cosmographicum



Johannes Kepler (1571-1630)

Johannes Kepler may be considered as THE key genius of the European Scientific Revolution

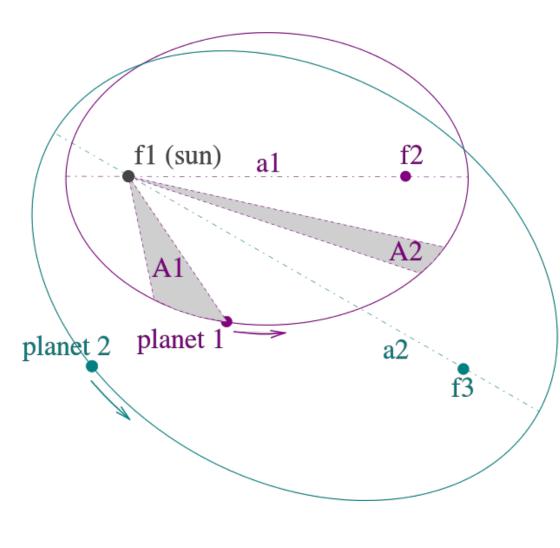
In his 3 books he established an entirely new, revolutionary, look on the workings of the Universe, the cosmology of Kepler,

Mysterium Cosmographicum	1596
• Astronomica Nova	1609
• Harmonices Mundi	1619

His main goal was to reveal the divine laws and plan dictating the motion of the planets according to Copernicus heliocentric system,

- establishing that the orbits of the planets are elliptical and formulating the 3 laws of Kepler for planetary motion
- strongly leaning on mathematics as the language of nature, much in line with Pythagoras and Plato.

Kepler Laws



Kepler laws of planetary motion

1. The orbit of a planet is an ellipse with the Sun at one focus.

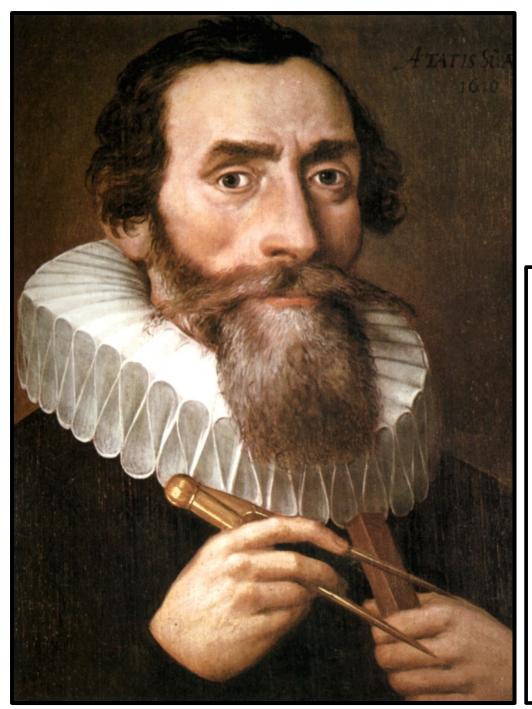
2. A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of ime.

(planets do not move with uniform speed along their orbit).

3. Relation Orbital Time – Size orbit:

The square of the orbital period of a planet is proportional to the cube of the orbit's semi-major axis

 $T^2/a^3=const.$



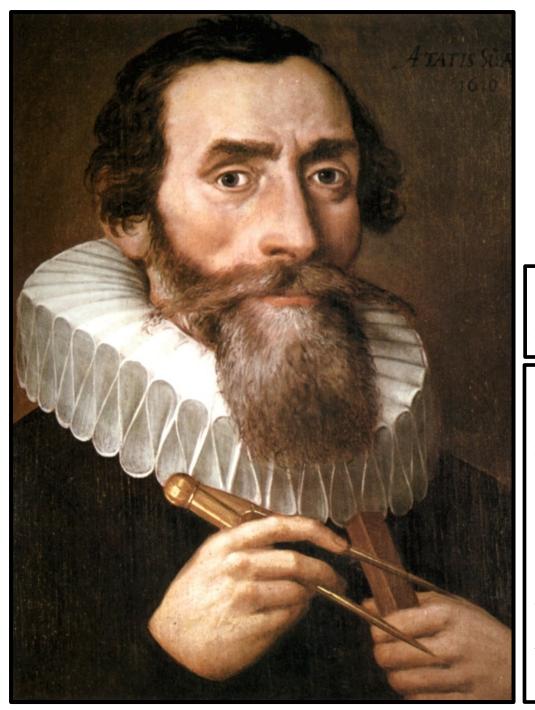
Johannes Kepler (1571-1630)

Fields: astronomy, astrology, mathematics, natural philosophy

Kepler described his new astronomy as "celestial physics":

his entire astronomical career devote to elaboration of the following questions:

- why are there six planets (then known)?
- why are they spaced around the Sun as they are.
- why do they move as they do ?



Johannes Kepler (1571-1630)

Fields: astronomy, astrology, mathematics, natural philosophy

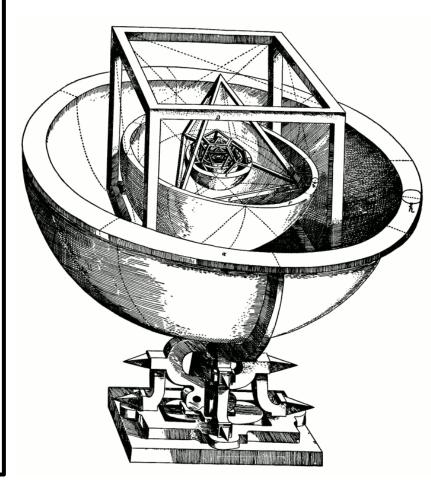
Kepler described his new astronomy as "celestial physics",

as "an excursion into Aristotle's Metaphysics", and as "a supplement to Aristotle's On the Heavens",[[]

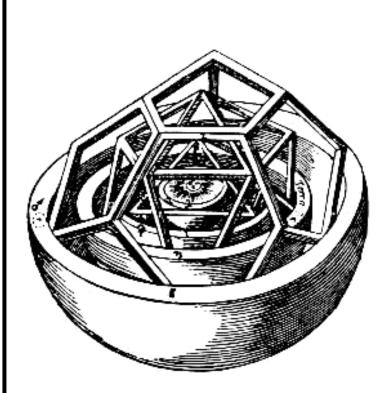
transforming the ancient tradition of physical cosmology by treating astronomy as part of a universal mathematical physics.

Prodromus dissertationum cosmographicarum, continens mysterium cosmographicum, de admirabili proportione orbium coelestium, de que causis coelorum numeri, magnitudinis, motuumque periodicorum genuinis & proprijs, demonstratum, per quinque regularia corpora geometrica

Forerunner of the Cosmological Essays, Which Contains the Secret of the Universe; on the Marvelous Proportion of the Celestial Spheres, and on the True and Particular Causes of the Number, Magnitude, and Periodic Motions of the Heavens; Established by Means of the Five Regular Geometric Solids



- First published defense of Copernican system
- published 1596 (at age 26 !)
 2nd ed. 1621 (half as long)
- Book explains Kepler's cosmological theory: God's Geometrical Plan for the Universe
- based on the Copernican system: first published defense of Copernican system
- Five Pythagorean regular polyhedra dictate the structure of the universe and reflect God's plan through geometry.
- Kepler found that each of the five Platonic solids could be uniquely inscribed and circumscribed by spherical orbs;
- nesting these solids, each encased in a sphere, within one another would produce six layers, corresponding to the six known planets
- Mercury, Venus, Earth, Mars, Jupiter, and Saturn.
- By ordering the solids correctly
- octahedron, icosahedron, dodecahedron, tetrahedron, cube



Kepler found that circumscribing spheres could be placed at intervals corresponding

(within the accuracy limits of available astronomical observations)

to the relative sizes of each planet's path, assuming the planets circle the Sun



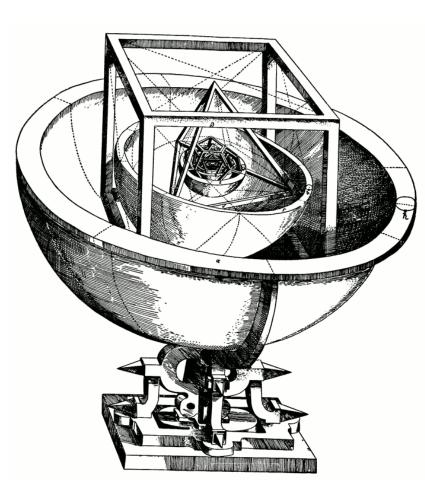
Kepler thought he had revealed

God's geometrical plan for the universe.

Much of Kepler's enthusiasm for the Copernican system stemmed from his theological convictions about the connection between the physical and the spiritual.

The universe itself was an image of God,

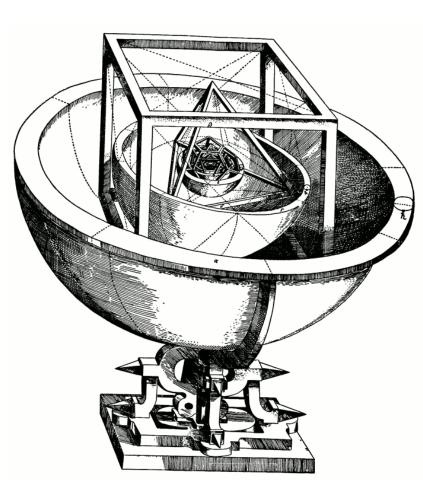
- His first manuscript of Mysterium contained an extensive chapter reconciling heliocentrism with biblical passages that seemed to support geocentrism.[[]
- Kepler never relinquished the Platonist polyhedral-spherist cosmology of Mysterium Cosmographicum.
- His subsequent main astronomical works were in some sense only further developments of it,



Modern astronomy owes much to

Mysterium Cosmographicum

- Despite flaws in its main thesis, "since it represents the first step in cleansing the Copernican system of the remnants of the Ptolemaic theory still clinging to it." (Dryer)
- Especially when dealing with the geometry of the universe, Kepler consistently utilizes Platonic and Neo-Platonic frameworks of thought.
- The entirety of the polyhedral idea is based on the same "formal cause" postulated by Plato for the structure of the universe.
- In an argument from design, Kepler postulates the existence and necessity of God the Creator as this "efficient cause



Astronomia Nova

Full title:

Astronomia Nova AITIOΛΟΓΗΤΟΣ seu physica coelestis, tradita commentariis de motibus stellae Martis ex observationibus G.V. Tychonis Brahe

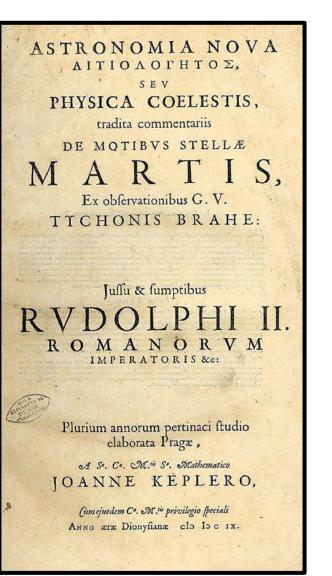
Published 1609

One of the most important works of the Scientific Revolution

Reports Kepler's 10 year long investigation of motion of planet Mars.

In addition to providing strong arguments heliocentrism, it describes the motion of planets, incl. elliptical shape of orbits

- first 2 laws of Kepler



Astronomia Nova

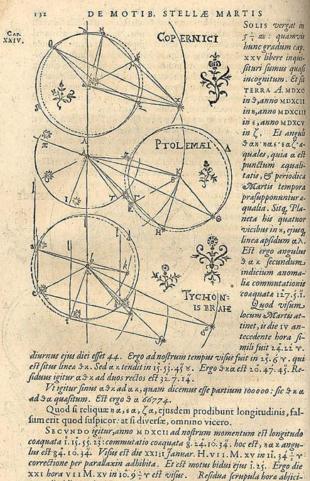
Published 1609

One of the most important works of the Scientific Revolution

In addition to providing strong arguments heliocentrism, it describes the motion of planets, incl. elliptical shape of orbits:

- first 2 laws of Kepler:
 - 1. The orbit of a planet is an ellipse with the Sun at one focus.
 - 2. A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time.

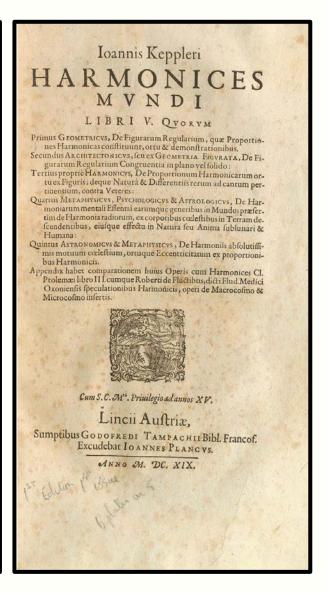
(planets do not move with uniform speed along their orbit).



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Harmonices Mundi

- Harmony of the World
- Published 1619
- In a sense return to Pythagoras'
 "Music of the Spheres". However, not based on numerology, but on Geometry !
- Kepler discovered physical harmonies in planetary motion:
 - difference maximum minimum angular speeds of a planet approximates harmonic proportion
 - eg. the maximum angular speed of Earth as measured from the Sun varies by a semitone (ratio: 16:15)

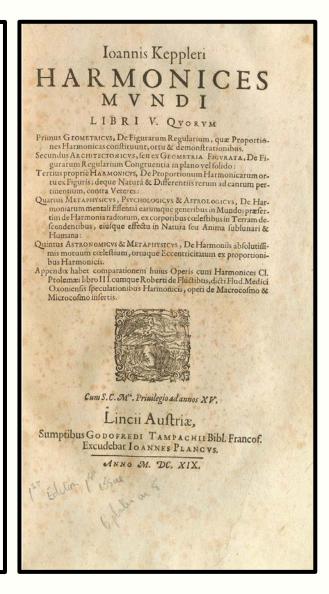


Harmonices Mundi

- Harmony of the World
- Published 1619
- Musical harmonies for arrangement and motion of heavenly bodies
- Celestial choir:

soprano
alto
alto
tenor
tenor
bass

- Mercury large elliptical orbit
 - greatest number of notes
- Venus orbit nearly a circle
 - only a single note

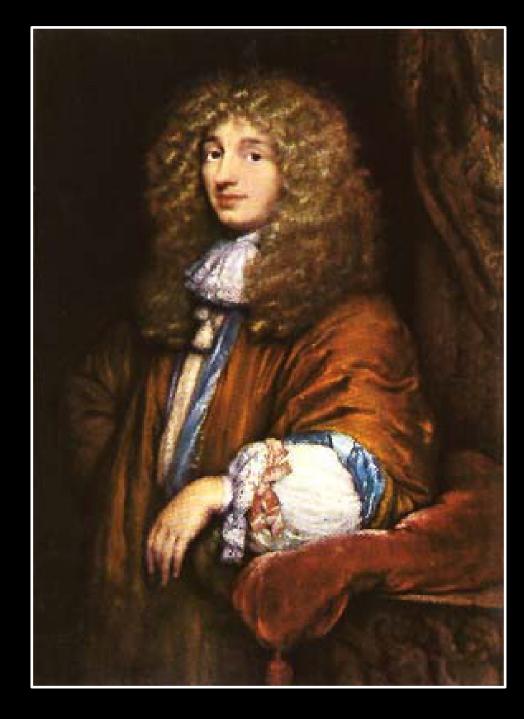


Harmonices Mundi

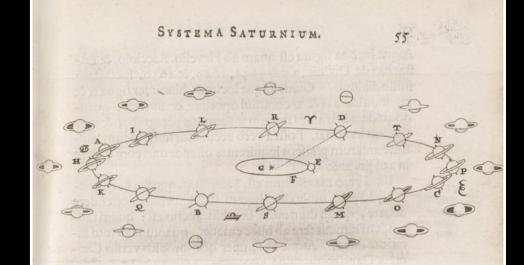


Christiaan Huygens

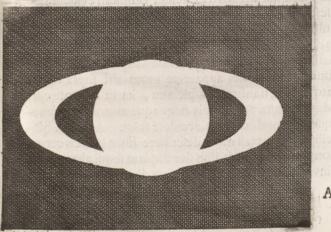
(1629-1695)





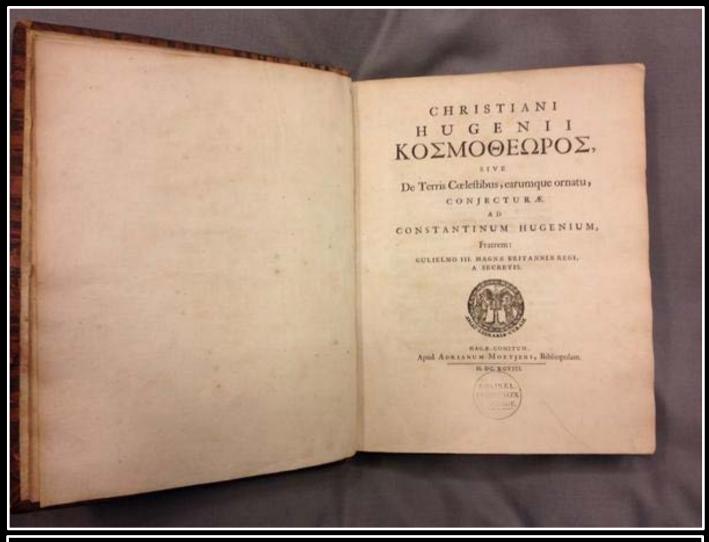


Cujus phaseos vera proinde forma, secundum ea quæ supra circa annulum definivimus, ejus modi erit qualis hîc delineata cernitur, majori ellipsis diametro ad minorem se habente fere ut 5 ad 2.



Atque

Cosmotheoros



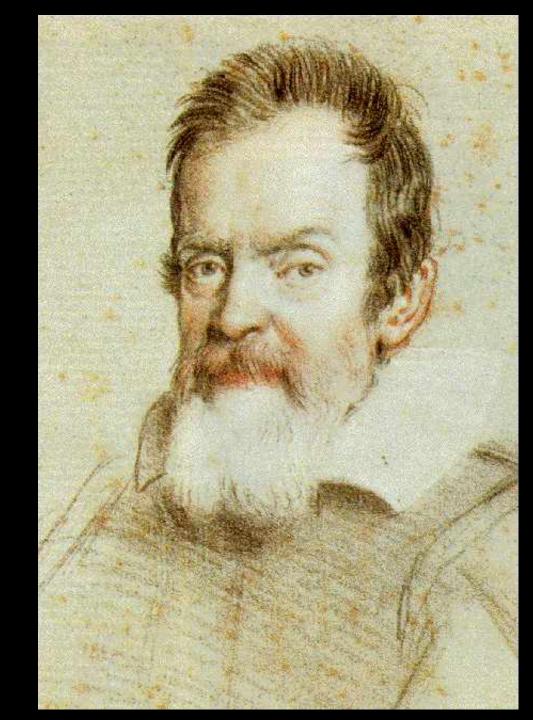
1695-1698:

- Speculation on the existence of extraterrestrial life
- Identification (liquid) water as main condition for the emergence of life
- Method for estimating distances

Galileo Galilei

(1564-1642)

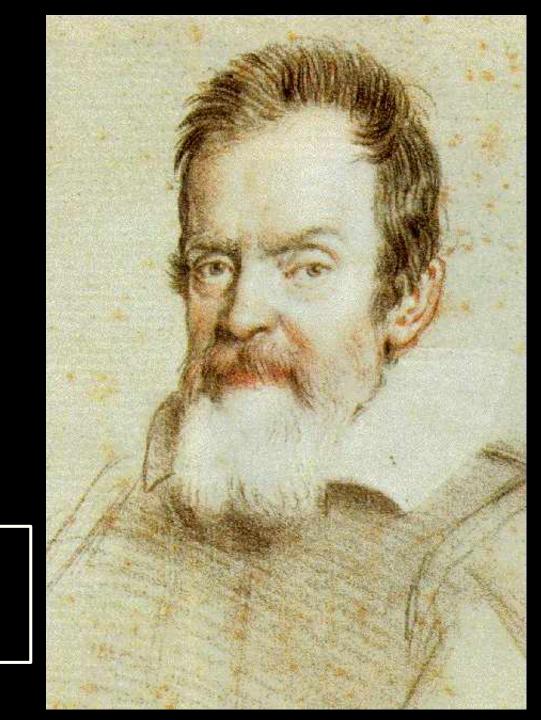
(Pisa-Arcetri)



Galileo Galilei

(1564-1642)

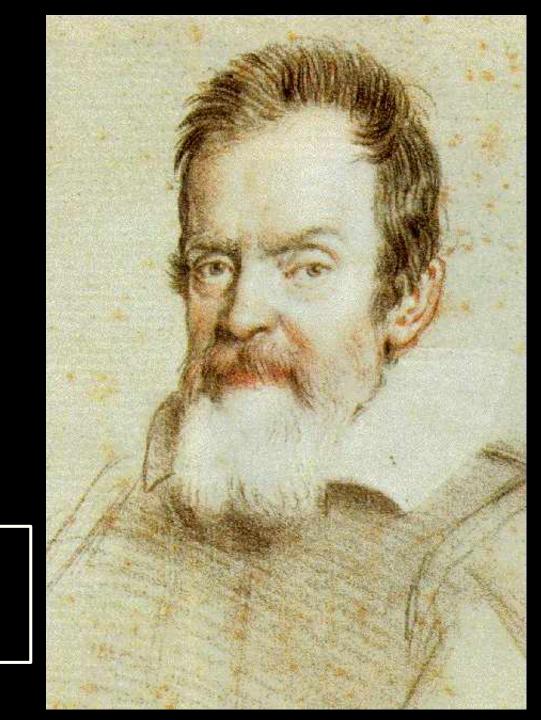
father of observational astronomy father of modern physics father of scientific method



Galileo Galilei

(1564-1642)

astronomer, physicist, engineer, philosopher, mathematician



Telescope (1609)

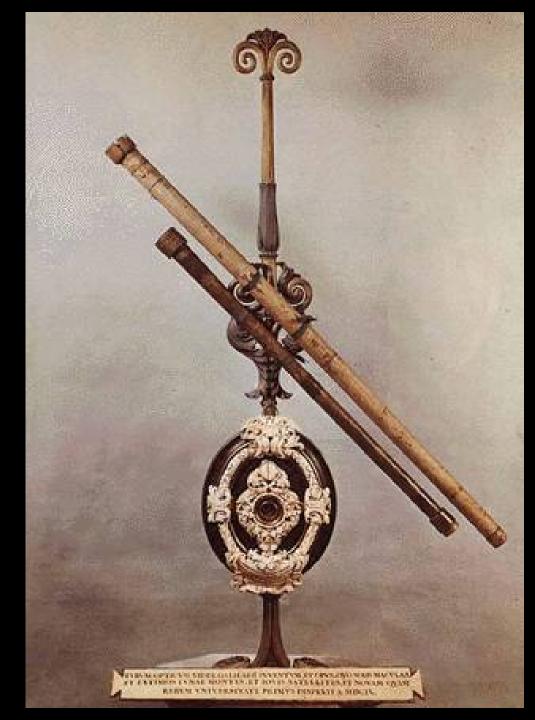
Following vague descriptions of the patent for a telescope by Lippershey in the Netherlands (1608),

basically 2 lenses in line cause a magnification,

Galilei developed his own telescope in 1609:

- 3 x magnification
- 30 x magnification (later).





Siderius Nuncius

1610

Starry Messenger

Publication of initial telescope astronomical observations.

SIDEREVS NVNCIVS

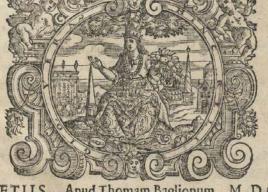
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PERSPICILLI Nuper à se reperti beneficio sunt observata in LVN- & FACIE, FIXIS IN-NVMERIS, LACTEO CIRCVIO, STELLIS NEBVLOSIS, Apprime verò in

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VENETIIS, Apud Thomam Baglionum. M DC X. Superiornm Permiju, & Primilegio. M VIIII: 22.14.

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VIII. 11. 14.

- would take another 236 years before it was discovered as planet by Le Verrier
- Sunspots

- Contents:
- 70 drawings of
- Moon: real world of valleys & mountains 0

> 10 x number of stars

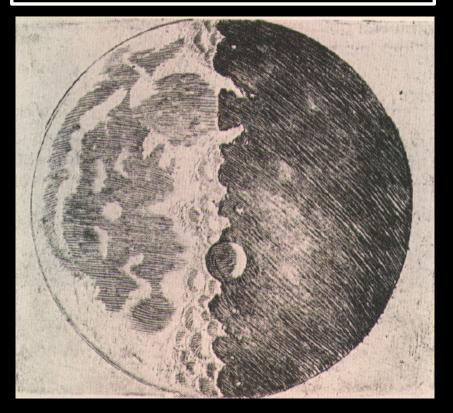
- Orion
- Pleiades:
 - Taurus than visible by eye
- Milky Way: congeries of innumerable stars 0 grouped in clusters
- Galilean Moons (Medicean stars):
 - illustrations of relative positions between Jan. 1610 - Mar. 1610
 - remain on same line: orbiting Jupiter
 - in conflict with Aristotelean cosmology (which states everything orbits Earth)
- Phases of Venus:
 - soid evidence for Venus and Earth orbiting the Sun
- Planet Saturn:
 - did not realize he saw rings, and thought Saturn was 3 objects
- Neptune
 - Galilei did see Neptune, but did not realize it was a planet

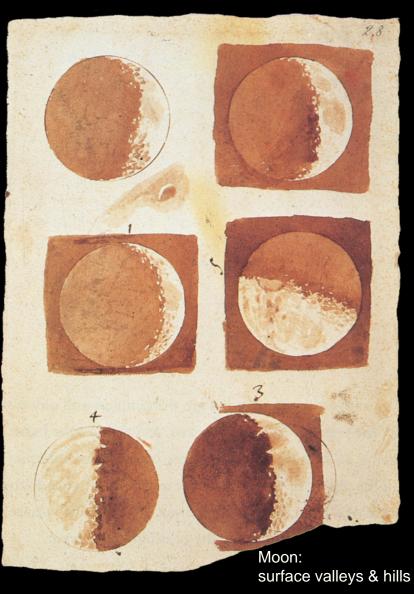
the Moon

Galilei's telescopic study of the Moon revealed it was a real world of its own,

with valleys, mountains, etc.

• Directly conflicting serene & perfect Aristotle's & Ptolemaic cosmology









Galilean Moons of Jupiter:

Ganymedes, **Io**, Callisto, Europa

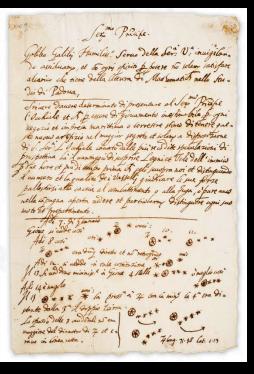
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Galilean Moons

Ganymedes, Io, Callisto & Europa:

discovery of their orbital motion, demonstrated that Earth was not the only center in the Universe

directly conflicting Ptolemaeic and Aristotle's cosmology



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Phases of Venus

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Phases of Venus

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Evidence for heliocentric Universe:

- Phases of Venus correlated with size of Venus' disk
- Full Venus: small disk
- New Venus: large disk

Dialogue concerning the two chief world systems

(1632)

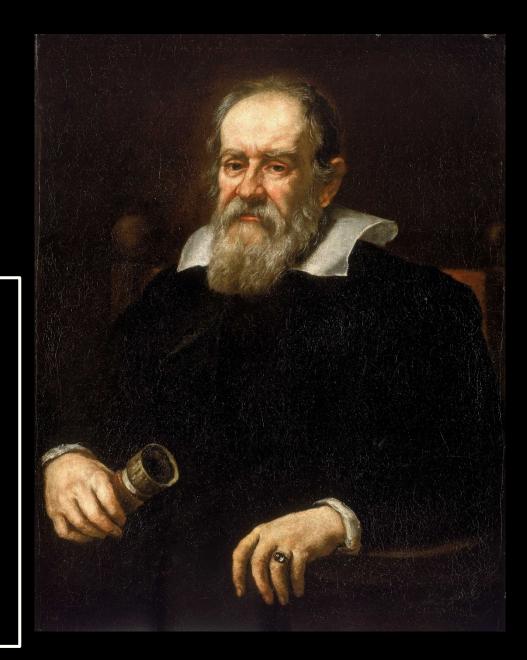
Latin: Systema Cosmicum

book comparing the Copernican system with traditional Ptolemaic system

- Stated intention was to be objective.
- However, could not hide Galilei's conviction that Copernican system represented the physical reality
- book considered attack on Aristotelian geocentrism
- also insulted the pope

1633:

- Galilei accused of heresy
- Dialogo on Index of Forbidden Books (until 1835)
- Galilei narrowly escapes torture
- house arrest for the rest of his life.





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 fi discorre fopra i due

MASSIMI SISTEMI DEL MONDO TOLEMAICO, E COPERNICANO;

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

CON PRI



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IN FIORENZA, Per Gio:Batifta Landini MDCXXXII.

CON LICENZA DE' SVPERIORI.

Galilei facing the Roman inquisition

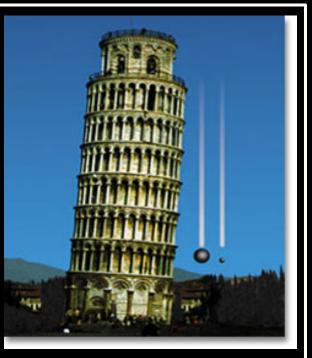
Galileo Galilei

Scientific significance stretches to at least 2 other main aspects:

- Physics
- Scientific Method

Physics

- velocity & speed, gravity,
- free fall
- principle of relativity
- inertia
- Pendulums & Hydrostatic balances
- Thermoscope



tower of Pisa: heavy objects fall equally fast as light objects



Galileo Galilei

Scientific significance stretches to at least 2 other main aspects:

- Physics
- Scientific Method

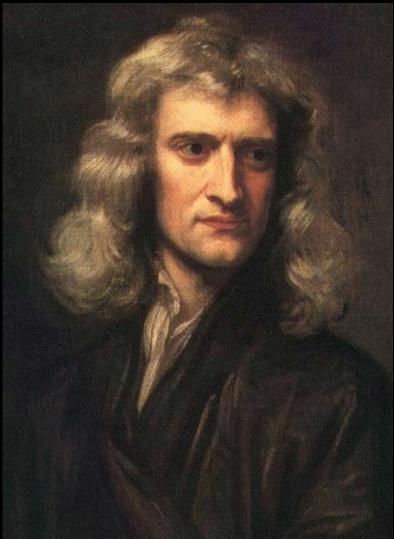
Scientific Method

- Innovative combination Experiment Mathematics
- Laws of Nature are mathematical
- in book "The Assayer":
- "Philosophy is written in this grand book, the universe ... It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures;..."
- Appreciation proper relationship mathematics, theoretical physics & experimental physics



Isaac Newton (1643-1727)

"If I have seen further it is by standing on the shoulders of giants "



Isaac Newton

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FI

Birthhouse Woolshorpe



PHILOSOPHIÆ NATURALIS PRINCIPIA MATHEMATICA

Autore J S. NEWTONG Trin Coll. Cantab. Soc. Mathefeos Professore Lucasiano, & Societatis Regain Sodali. el Schube Regin locietates preside

> IMPRIMATUR. S. PEPYS, Reg. Soc. PRÆSES. Julii 5. 1686.

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Juffu Societatis Regiæ ac Typis Josephi Streater. Proftat apud plures Bibliopolas. Anno MDCLXXXVII.

Isaac Newton

(1642 - 1726)

Newton's Laws of Motion

Newton's 1st Law:

zero force - body keeps constant velocity

$$\vec{F} = 0 \implies \vec{v} = cst.$$

Newton's 2nd Law:

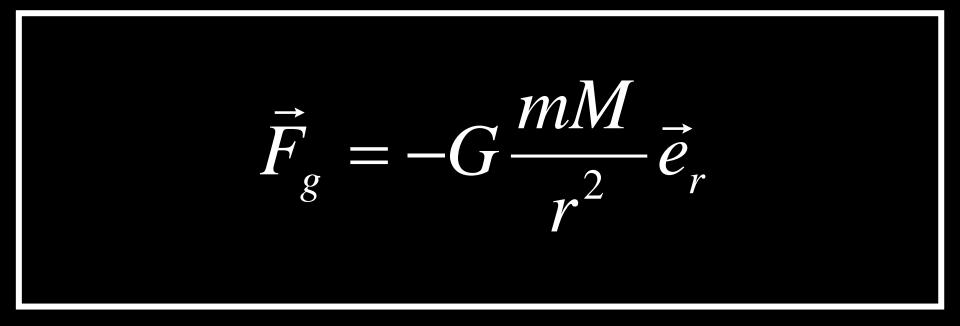
force = acceleration x mass = change of velocity x mass

$$\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt}$$

Newton's 3rd Law: action = reaction

$$\vec{F}_a = -\vec{F}_b$$

Newton's Gravity



If I have seen further it is by standing on the shoulders of giants.

Isaac Newton