ASTC25

Lecture 1-2
Planetary Systems.

Course details and
Historical overview until Newton

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Physical and Environ. Sci. UTSC
& Dept. of Astronomy and Astroph. UofT

https://planets.utsc.utoronto.ca/~pawel/ASTC25

ASTC25 - Astrophysics of Planetary Systems

Introducing the lecturer: Pawel Artymowicz

[guide to Polish pronunciation: substitute w → v, z → h,
neglect some diacritical marks & viola... things become readable.]

My milestones, for those of you who want to see en example of scientific career in academia:

- 5 years undergraduate Physics + Astronomy, Univ. of Warsaw, Poland
- 4 years graduate study at the Space Telescope Science Institute, Baltimore, MD, U.S.
- PhD from Polish Acad of Sci. in 1990
- 3 years: postdoctoral NASA Hubble Fellow at Univ. of California, Santa Cruz (UCSC)
- 11 years: senior researcher, asst. then assoc. prof. in Stockholm Obs., Stockholm University, Sweden
- 19 years: full tenured prof. of Physics and Astrophysics at UofT

My areas of expertise:

- Planetary systems, origins:
  - Dusty disks like β Pictoris, dust avalanches, dust disk instabilities
  - Migration of protoplanets in disks
  - Flow of gas around planets, numerical hydrodynamics (CFD)
- Young binary stars
- Galactic dynamics, black holes and active galactic nuclei
- Supercomputers and their parallel programming using both CPUs & GPUs (you can take PHYD57 in the Fall of 2024)
- Aerodynamics and aviation (FAA & TC pilot; investigated a 2010 airliner crash to assist Polish authorities)

Organization of the course (2024)

Where to look for course information: syllabus, home assignments, contact information and such.

- **Do not randomly google ASTC25 or search for syllabus on Quercus or UTSC net.**

  Chances are you'll find old or irrelevant information. Lecturers of ASTC25 change often.

  Make a bookmark to the correct course home page below, and every week re-download

  the syllabus and lecture notes from the course page.
- Quercus only for announcements, exam files during exam, and for submission of your work (assignments) and viewing the marked term work (not exams; exams are in-person)
- Web page of ASTC25 - policies, grading scheme, assignment texts, contact information, lecture notes, extra books and links & other materials. Read it please.

https://planets.utsc.utoronto.ca/~pawel/ASTC25

- We do sometimes suffer power & network outages, scheduled and unscheduled, close to a deadline or exam. Server 'planets' may be down for a day or two. Your periodic downloads from the course webpage will be a life-saver on such occasions.

- Your TA marker is Hamid Moezzi-Rafie (h.moezzi@mail.utor...). Ask TA questions related to assignments; when unresolved – ask me.

- Please ask freely any questions during the lecture, or wait till the

- Office hour: walk with me to SW506G (5th Phys/Astro floor) between the lectures & tutorial or after tutorial
- Send email about individual matters to me at either pawel@utsc.utoronto.ca or pawel.artymowicz@utoronto.ca

If you have a fever or cough, please respect the health of others & do not come into the building for either a lecture, tutorial or exam.

Recorded information from 2023 lectures will be found on Quercus.

Outline of course ASTC25, Astrophysics of Planetary Systems
Find more detailed syllabus on our course page
https://planets.utsc.utoronto.ca/~pawel/ASTC25/

- Introduction to the course
- Antiquity to Newton - history of key ideas
- Gravitational mechanics of planetary systems, part I—III
  2-B problem, tides, precession, R3B,
  Roche lobes, orbital resonances, chaos
- Formation od planetary systems, part I :
  Solar nebula as accretion disk. Formation of disks and stars.
  Gravitational focusing, runaway growth of solid cores of planets
- Formation od planetary systems, part II : competing theories of giant planet formation

Mid-term exam (1 hr in class, 29 Feb) after L12 & the reading week

- Minor bodies of the Solar System: meteorites, asteroids, comets
- Planetary interiors and figures, surfaces of some Solar System bodies
- Elementary intro to atmospheric physics
- Planetary rings
- Extrasolar planetary systems, examples and methods of discovery
- Dusty circumstellar disks as exoplanetary systems
- Theories of migration of planets in disks
- Astrobiology and SETI: question of life in the Universe

Final exam in April (3 hr)

Lecture 1 **ASTC25**

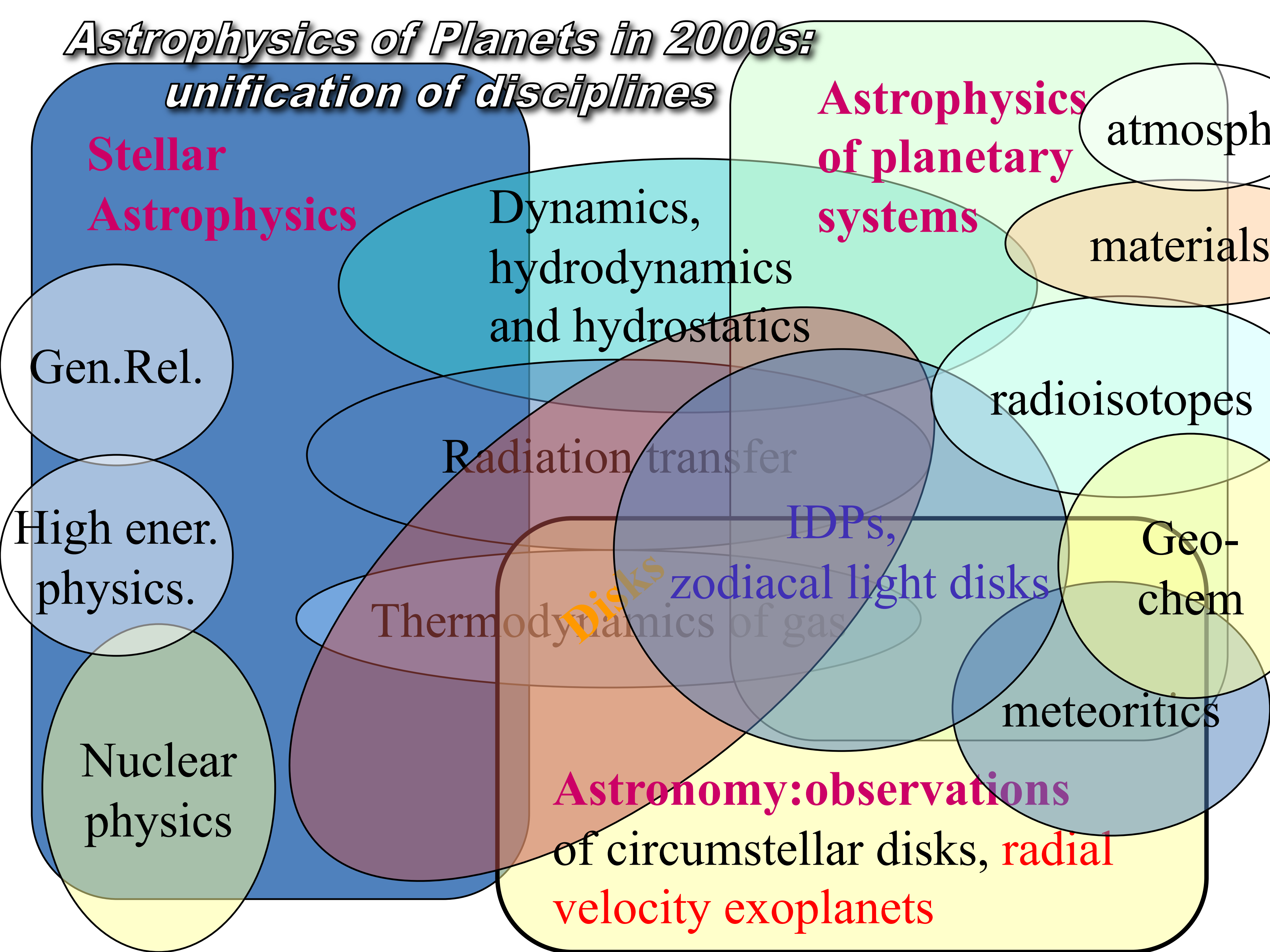
1. Planetary astrophysics as interdisciplinary union of physics and astronomy

2. History of some key techniques and the idea of "other worlds" in antiquity

3. Copernican scientific revolution

4. Laws of Kepler

5. Newton, friends/enemies & the story of his great scientific achievement: derivation of Kepler's laws from $1/r^2$ force law



Astrophysics of Planets in 2000s:
unification of disciplines
Stellar
Astrophysics
Astrophysics
of planetary
systems
atmosph
materials
Dynamics,
hydrodynamics
and hydrostatics
Gen.Rel.
radioisotopes
Radiation transfer
High ener.
physics.
IDPs,
zodiacal light disks
Geo-
chem
Disks
Thermodynamics of gas
meteoritics
Nuclear
physics
Astronomy:observations
of circumstellar disks, radial
velocity exoplanets

EXAMPLES OF FUNDAMENTAL QUESTIONS:

- **What's our Solar System like and how does it physically work?**

- **What's the connection between Kepler's laws & $1/r^2$ gravity force? Can one predict a position of a new, previously unseen planet?**

- **Are there any other planetary systems? How many? How do they look like? How to explain their similarities & differences with the Solar System? How to find them?**

- **How do planets form?**

- **The dusty disks around stars: planetary systems?**

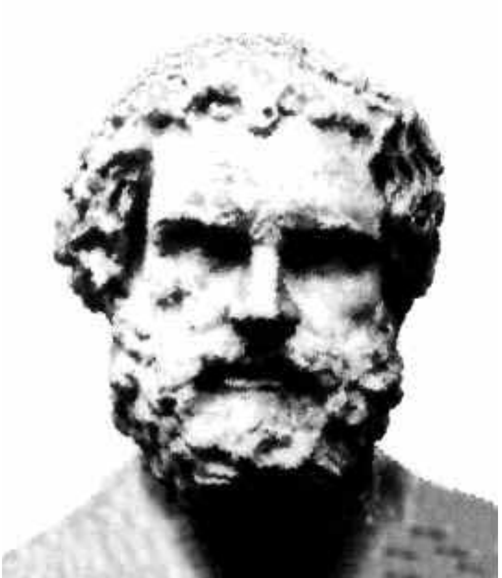
- **Do E.T.s exist?**

Already the Ancient... Classical Greece

One pre-Socratic school of ancient Greek philosophy had a surprisingly modern view of Nature, including star and planet formation. They were materialists and atomists.

Some of the earliest recorded physics was very far-sighted, modern in today's sense & essentially correct!

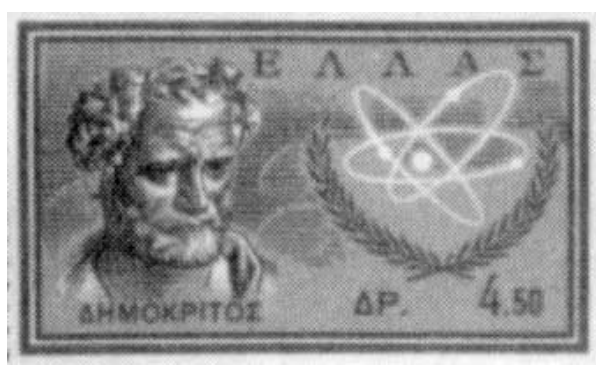
- Firstly, atomic theory emerged. This corresponds to elementary particles today, though they're no longer atoms, as we've split atoms 100 yrs ago
- Atomic theory *predicted*: evolution (formation/decay) of planets, the role of disks, and the diversity of "worlds" (planetary systems)



Λευκιππος (Leukippus, 5th cent. BC)

teacher of

Δεμοκριτος (Democritus, 460-370 BC)



Atomic doctrine was saw the world consist of two ingredients: atoms and vacuum, both equally real and necessary for motion and change, for infinite possibilities of association of atoms. All other phenomena and names we give them do not (independently) exist in Nature.

νόμωι (γάρ φησι) γλυκὺ καὶ νόμωι πικρόν, νόμωι θερμόν, νόμωι ψυχρόν, νόμωι χροιή, ἐτεῆι δὲ ἄτομα καὶ κενόν

"By convention sweet and by convention bitter, by convention hot, by convention cold, by convention color; but in reality atoms and void."*

(Demokritos, accord. to Tetralogies of Thrasyllus, 9; Sext. Emp. *adv. math.* VII 135)

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*- or "We say (by convention) sweet, we say bitter, we say..."

Antique theory #1: Plurality of worlds

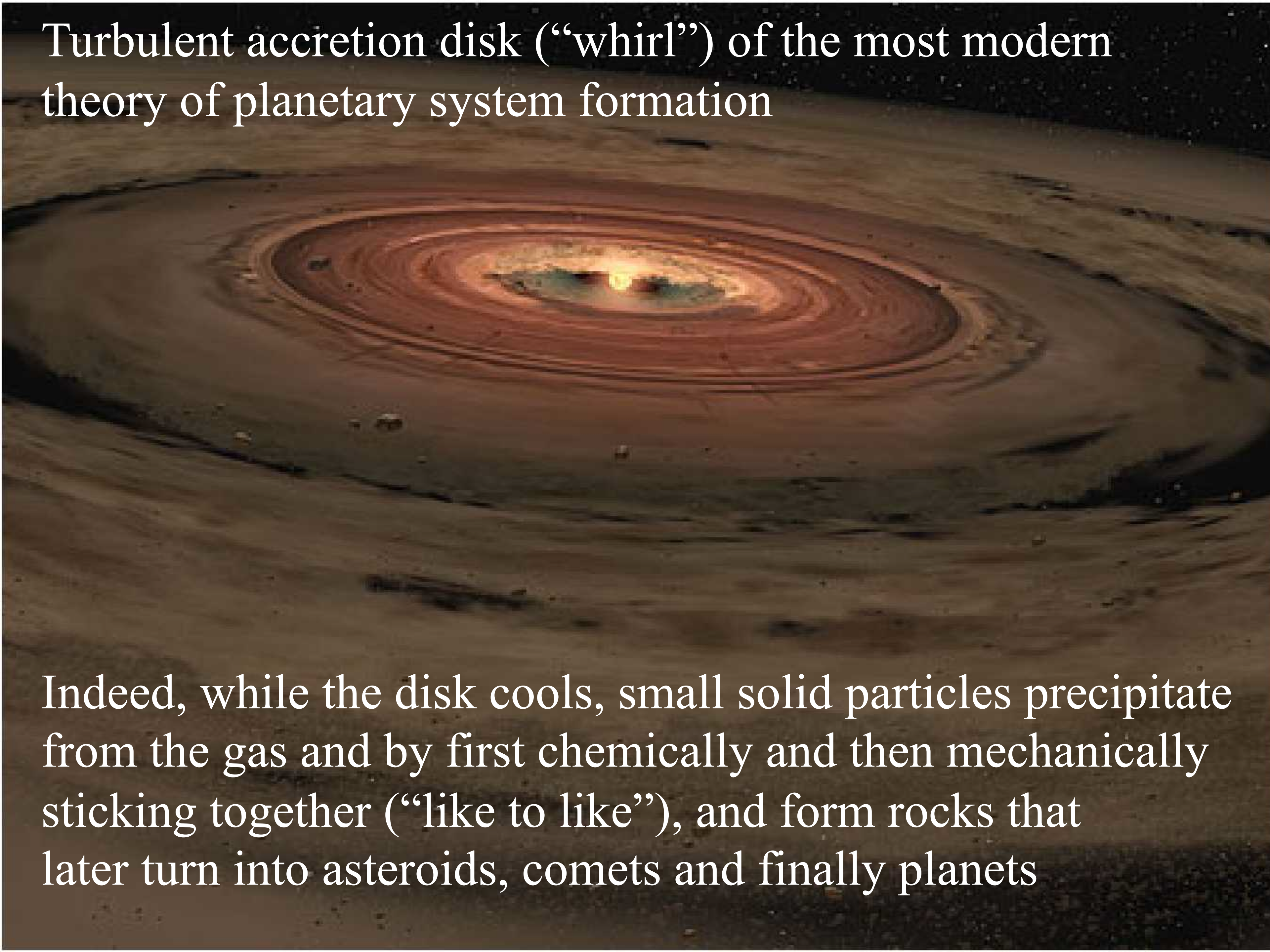
Kosmos: unique or multiple (infinite in number?).

Greek atomists Leucippus and Democritus considered the world built of the same (`solar abundance') atomic matter that forms the Earth, subject to constant motion through vacuum, collision, and coalescence (accretion).

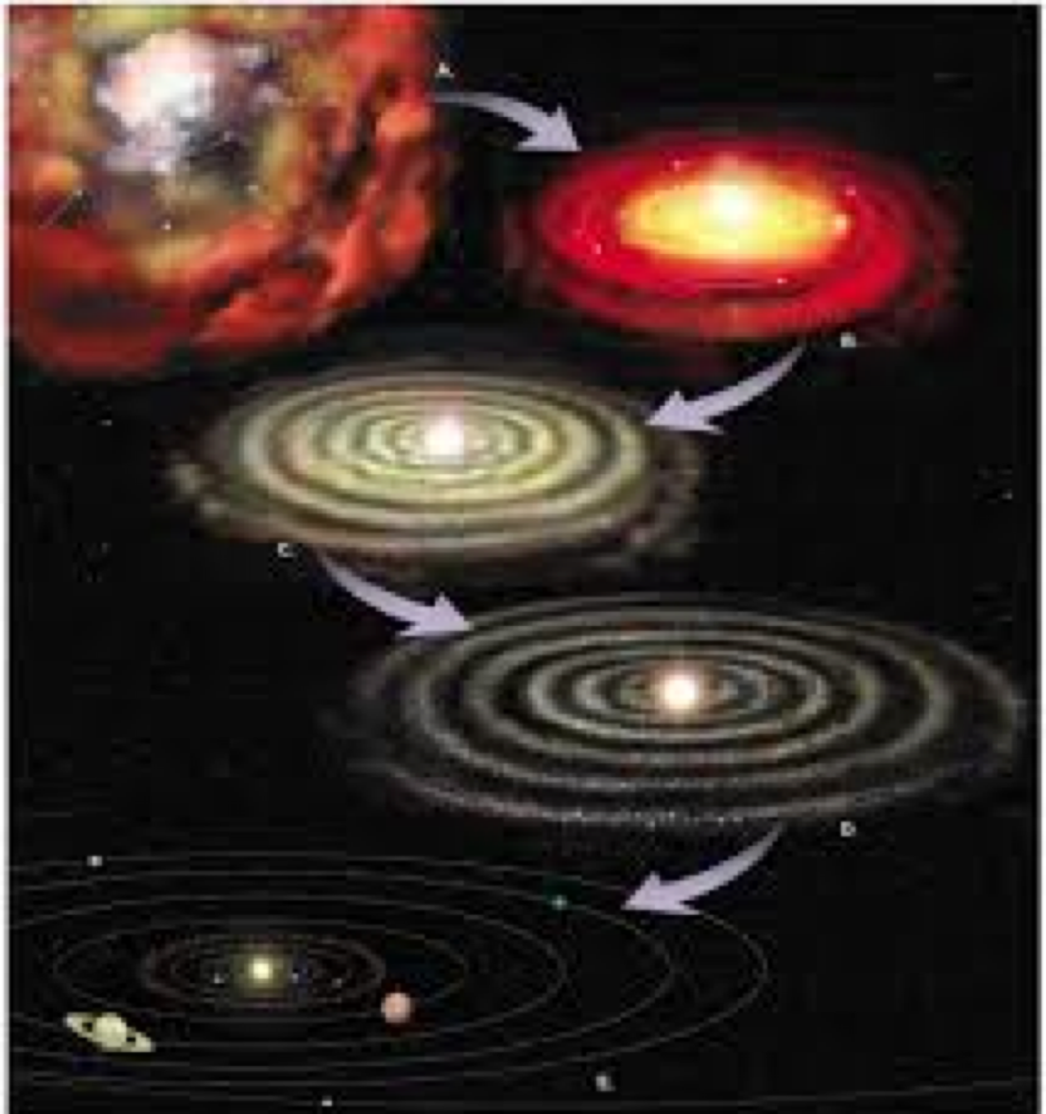
Who invented the so-called Kant-Laplace solar nebula: I. Kant & J. Laplace or Leucippus?

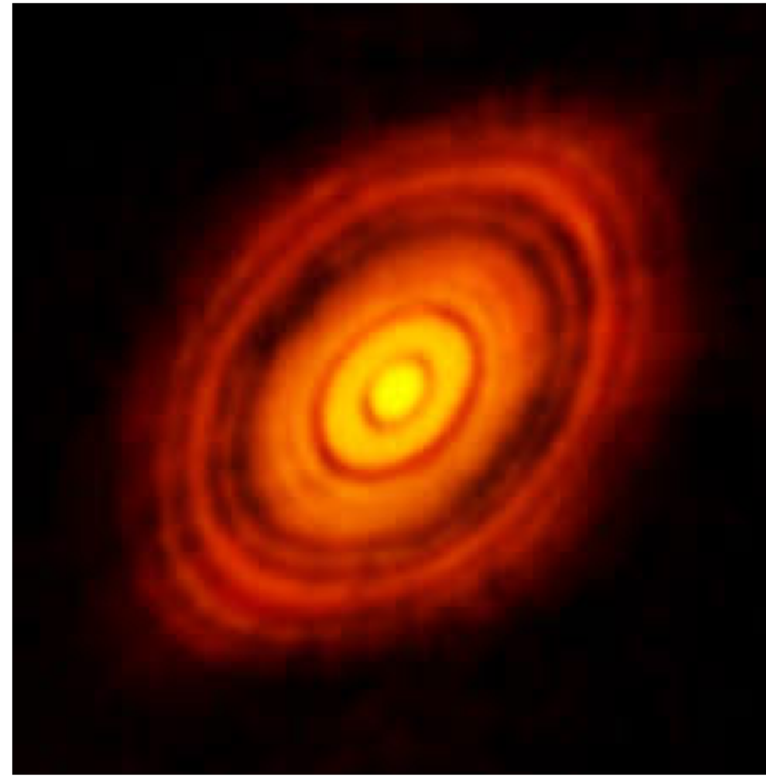
The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void;
they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like to like.

Leucippus (480-420? BC), after Diogenes Laertios (3rd century AD)


Turbulent accretion disk ("whirl") of the most modern theory of planetary system formation
Indeed, while the disk cools, small solid particles precipitate from the gas and by first chemically and then mechanically sticking together ("like to like"), and form rocks that later turn into asteroids, comets and finally planets

Modern "whirls" (schematic stages vs. recent observations)





The first detailed picture of a young planetary system: HL Tauri
(ALMA observatory, 2014)

The earliest consideration of worlds (planets) around pulsars and binary stars; evolutionary aspect stressed; hot planets predicted.

In some worlds there is no Sun and Moon, in others they are larger than in our world, and in others more numerous. In some parts there are more worlds, in others fewer (...); in some parts they are arising, in others failing. There are some worlds devoid of living creatures or plants or any moisture.

Democritus (ca. 460-370 B.C.), after Hyppolytus (3rd cent. A.D.)

Plurality and diversity of planetary systems reaffirmed:

There are infinite worlds both like and unlike this world of ours. For the atoms being infinite in number, as was already proven, (...) there nowhere exists an obstacle to the infinite number od worlds.

Epicurus (341-270 B.C.)

Later there were similar writings by **Lucretius (ca. 99-55 B.C.).**

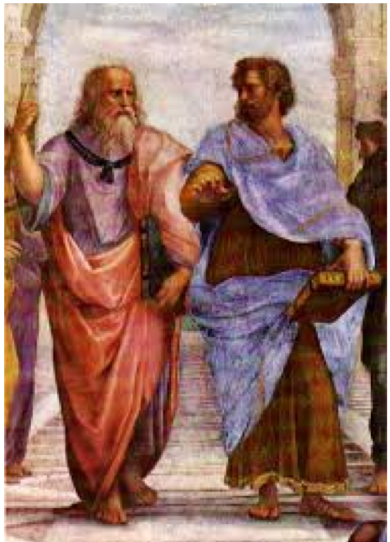
Antique theory #2: a unique terrestrial system

The atomist system was eclipsed by a cohesive system of **Aristotle (384-322 B.C.),** a student of **Plato** and tutor of Alexander the Great. He was not very interested in extrasolar planetary systems or other unobservable things. But (unfortunately) he was extremely influential after $1.5*10^3$ yrs. His world was geocentric, unchanging and unique.

The four elements moved each to their 'natural place' with respect to the center of the world. Existence of many such centers was unthinkable:

> *There cannot be more worlds than one.*
> Aristotle [*De Caelo*]

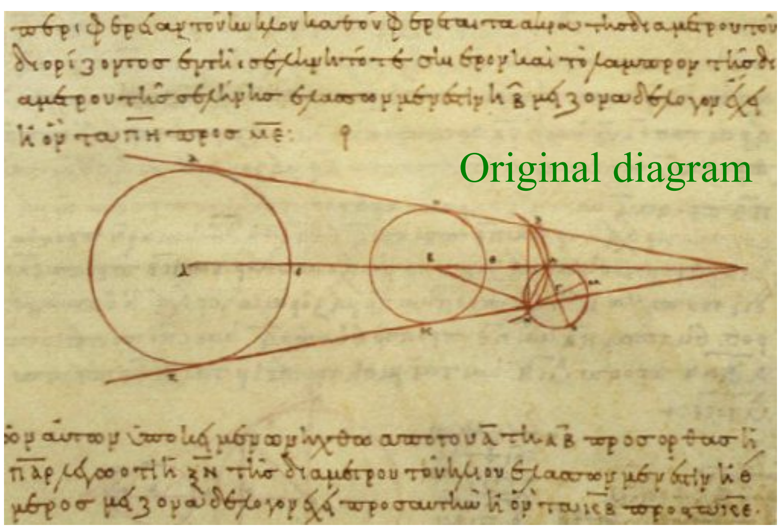
Schema huius præmissæ diuisionis Sphærarum.



Already the Ancient...

Greek astronomers in the Hellenistic Greece (period, which started in 323 B.C. when Alexander of Macedon died and his empire started fragmenting) possessed a fantastic ability to use the Geometry, much of which they first discovered (think of Ευκλιδες = Euclides, a.k.a. Euclid ~300 BC) in their study of the Solar System. They also began the Scientific Method, which fully bloomed 1500 years later...

You may wonder how the Ancient Greek scientists knew so much (pretty accurate distance & size of the Moon, size of Earth etc.). Let's look at Aristarchus of Samos (Αρισταρχος ο Σαμιος, 310-230 BC)



Original diagram

Fake depiction of the astronomer, and crater Aristarchus on the Moon

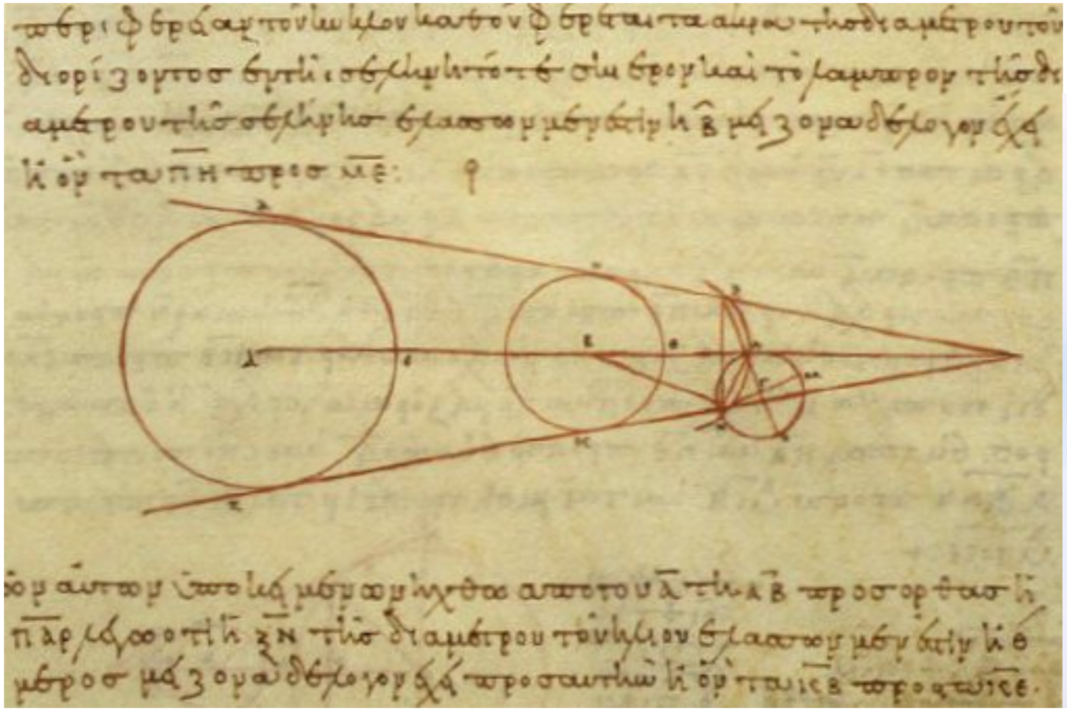
“Περὶ μεγεθῶν καὶ ἀποστημάτων [ἡλίου καὶ σελήνης]”

pron.: Perì megethôn k[a]ì apostēmátōn [h]ēlíou k[a]ì selḗnēs

“On the sizes and distances [of the sun and moon]”

The book written around 250 B.C., main work of Aristarchus of Samos, in which he calculates the quantities listed in the title. Unlike the Moon’s, the Sun’s distance was computed with a sizeable error due to one inaccurate input datum. This was corrected by Hipparcus, Eratosthenes and C. Ptolemaeus (Ptolemy). In the tutorial, you will step in Aristarchus’ shoes.. or sandals, to perform analysis similar to his.

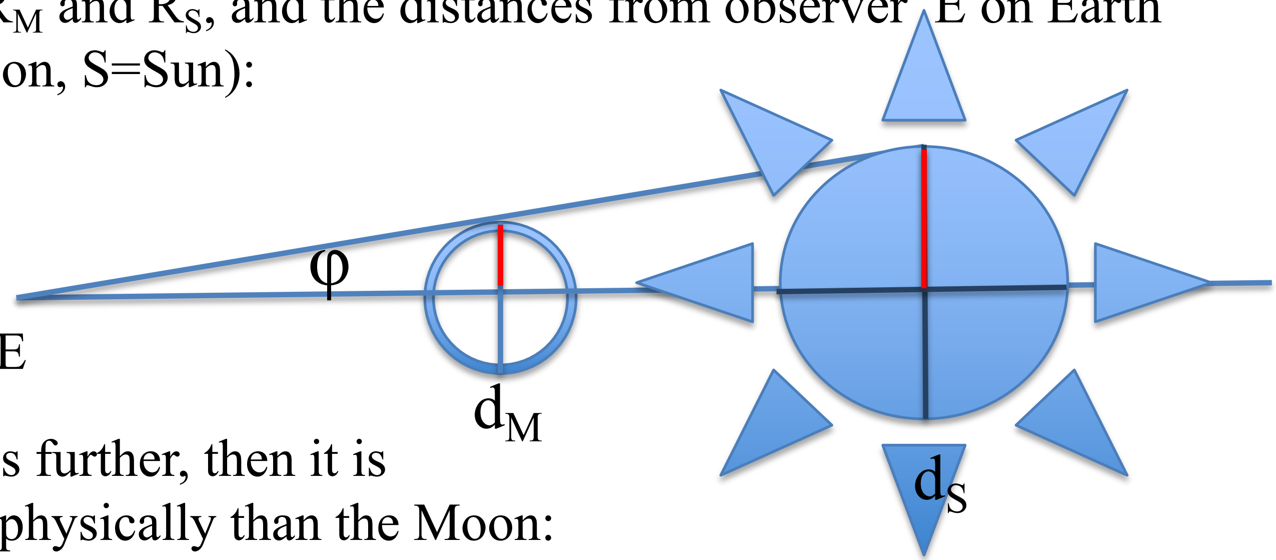
The original is lost, but there is a 10th century AD copy of the book.



STEPS IN ARISTARCHUS'S CALCULATIONS

1. From observations of **total solar eclipses**, we know that the angular sizes of sun and moon almost exactly coincide, and that the common angular radius is equal $\varphi = ½\ 0.53°$. The value of $\varphi = 0.255\ \pi/180$ in radians is a conversion factor between the physical radii R_M and R_S, and the distances from observer E on Earth d_M and d_S (M=Moon, S=Sun):

$$R_M = \varphi\ d_M$$
$$R_S = \varphi\ d_S$$



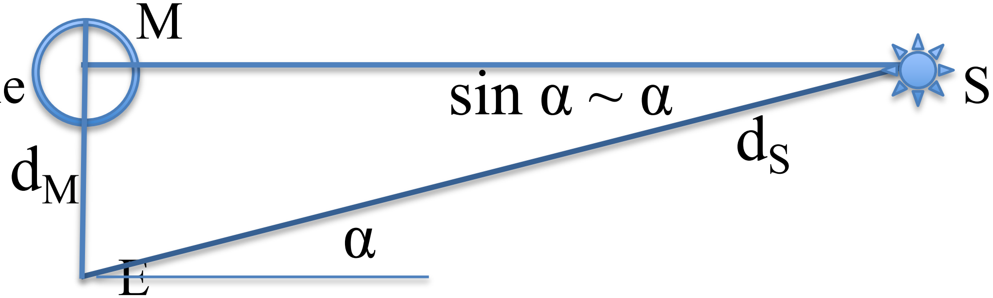
If the Sun is ξ times further, then it is also ξ times larger physically than the Moon:

$\xi = R_S/R_M = d_S/d_M$. This ratio was at first unknown, but Aristarchus was clever.

2. Sun/Moon size ratio ξ can be found from a careful observation of the Moon and Sun at the time of **exact half-Moon** provided one can measure the small angle

$\alpha \sim 9' = (9/60)°$ (modern value)

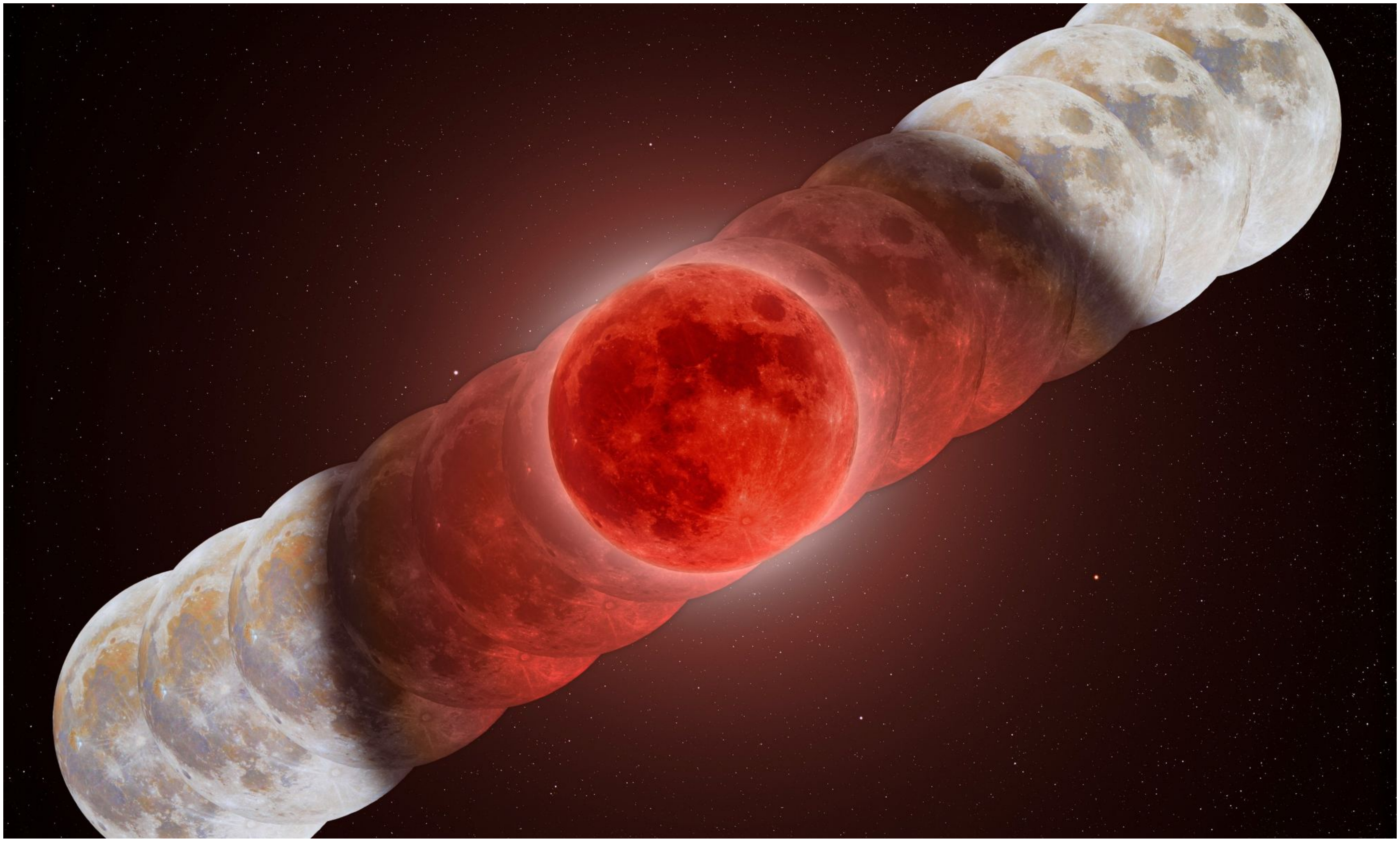
$\alpha \sim \sin\alpha = d_M/d_S = 1/\xi$



Substituting α in radians, we can get ξ.

Do it and you'll learn how much further there is to the Sun than to the Moon.

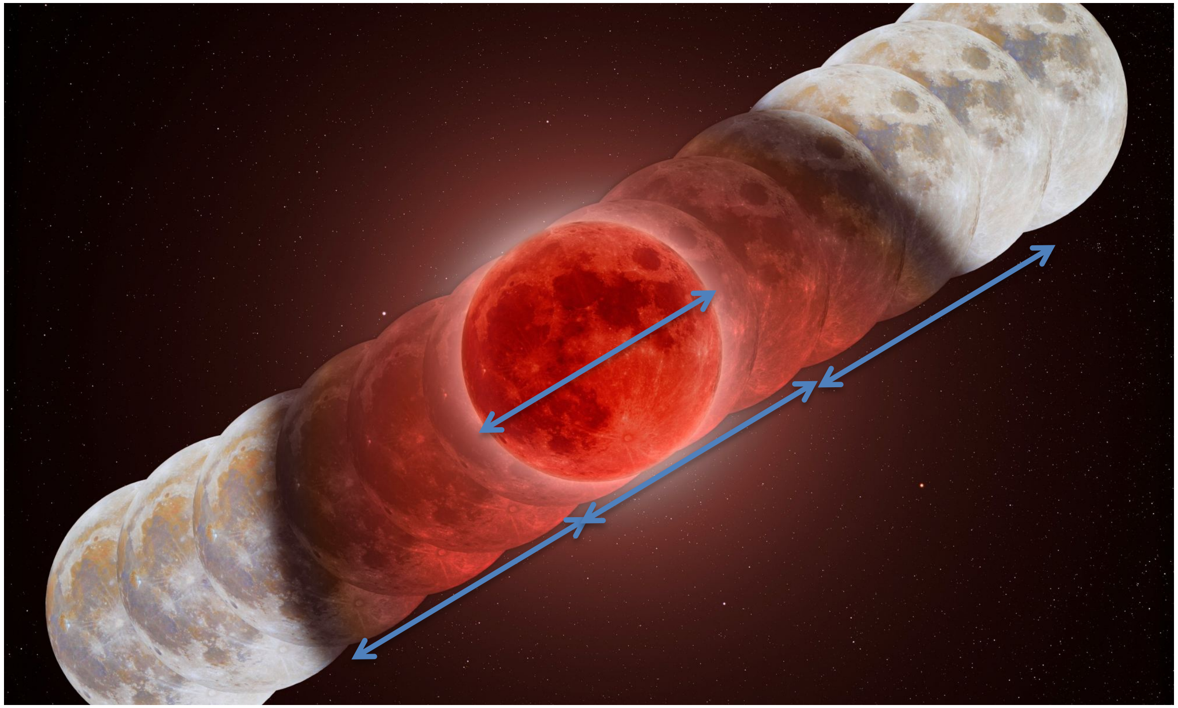
3. Finally, the 3rd observation invoked by Aristarchus is the **total lunar eclipse**. By the way, many ancient cultures including Greeks knew very well that the Earth is a sphere from such observations, showing a round outline of Earth's shadow.



Mosaic of snapshots, total eclipse of the Moon on Nov. 8, 2022 *(c) Andrew McCarthy*

STEPS IN ARISTARCHUS' CALCULATIONS

3. Finally, the 3rd observation invoked by Aristarchus is the **total lunar eclipse**.
The angular radius of the Moon is about 2.6 times smaller than the radius of Earth's shadow. Can you see this?
The arrows have equal length.

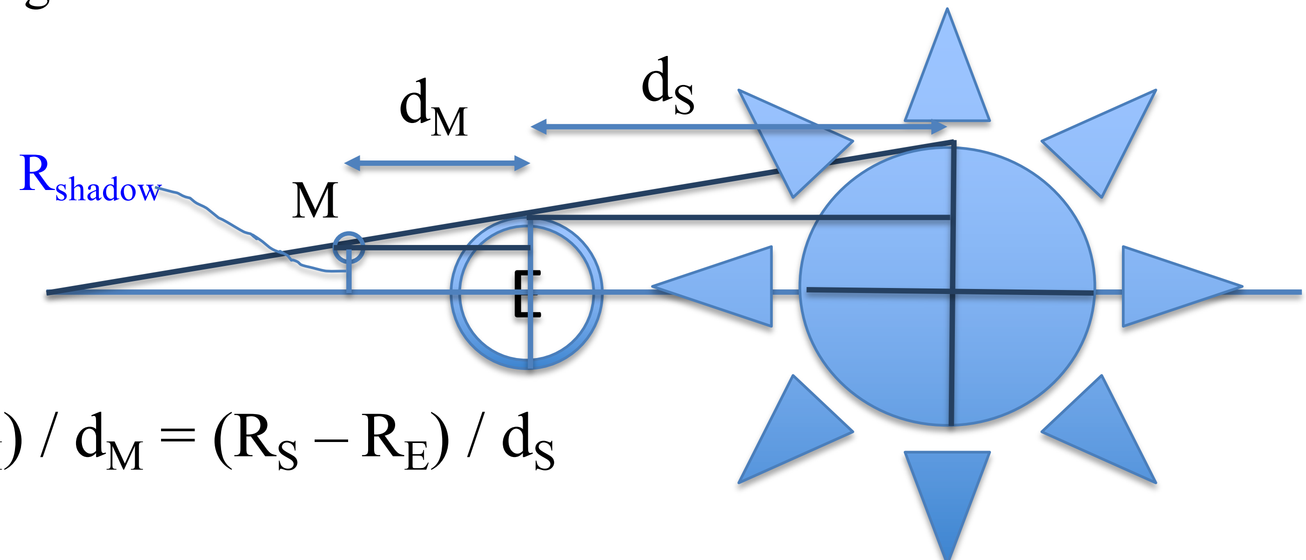


4. Moreover, Eratosthenes (Ερατοσθενες, 276-195 BC), chief librarian of Alexandria, computed an impressively exact radius of Earth from solstice observations at Syene where the sun reached zenith, and at Alexandria (800 km N of Syene), where shadows were cast at the angle of 7.2° to the vertical (1/50 of the full circle. Hence, the circumference of Earth must be 50*800 km = 40000 km. ➔ $R_E = 6366$ km. The actual value is 6357 km polar & 6378 km equatorial, or 6371 km on average, a difference of only 0.1%).

Great results of ARISTARCHUS'S CALCULATIONS with more modern inputs

3. From observations of **total lunar eclipse**, we know that
$R_{shadow} = 2.6\, R_M$. There are two (actually, more) similar triangles in the picture.

Exercise: First argue that



$$(R_E - 2.6\, R_M) / d_M = (R_S - R_E) / d_S$$

Then calculate from this:

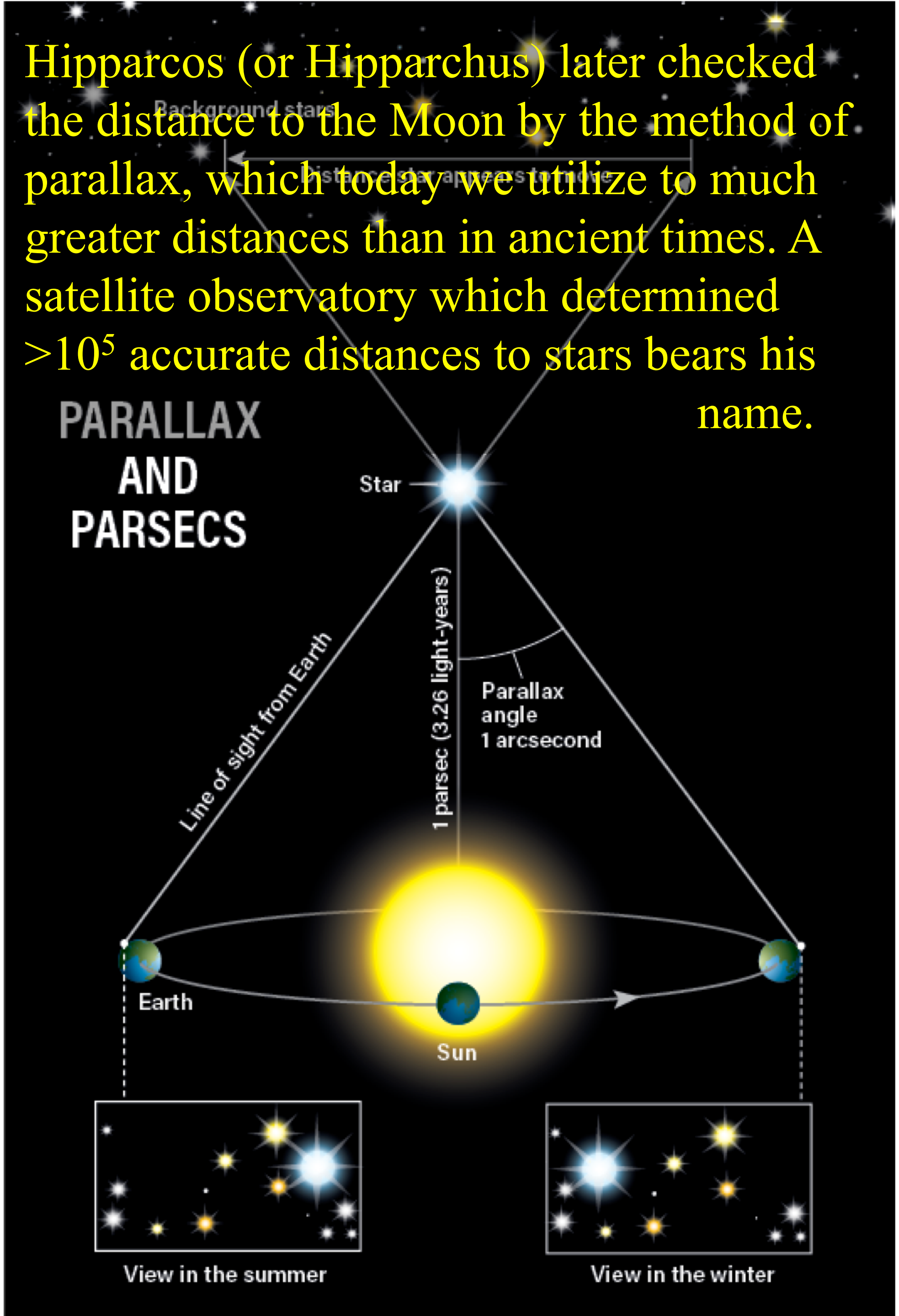
$R_M = R_E/3.6$
$R_M = 1770$ km
$d_M = 382600$ km

Those values agree very well with modern measurements. (today, we measure d_M by bouncing laser beams off mirrors left on the Moon's surface by American astronauts and by the Soviet Lunokhod rover)

Distance and size for the Sun follow from the factor ξ. We obtain $d_S = 149.2$ mln km, which is very close to the actual average distance 1 AU = 149.5 mln km.

All this and Aristarchus's reported heliocentric system (no extant works) demonstrated great mastery of astronomy and geometry by Hellenistic astronomers.

Hipparcos (or Hipparchus) later checked the distance to the Moon by the method of parallax, which today we utilize to much greater distances than in ancient times. A satellite observatory which determined $>10^5$ accurate distances to stars bears his name.



Digression: Parallax and parsecs

Daily parallax of the Moon is caused by Earth's rotation. Observer by moving sideways by 1 R_E (perpendicular to the line of sight) sees the Moon change the angular position on a stellar background by $R_E/d_M = 0.0166$ rad $= 0.95° = 57'$

Yearly motion of Earth around Sun and improved accuracy measured in units of arcseconds
($1'' = 1'/60 = 1/60$ of arcmin $= 1°/3600$)
allowed astronomer/mathematician Bessel in the 18th cent. to measure the distance to star 61 Cygni, equal 3.49 pc.

1 pc = 206265 AU; nearest stars are at ~1 pc. Definition:
1 AU at the distance 1 pc spans 1" (arcsec).
Parsec's name derives from:
parallax = 1 arcsecond at 1 parsec

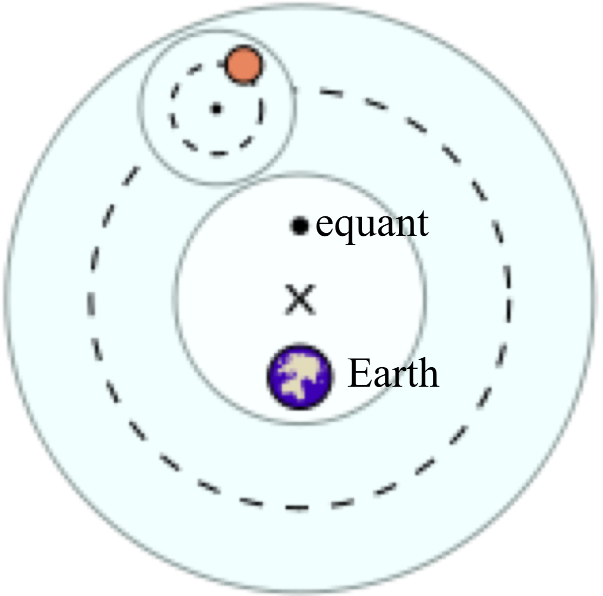
The Geocentric Model of the Universe in Ptolemy's "Almagest" (~140 AD or CE)

The best known astronomer of antiquity was Ptolemy (Claudius Ptolemeus, Πτολεμαῖος, 90-168 CE). He weakened the first principles of Aristotle by moving Earth a little off-center in his model, and by inventing a way to slightly vary the linear speeds. Motion on deferent was uniform, that is preserving constant angular speed, as seen from the so-called equant point (black dot in the figure). This made his model a better match to observed motions of planets in the sky.

Μαθηματικὴ Σύνταξις (*Mathēmatikē Syntaxis*), Magna Syntaxis, The Almagest, *al-majisṭī in Arabic*, or the "Great Treatise" was the first comprehensive astronomical textbook.

Some people said equant was "ugly" and some that it is not truly geocentric but rather geostatic. Save for actual practitioners, nobody much liked it.

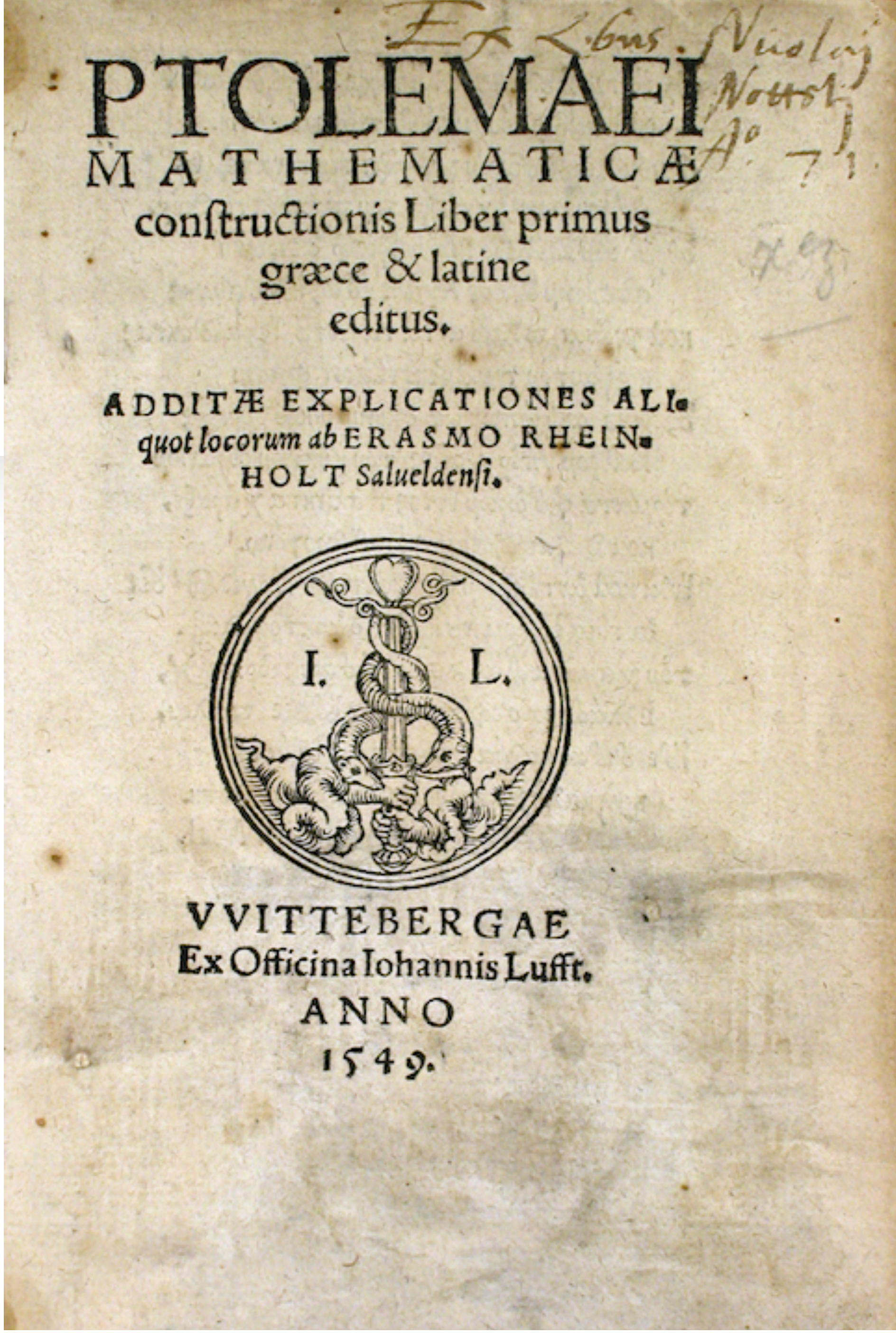
We will return to this issue and argue that the equant was, in fact, a surprisingly accurate construct.



The Geocentric Model of the Universe: Ptolemy's "Almagest" (~140 AD or CE)

Μαθηματικὴ Σύνταξις (*Mathēmatikē Syntaxis*)

- Latin translation, printer: Johannes Lusst (Wittenberg, 1549)
  - Almagest reads much like a work of modern science. In fact, the Hellenic period's science was already 'modern' by the virtue of using *scientific method*:
  - posing quite abstract theories/models, and then
  - proving/disproving them by observation (or experiment)



ARCHIMEDES AND HIS PALIMPSEST

palimpsest = parchment (calves skin) rubbed/erased to make space for a new text (medieval prayer book, in this case)

We don't know how Archimedes really looked. A fake portrait appears on the world's highest mathematical prize awarded by Fields Institute in Toronto (UofT)

Archimedes (Ἀρχῐμήδης, 287-212 BC) lived in the Greek colonial city of Syracuse, Sicily (Italy). He created the first laws of mechanics, such as the laws of the lever and pulleys, buoyancy etc. In mathematics, until recently he was celebrated for his calculation of the area of circle, area under the parabola, area and volume of the sphere and the ratio of volumes of a cylinder and an inscribed sphere. But in a recent investigation, we found out from a previously lost book (Codex C or Archimedes' Palimpsest) that he understood and used infinity and infinitesimals and limits in ways not supposed to have been known for another millenium. It seems that in order to derive areas and volumes, Archimedes was using what we now call Riemann integral, two thousand years before Riemann.

A mysterious mechanism probably designed in Archimedes's workshop in Syracuse, Sicily, was found by divers in a shipwreck near the Greek island of Antikythera in 1900.

ANTIKYTHERA MECHANISM, the first known (mechanical) computer

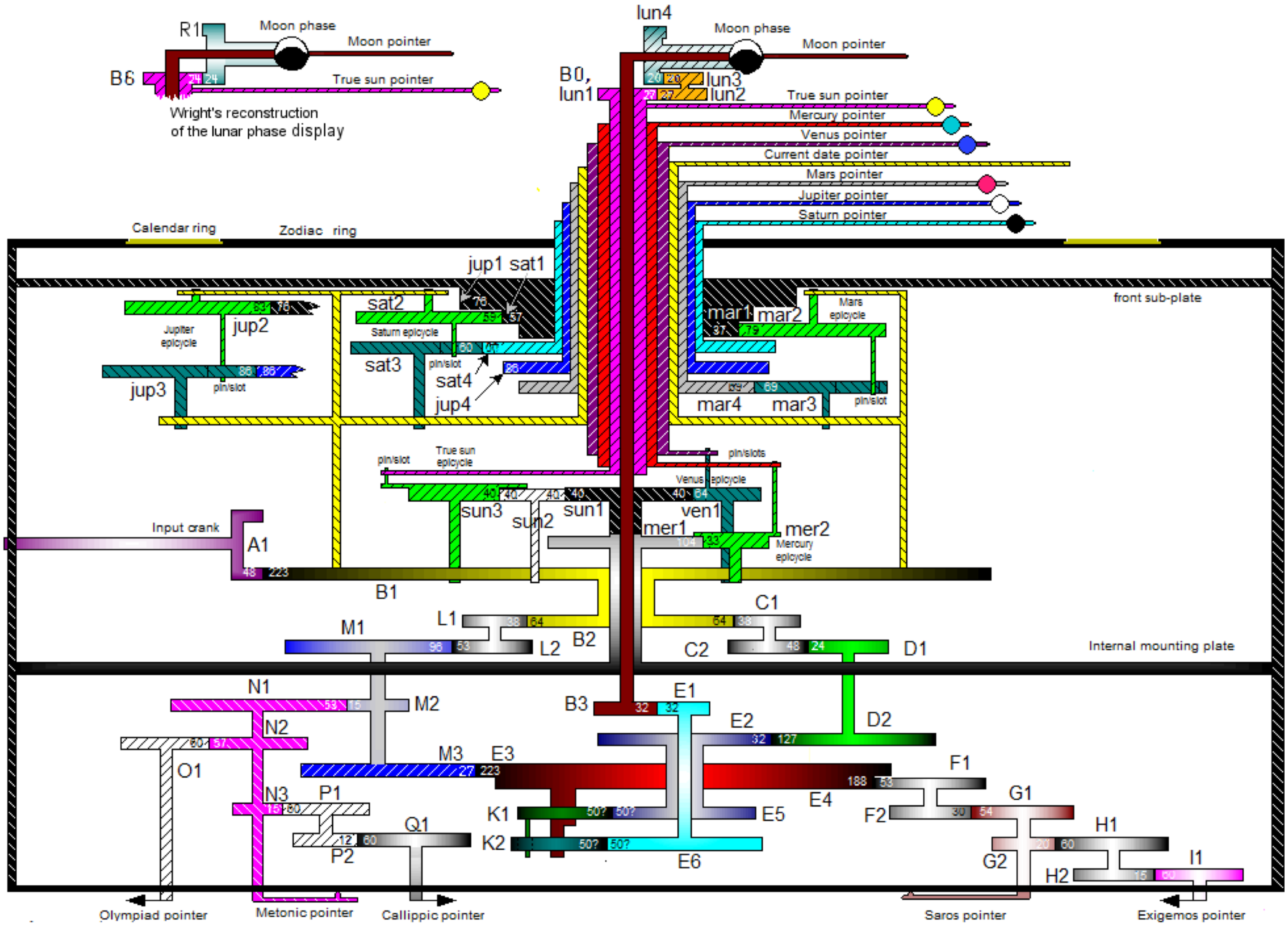
An ancient shipwreck was found a century ago near the Greek island called Antikythera, south of a bigger island of Kythera. Among the recovered items was a fragile, complicated set of tooth-wheels (remembering wrist-watch) that fits within a shoebox. It was recently 3D-scanned using X-rays in a specially built machine, in order to reveal the purpose of the strange apparatus.

It turned out to be a digital+analog calculator of future positions of planets on the sky, dates of movable holidays like the Olympiads, eclipses of the sun and moon (including their Saros cycle), lunar phases, and zodiacal signs.

It is a complex, special-purpose astronomical computer.

Parts of the machine are lost, but *functioning* replicas were built.

watch https://www.youtube.com/watch?v=MqhuAnySPZ0



Medieval theories: The pendulum starts swinging

Aristotle's work is rediscovered in 13th century, starts Renaissance in Europe.

For 100 years everybody agrees with the Philosopher on most issues.

Roger Bacon (1214-1292) at Oxford cites the argument about the impossibility of vacuum between the planetary systems. Similar thinking prevailed at other rising universities, like Sorbonne in Paris.

But the Aristotelian insistence on unity and uniqueness begun to contradict the Christian doctrine of the time.

In **1277 Etienne Tempier**, the bishop of Paris, condemned opinions based on 219 statements in Aristotelian writings, among them "that the First Cause cannot make many worlds".

The many-worlds opinion was hotly contested at the universities but prevailed, as was mandated by the Church under the threat of excommunication.

William of Ockham (ca. 1280-1347) supported the plurality of worlds.

But then begun a strong opposition to the idea. The religious critics pointed out that neither other worlds nor the creation of man elsewhere, were mentioned in the Scriptures.

William of Vorilong noticed the thorny question (for the Christians both 500 years ago and now) of Jesus Christ's status in extrasolar planetary systems:

> ***As to the question whether Christ by dying on this earth could redeem the inhabitants of another world, I answer that he is able to do this even if the worlds are infinite, but it would not be fitting for Him to go into another world that he must die again".***
>
> **William of Vorilong (ca. 1450)**

The heliocentric system of Nicolaus Copernicus (1543) was received as supporting the plurality of planets and their systems in the Universe.

Giordano Bruno explains his conviction about infinite number of terrestrial planets and the inhabitability of both planets and stars (non-selfluminous and self-luminous bodies) [*On the Infinite Universe and Worlds,* 1584].

In 1592, Bruno falls into the hands of Holy Inquisition, and in 1600 dies at the stake, but **not** because of his cosmological views.

Kepler did not believe that the stars making up the Milky Way (as surmised by Democritus and argued based on telescopic observations by Galileo) are of the same brightness or status as our sun, or that they have planets.

And so on... the pendulum of opinion was swinging until 1990s when observations finally settled the question.

If you want to know more about this subject, you may find these books interesting:

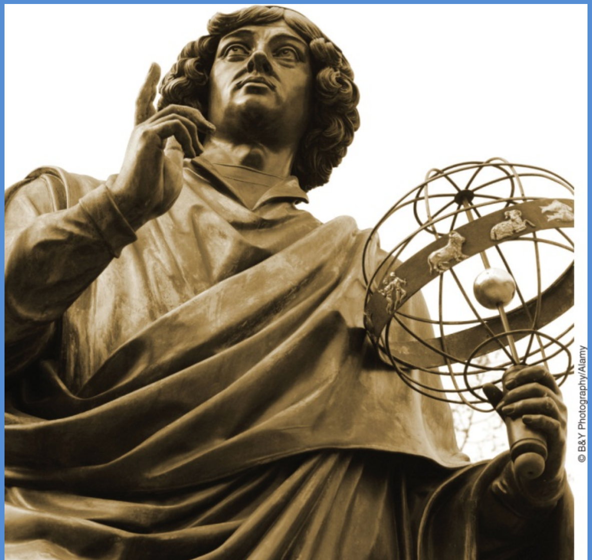
Diogenes Laertios "Lives of famous philosophers" (1st ed. ~250 AD)

S. J. Dick "Plurality of Worlds" (1982, Cambridge Univ. Press).

Nicolaus Copernicus (1473-1543)

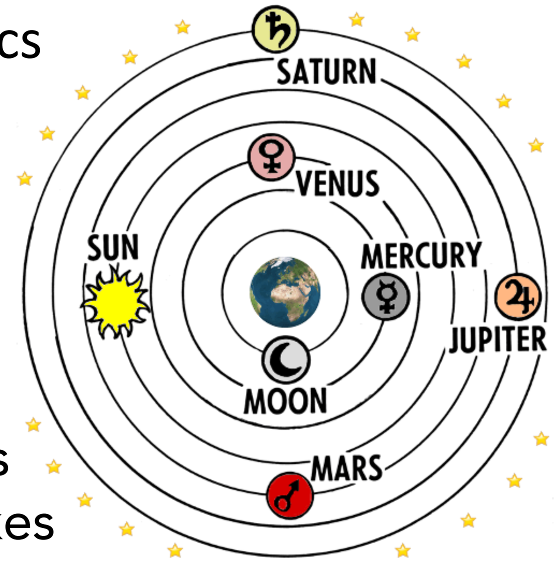
- Mikołaj Kopernik (*Latin:* Nicolaus Copernicus) was born in Toruń, Poland and lived in a region of Warmia that joined Poland.
- Supported by Prince-Bishop uncle (Lukas Watzenrode) Kopernik studied at University of Cracow, Poland, and later Univ. of Bologna, Padua and Ferrara in Italy
- Became the Catholic Church official: canon (church law expert)
- Organized defense of Frombork on the Baltic seashore from the Teutonic Knights
- Was a diplomat, physician, economist and polyglot

The 2008 forensic facial reconstruction – the grave was found in 2005 after centuries. DNA-identified, & re-buried 2010.



The universe: geocentric or heliocentric?

Throughout the middle ages and Renaissance, universities in their astronomy courses were teaching the Aristotelian Physics and Aristotelian ***geocentric*** cosmos. All the learned mathematicians/astronomers agreed on a unique, unchanging, eternal universe centered on Earth.



The opposing ***heliocentric*** (meaning sun-centered) *hypothesis* was known to many ancient philosophers: Pythagoras (who simply chose to believe it), Hipparchus (who, however, decided that the geocentric model makes more sense), and to Aristarchus of Samos who, as we discussed, proved that the Sun is a much much larger body than Earth & proposed heliocentric view with sun being the central fire in which Pythagoras was believing.
Thus the conjecture of a heliocentric cosmos was known in antiquity, though never popular.

BTW, Copernicus probably did not know Aristarchus' views in detail. The ancient texts were very rare, most were lost forever. Copernicus knew Aristarchus was a believer in a moving Earth. But it's doubtful if Copernicus read the only clear passage specifically about Aristarchus and his idea of a circular motion of Earth around the Sun, in one paragraph of "Sand Reckoner" by Archimedes.

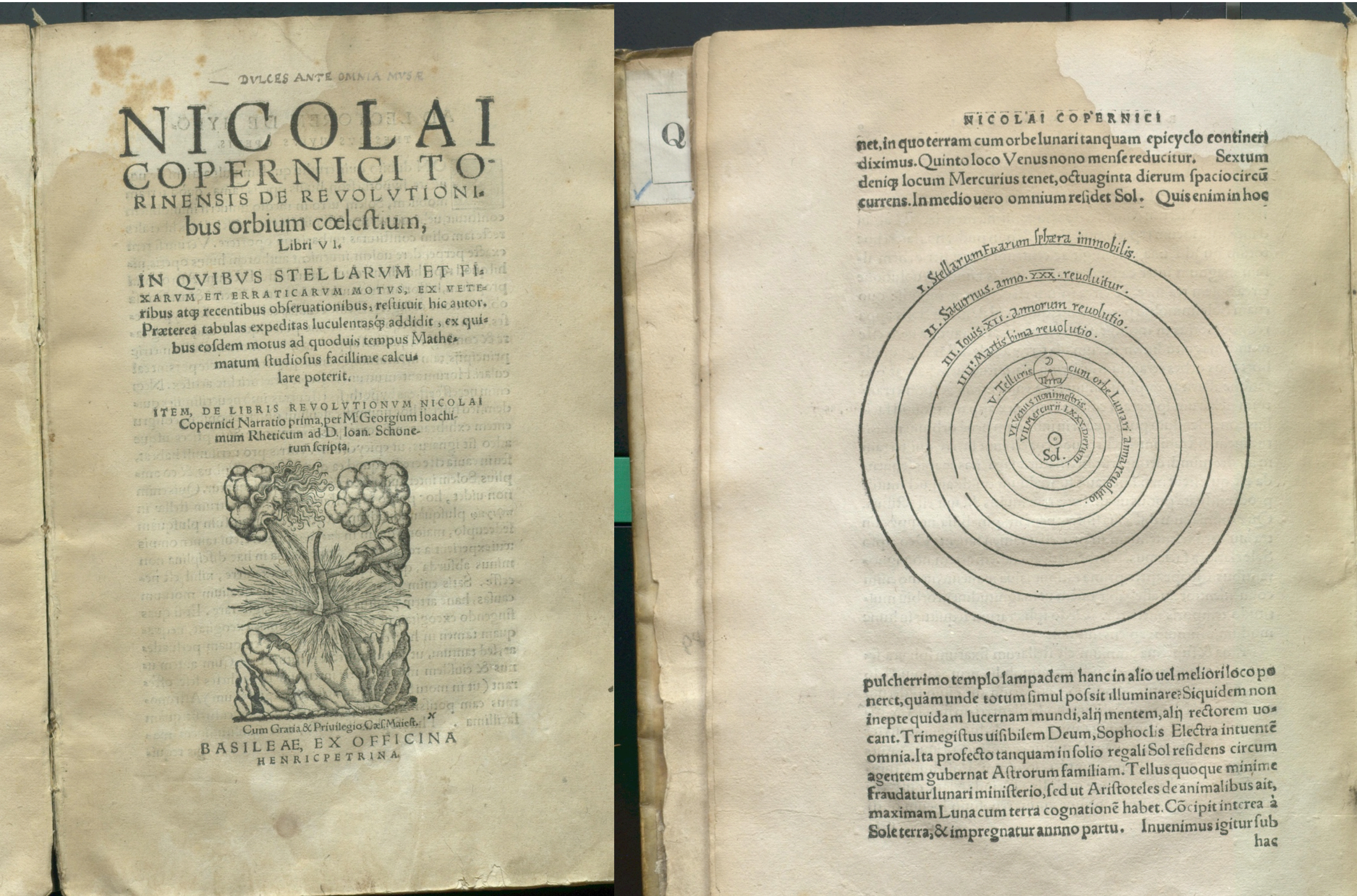
Mikołaj Kopernik and his motivation

Throughout his life, astronomy was based on Ptolemy's (~150 CE) model of Aristotle's universe. Ptolemaic model was a good but not great predictor of planetary positions. Although this was a concern for astrologists, it was not why Copernicus was driven to overturn it. [As a priest he did not serve as astrologer & had literally zero interest in it. Still, he was trolled by Martin Luther, who called him "upcoming Astrologer" writing nonsense ☺]

- Kopernik cared about the greater simplicity and logic of the heliocentric system, in which the sun is the body apparently directing the motion of small planets (sun was known to be much larger than Earth and Moon, as we have seen). Copernicus wanted achieve this, while also realizing Plato's dream of constructing motion of planets using *only uniform circular motions* (compound motions if need be).
- Like Islamic astronomers before him, Copernicus hated Ptolemy's equant mechanism that reproduced the uneven speed of planets along their guiding circles (deferents).

Tower that Copernicus bought as home in Frombork, a town on the shore of the Baltic Sea in Polish Prussia

De revolutionibus Orbium Coelestium (1543) in the old manuscript wing of Roberts Library in St. George campus of UofT



- By 1514 Copernicus wrote a short pamphlet summarizing his model and distributed it to friends. "*Commentariolus*" ("Little Commentary”), a 40-page manuscript, was printed only in the 19th century. It was known to a number of top scholars in Europe in his days, and distributed widely by Tycho Brahe after Copernicus died.

- But the main work (De Revolutionibus Orbium Coelestium) was being constantly delayed... he actually saw the first edition of it first on his death-bed in 1543, almost 30 years after Commentariolus.

- Why did Copernicus publish his work so hesitantly and so late? What was he afraid of? Was he fearing the reaction of the Church?

- Was the Church forbidding or discouraging Copernicus from publishing the heliocentric theory? Not at all. That is a modern myth.
- In 1533, secretary of the Pope J. Widmannstetter delivered lectures in Rome outlining Copernican theory.

Cardinals of Vatican encouraged Kopernik to publish his model, even offered to pay for the publication. His mathematical model could have been useful in the planned Gregorian reform of the calendar.

Still, Copernicus delayed the publication for two main reasons:

(i) fearing the *ridicule by the academia, i.e. professors*.

(ii) much more work remained on elimination of *equant* mechanism which, as many have noticed, had contradicted the uniform circular motion as a basis of planetary motion.

De revolutionibus was published at the prodding of a young apprentice who traveled from the University of Wittenberg in Germany, Joachim de Porris (better known as Joachimus Rheticus).

Already the *Commentariolus* contains some mysteriously prescient concepts and data, e.g.: the relative sizes of orbits are correct!

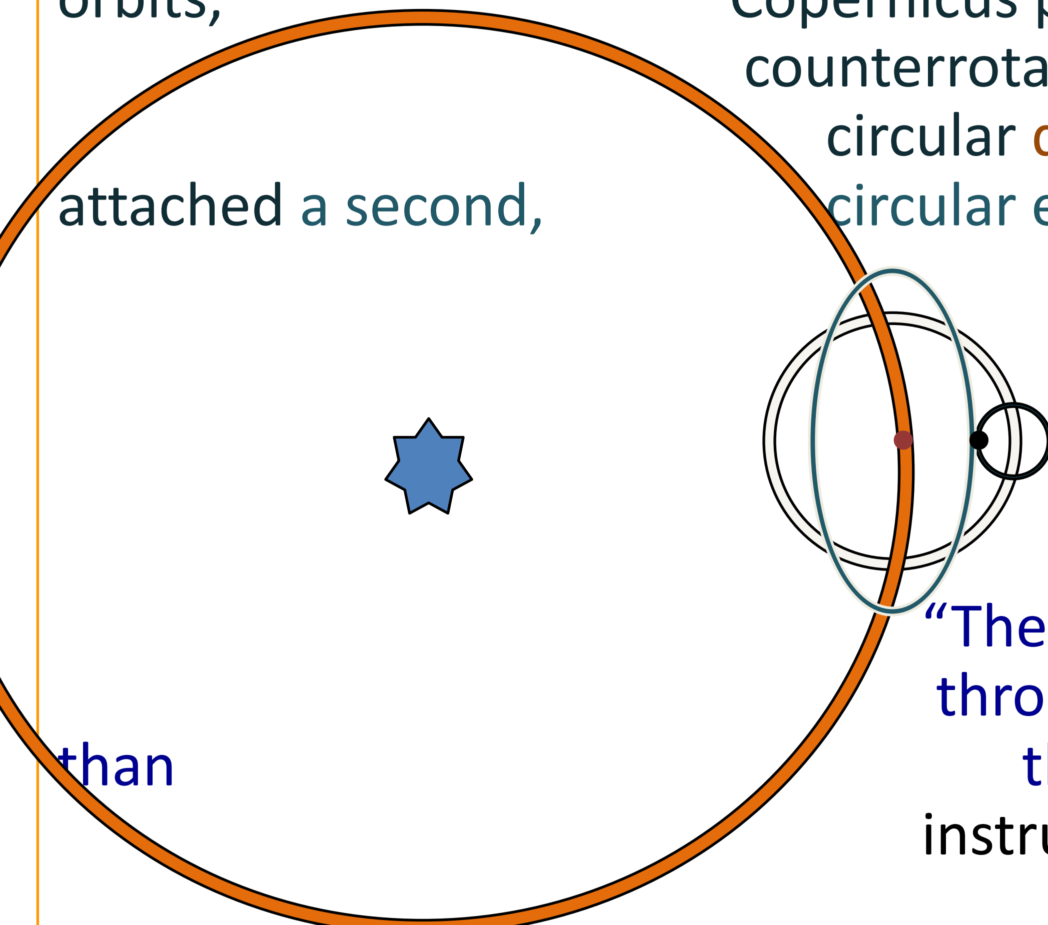
a = mean planetary distance from the sun (semi-major axis *a*) in units of AU [1 AU = Earth-sun distance by definition].

planet	Ptolemy recalc. to heliocentric *	*a* (Kopernik)	*a* (modern)
Mercury	0.375	0.376	0.378
Venus	0.717	0.720	0.723
Earth	1.000	1.000	1.000
Mars	1.519	1.520	1.524
Jupiter	5.217	5.217	5.206
Saturn	9.231	9.233	9.580

* - Ptolemy's sizes of deferents and epicycles in geocentric model (deduced from long ancient observations) were used by Mikołaj Kopernik to put planets in correctly sized orbits. Kopernik added few own observations (50 or so)

Copernican model with double circular epicycles

The eccentricity of the orbit of Mars & the planets was mentioned as well in Commentariolus. In order to reproduce Mars orbit, in fact all planetary orbits, Copernicus placed one uniformly counterrotating circular epicycle on a big circular deferent and on that epicycle he attached a second, circular epicycle:



"The first [epicycle's] radius is throughout three times greater than the second [epicycle's radius]" instructed Copernicus.

The uniform counter-rotation of two circular epicycles combine into a non-uniformly moving point on a **nearly elliptic curve** shown, which has axial ratio 1:2 (twice as large along the orbit than in radial direction from the sun)

Copernicus's & Ptolemy's models were accurate to order O(e^2)

This 1:2 ratio (and the 1:2 ratio of speeds as well) is the precise ratio following from the angular momentum conservation (also from empirical 2nd law discovered later by Kepler). But that could be understood only much later, after Newton.

The double epicycle construct, just like another geometrical construct of the so-called equant and deferent, make the Copernican model exact to order O(e^2), as modern astronomers would say. Here, e stands for the orbital *eccentricity* parameter

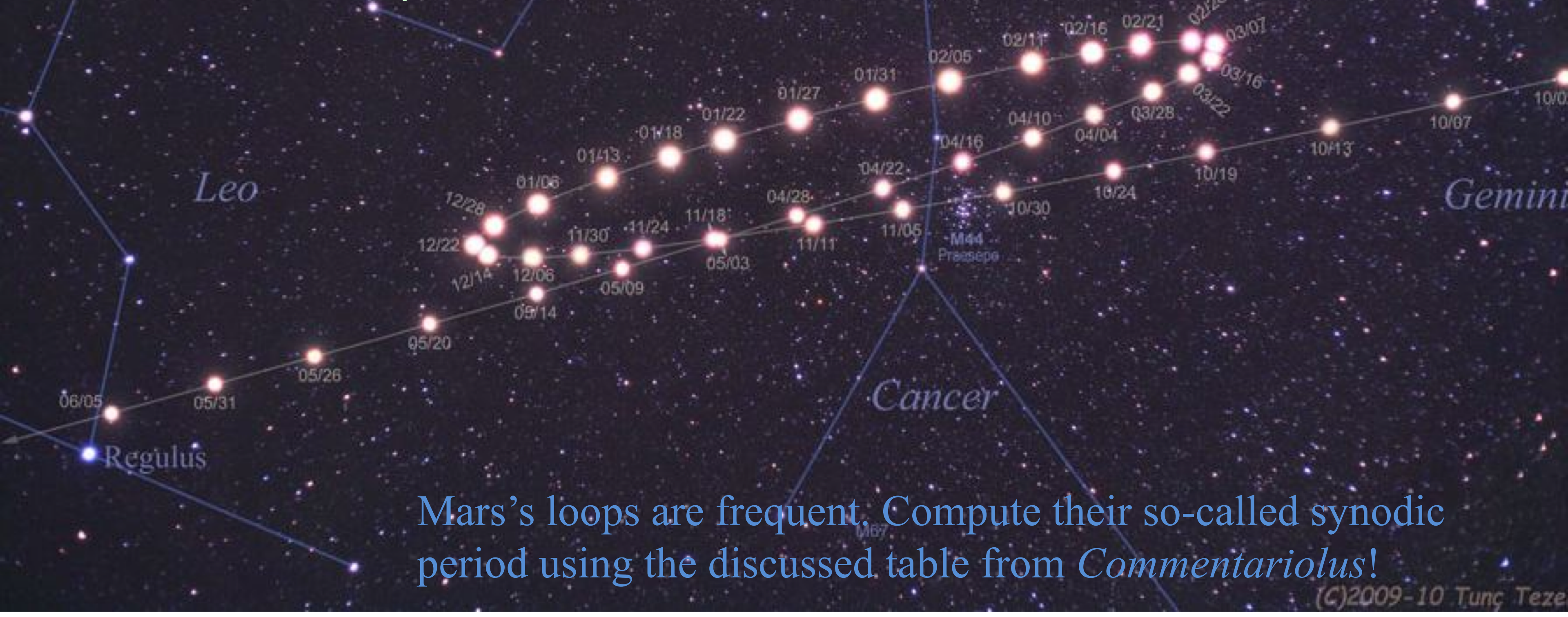
($e \sim 0.094$ for Mars; we will return to the precise definition later).

The Ptolemaic theory was also accurate to that order.

Copernicus knew the value of e with surprising accuracy already 30 years before his main work appeared. But in 1514 Copernicus only knew a summary of Ptolemy's *Almagest*, which was printed in full only somewhat later, so it's not clear how he learned about the values of eccentricities. (He did some observations of his own.)

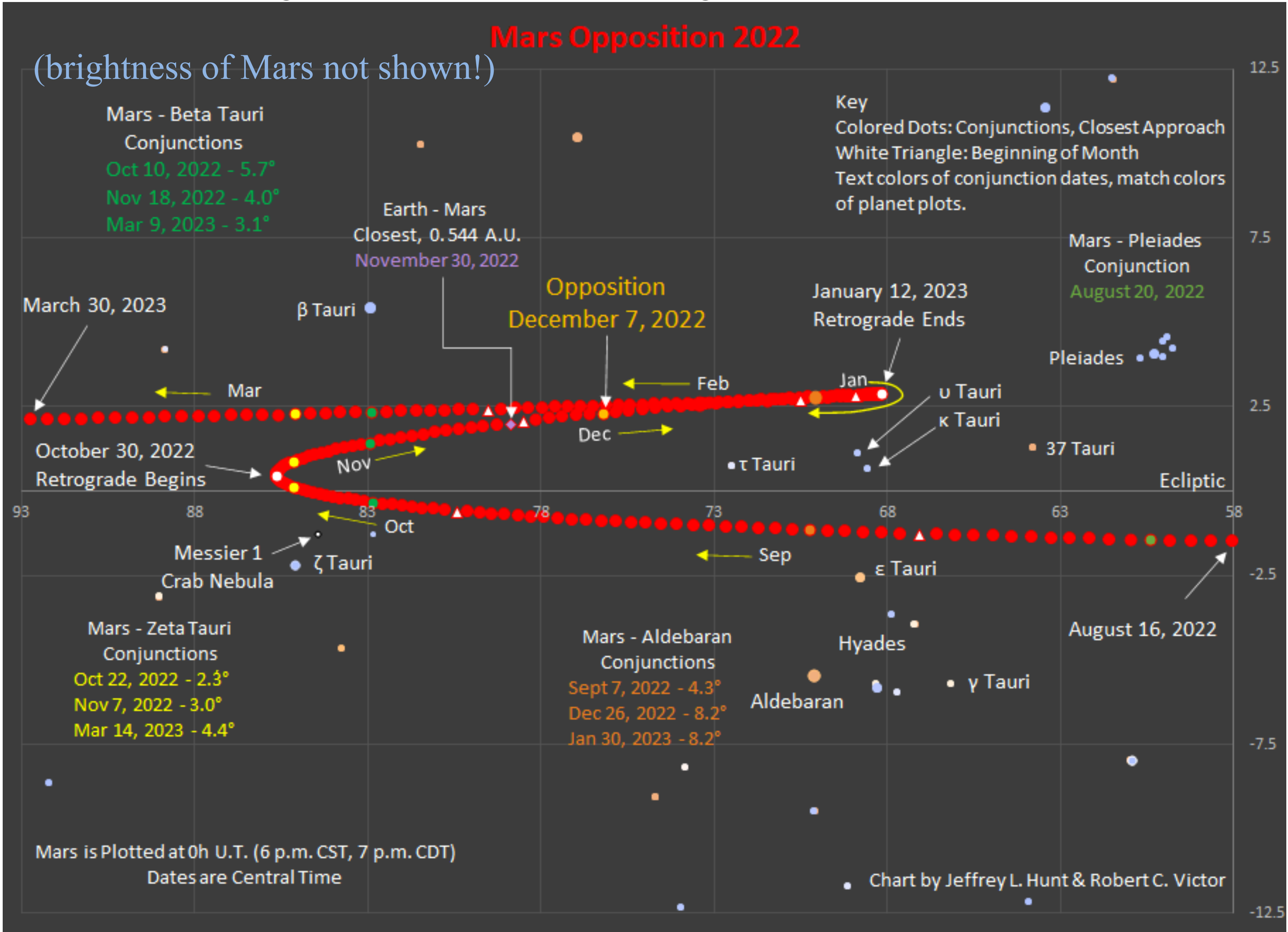
Mars near opposition to Sun, images every 4-6 days

A loop that Mars traced on the patch of the sky opposite the direction to the sun (observations from Oct 2009 to June 2010). We call it opposition, since Mars is then seen directly opposite the Sun. Notice the large brightness, which always accompanies retrograde motion & opposition. The second coincidence was postulated but not explained by the geocentric system of ancient Greek astronomy.



Mars's loops are frequent. Compute their so-called synodic period using the discussed table from *Commentariolus*!

Mars ended retrogradation near Pleiades during Lecture 1 of ASTC25 course in 2023



-  In De Revolutionibus, the retrograde motion of the planets was explained in a straightforward way as Earth overtaking a planet, without the big epicycles and the so-called equant that Ptolemy had used.
- A total of 34 circles (epicycles and deferents) were used by Copernicus to improve the positional fit to the data, but they were small, <<1 AU, compared with the Ptolemy's 24 or so big epicycles, which essentially must be on the scale of 1 AU)
- It is thus a modern myth that Copernican model was much more accurate or much simpler than the geocentric model, because it discarded the allegedly superfluous epicycles of Apollonius and Ptolemy.

- The hypothesis explained correctly the brightness at conjunctions and oppositions of planets with the sun. E.g., Mars was known to be very bright when it is rising while the sun is setting – a fact invoked & explained by M. Kopernik.

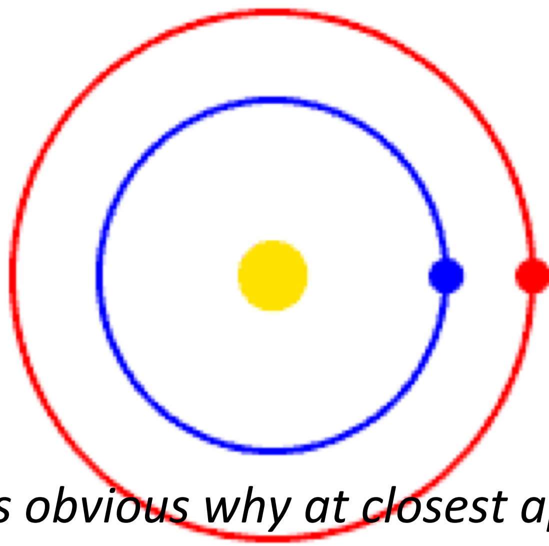
Why heliocentrism won with geocentrism

Motion of Mars (red) and Earth (blue)

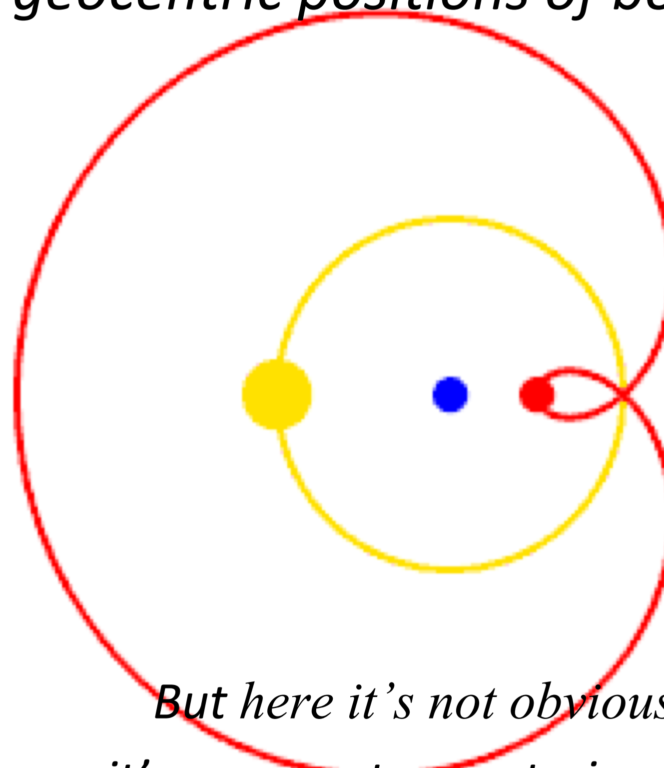
1. for an outside observer — *helicentric model*

2. relative to Earth, — *geocentric model*

It’s obvious which description looks simpler (unless we need sky maps, which by construction show geocentric positions of bodies).



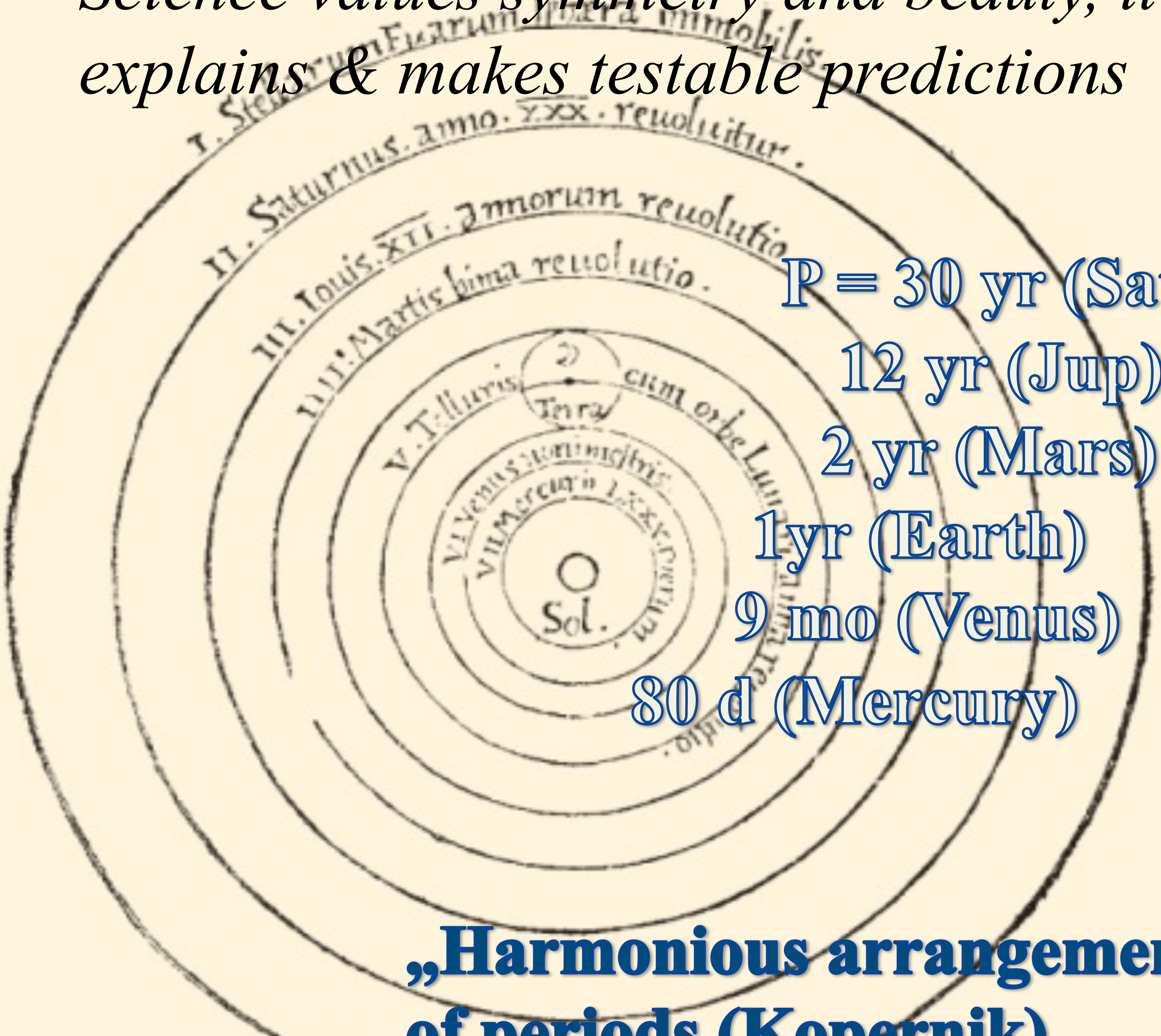
Here it’s obvious why at closest approach to Mars, Earth sees it in opposition with Sun (in opposite directions).



But here it’s not obvious, it’s a separate, mysterious law

net, in quo terram cum orbe lunari tanquam epicyclo contineri
diximus. Quinto loco Venus nono menſe reducitur. Sextum
denique locum Mercurius tenet, octuaginta dierum ſpacio circū
currens. In medio uero omnium reſidet Sol. Quis enim in hoc

Science values symmetry and beauty, it explains & makes testable predictions

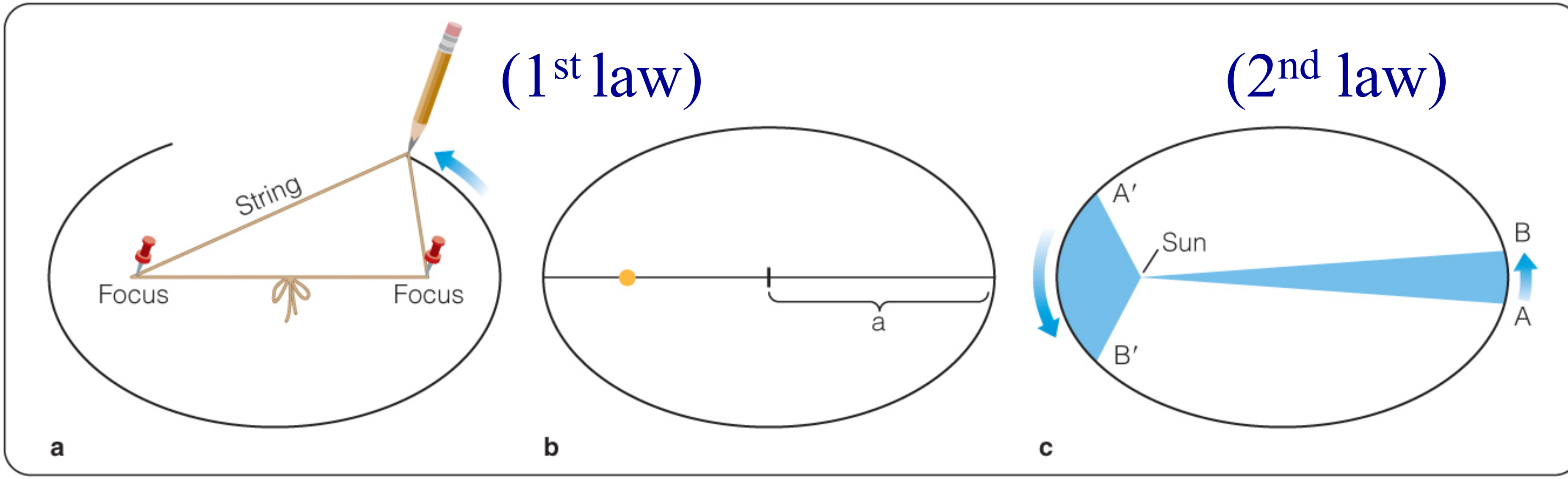


P = 30 yr (Sat)
12 yr (Jup)
2 yr (Mars)
1yr (Earth)
9 mo (Venus)
80 d (Mercury)

„Harmonious arrangement” of periods (Kopernik)

- In the Ptolemaic model, Mercury and Venus had to be treated differently from the rest of the planets (on account of them never deviating from the location of the sun by more than 47 degrees). Copernican model made no such distinction. It was not only *simpler*, it *unified* all the planets. It made testable predictions. These traits are call *beauty* by physicists and astronomers.
- How the Copernican hypothesis was gradually recognized as correct is called the *Copernican Revolution. It took a while.*
  - Heliocentrism was not just a new result, but a total change in the way astronomers and scholars thought about the place of Earth and humanity in the cosmos.
  - Copernicus has made Earth just a planet circling a star. It was no longer the center of the universe!


TYCHO BRAHE
JOHANNES KEPLER



Kepler's laws = empirical laws (from observ. or experience, with no explanation WHY they hold)

(3rd law) **Orbital period squared is proportional to the semi-major axis cubed.** Different, but equivalent forms:

$P^2 \sim a^3$ (proportionality)

$P \sim a^{3/2}$ (equivalent form of proportionality or 'scaling')

$(P\ /\ 1\ \text{yr})^2 = (a\ /1\ \text{AU})^3$ (exact equality); AU = astron. unit

$P = (a/1\text{AU})^{3/2}\ \text{yr}$ (exact equality, only around the sun)

It is important to notice that Kepler's three laws are empirical (or phenomenological); they 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 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 vortex in 'aether', which pushes planets *along* their orbits. This was similar to ancient Greek ideas, the idea that angels constantly push the planets *along* their orbs, and ideas of Rene DesCartes.
- One can say that this idea was wrong by ~90 degrees: In fact the force acts not along the orbit but toward the sun, but dynamics of that was not understood yet.

Galileo Galilei (1564-1642), hearing the descriptions of the invention of a Dutch lense-maker in the Fall of 1609, builds a working telescope in his workshop a year later.

He turned it as the 1st astronomer on the sky and made many great discoveries:

- mountains on Moon
- 4 satellites of Jupiter
- rings of Saturn
- phases of Venus
- Milky Way = stars

Courtesy Yerkes Observatory

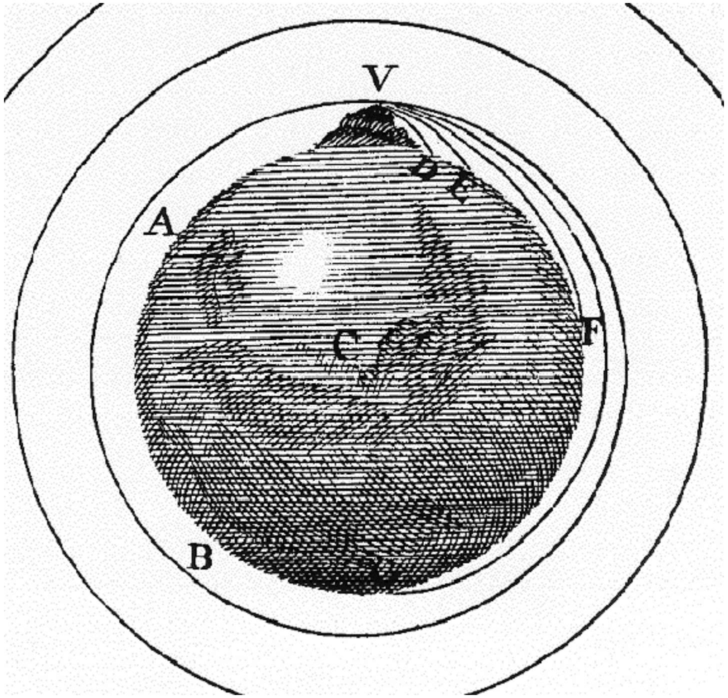
Gravity and Orbs: Newton, Hooke et al.

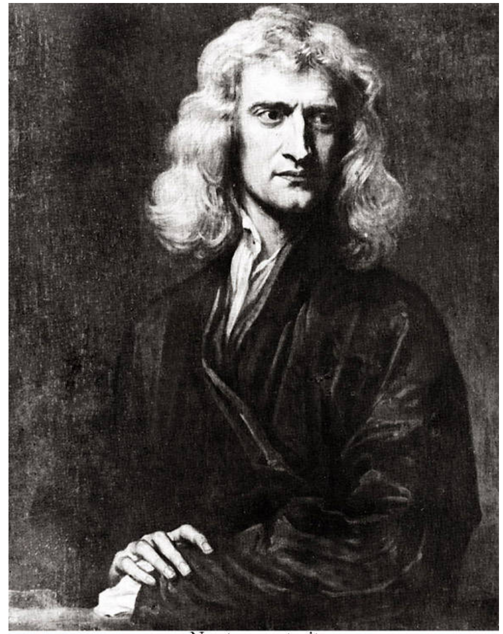
The problem of the place of Earth and humanity in the universe was resolved by the Copernican Revolution. The problem of planetary motion, though, was only partly solved by Kepler's laws. What gave rise to these laws was unknown.

Although Galileo made extraordinary progress in observations and formulated what is now known as the first law of Newton's dynamics, he was not able to relate his discoveries about motion to the heavens.

That final step was taken in the second half of the 17^{th} century by Isaac Newton and his contemporaries.

Isaac Newton (1643-1727)




Newton portrait

The publication of Newton's work in his book *Philosophiae Naturalis Principia Mathematica* in 1687 placed the fields of physics and astronomy on a new firm base. It happened in an interesting way:

– Helpful friend, astronomer Edmond Halley, as well as the rivalry with Robert Hooke (Newton's older colleague & arch-enemy) made Newton write and publish *Principia*!

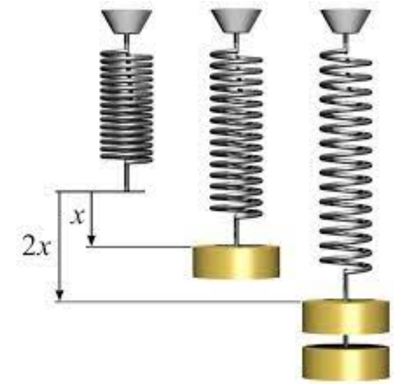
- Rivalry was a norm for Newton. He was slow to publish most of his discoveries, which later led to conflict with those who made them independently. Most famously, G. W. Leibniz discovered & published calculus, and R. Hooke formulated and published the idea of **universal gravitation *before*** Newton, in 1670 (printed in 1674).

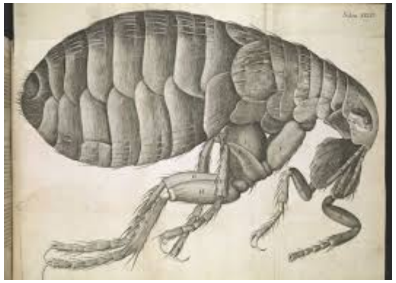
Robert Hooke (1635-1703):

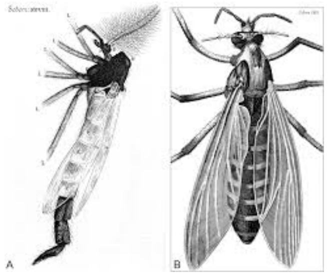
Physicist and inventor. Together with Christopher Wren surveyed London and helped rebuild many churches burned in the great fire of 1666.

Discovered so-called Hooke's law of ideal spring.

First identified and named cells in plants using his improved design of a microscope.







Robert Hooke

- Hooke made detailed drawings of fossils
- He discovered the Great Red Spot on Jupiter by perfecting the telescope.
- Hooke was a secretary of Royal Soc. in London,

and the first physicist paid for performing experiments every week (checking results for presentation to the Royal Society meetings). He was older than Newton, and when after his death Newton became the Secretary, he removed & destroyed all Hooke's instruments & all paintings showing Hooke.. We are now uncertain about the authenticity of ostensibly his portraits.

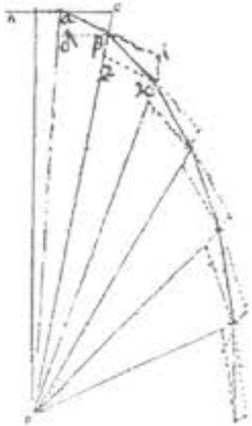
London's coffee-houses and the Universal Gravity

- Hooke suspected that universal gravitation acts between all massive bodies, whose strength follows the inverse square law of the form $\boldsymbol{F = const / r^2}$. He constructed funnels for balls, which simulated the motion in a gravity field, knew that a pendulum or a funnel simulates force $F = const * r$.
- Hooke also knew how the orbits follow from "compunding" the inertial straight-line motion and gravity, which

bends the trajectory by providing radial

increments to velocity.

And he told Newton about his compounding method!

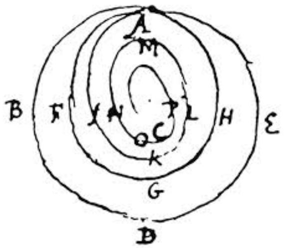


- For those interested in history of science: M. Nauenberg

"Robert Hooke's Seminal Contributions to Orbital Dynamics"
https://planets.utsc.utoronto.ca/~pawel/ASTB03/hooks-contrib.pdf

- At the time, some of Newton's ideas on that problem were

apparently incorrect (spiral trajectory of a body in vacuum?).



Isaac Newton

- Newton was a quiet child from a farming family in Woolsthorpe in Lincolnshire, England.
- His progress at school was impressive & he seemed so inept at agriculture that his parents decided that Isaac should become a priest, not a farmer.
  - His uncle financed his education at Trinity College, Cambridge – where he studied mathematics and physics
  - In 1665, bubonic plague epidemic swept through England, and the colleges were closed. Obligatory quarantine was introduced and enforced. During 1665 and 1666, Newton spent 1.5 years back home in the village of Woolsthorpe.
  - Yet he didn’t sit in the basement and binge-watch Netflix series. He was thinking and studying..

Isaac Newton

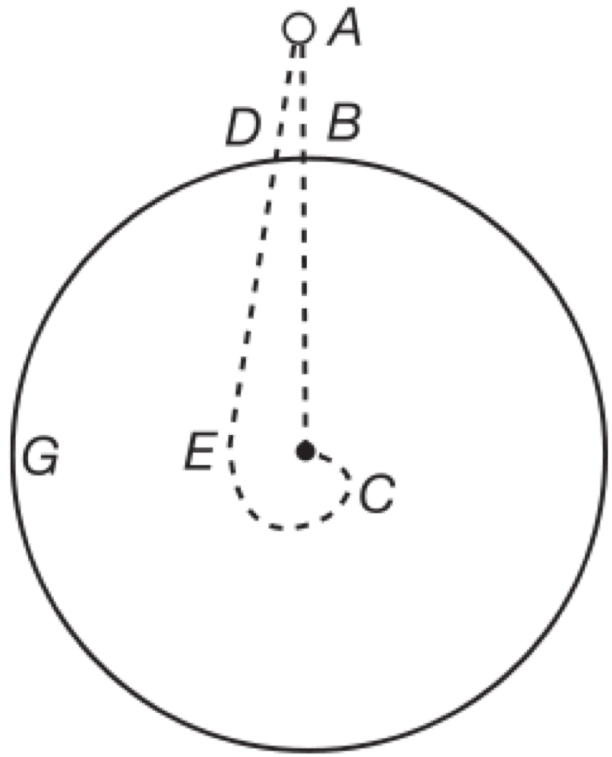
Newton claimed that it was during the ‘miraculous year’ (*annus mirabilis*) that he made most of his scientific discoveries. Historians agree that this timing of discoveries was distorted by Newton to make priority claims.

- The anecdote of an apple is likely just a nice story. It was told by Newton himself, though.
- Young Newton studied optics, and started quarreling with Hooke about the nature of light: according to him light is made of particles emitted in bursts; according to Robert Hooke and Dutch physicist Christian Huygens light is strictly a wave phenomenon.
- During the quarantine Newton developed laws of motion, perhaps *started* thinking about gravity (although there is not a slightest written trace of it before 1679), and partly worked out differential calculus

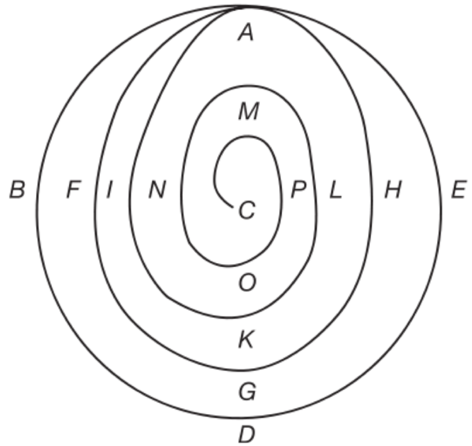
1680s: Discussions in the Coffee-Houses of London

- Astronomer Edmond Halley, architect Christopher Wren, mathematician John Wallis, and Robert Hooke had meetings and lively discussions at (novelty!) coffee-houses of London after Royal Society's brief weekly meetings.
- They were interested in physical causes of elliptic orbits discovered by Kepler and later confirmed in comets by Halley, although astronomers had problems tracing comets near the sun (Astronomer Royal John Flamsteed claimed that Halley's comet was stopped by the sun and repelled)
- Hooke had an exchange of letters 1679-1680 about it with Newton, which probably gave Newton both a motivation to study orbits (*which he admitted later*),
- and crucial ideas, like compound motion, i.e. combining inertia and gravity to produce trajectory in small steps, and the idea of Universal Gravitation (*all of which Newton later denied*)

Conflict between Newton and Hooke, with gravity and orbits in

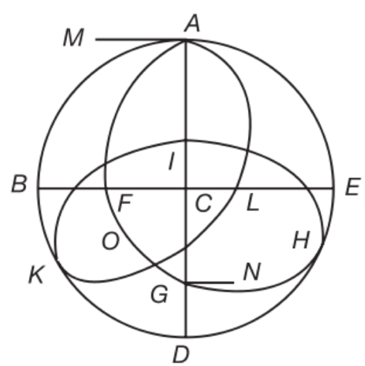


10. Newton's suggested path for an object dropped vertically from above the Earth's surface. The object's path is assumed to continue inside the Earth's surface as the Earth revolves around C anticlockwise (i.e. BDG).



11. Hooke in turn argued that the body described by Newton would revolve in the ellipsoid AFGHA, unless it experienced some resistance, in which case it would descend close to the centre of the Earth

away he was from the analysis of celestial motions he would adopt seven years later in the *Principia*, but he also hinted at a much more sophisticated way of dealing with the problem according to continuous and infinitesimally small elements of gravitational force. Moreover, he implied that he could deal with a force of gravity that did not remain constant but varied from the centre outwards.



12. Newton's response, with gravity and 'centrifugal force' alternately overpowering each other

As they exchanged seemingly polite letters and quarreled about trajectories, there was intense personal dislike behind this.

Incidentally, it shows that even in 1680s Newton did not have a full understanding of orbits and gravity. Hooke was often more right.

This suggests that Newton did not discover Universal Gravity in 1665-1666 as he claimed, but that he worked it out in response to original hypotheses of his contemporaries.

Isaac Newton – the story of *Principia*

- In 1684 Wren offered a reward for showing that

  $1/r^2$ force → elliptical orbit (1st Kepler's law)

Robert Hooke said he has a demonstration of this but said that he *can't find it* !

He said he'll provide it *next week*… but hasn't provided it the next week or the in the weeks after that.

(In fact, Hooke did have a demonstration explained to his friends in letters in 1685, but it was based on mechanical analogs, i.e. mechanical experiments with funnels and balls, not on mathematical physics)

Isaac Newton – the story of *Principia*

Edmond (or Edmund) Halley traveled in 1684 to Cambridge, to ask Newton the same question.

Newton also claimed that he had a proof of elliptical orbits following from an inverse-square law of gravity.

"Sir Isaac looked among his papers but *could not find it*, but he promised him to renew it and then to send it him…"

- Halley waited for two months. Just as he started doubting in both Hooke's and Newton's claims…

Newton made good on his promise! He wrote a brief account *De motu corporum in gyrum* (1684) & after much expansion that took 18 months, the

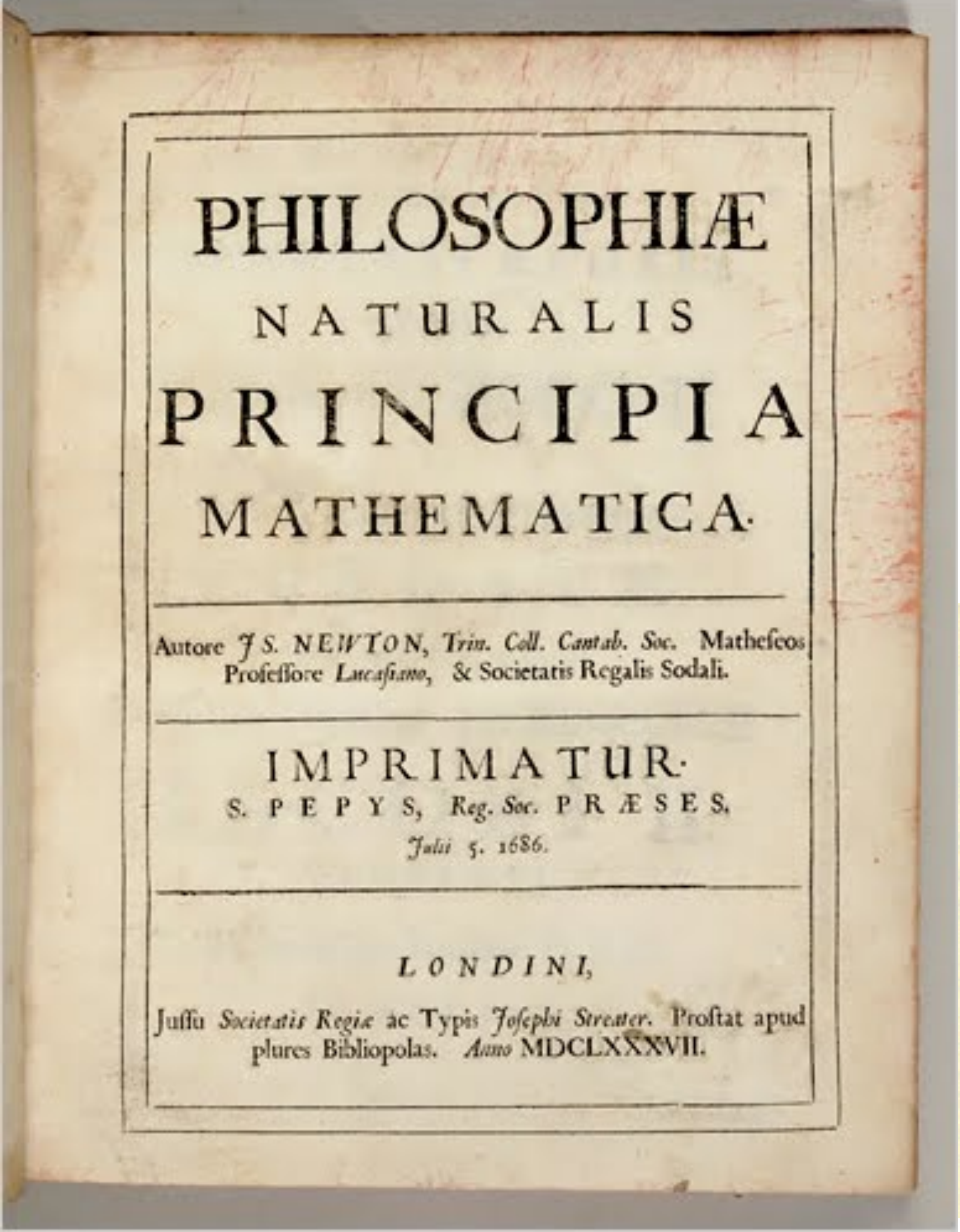
Philosophiae Naturalis Principia Mathematica (1687)

Mathematical Principles of Natural Philosophy

known in short as *Principia*.

E. Halley

Royal Society of London was low on cash and Newton was stingy, so the publication was edited and paid for by Edmond Halley himself. Newton even called it "your book" in private correspondence with Halley, his only friend among scientists.


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *JS. NEWTON*, *Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

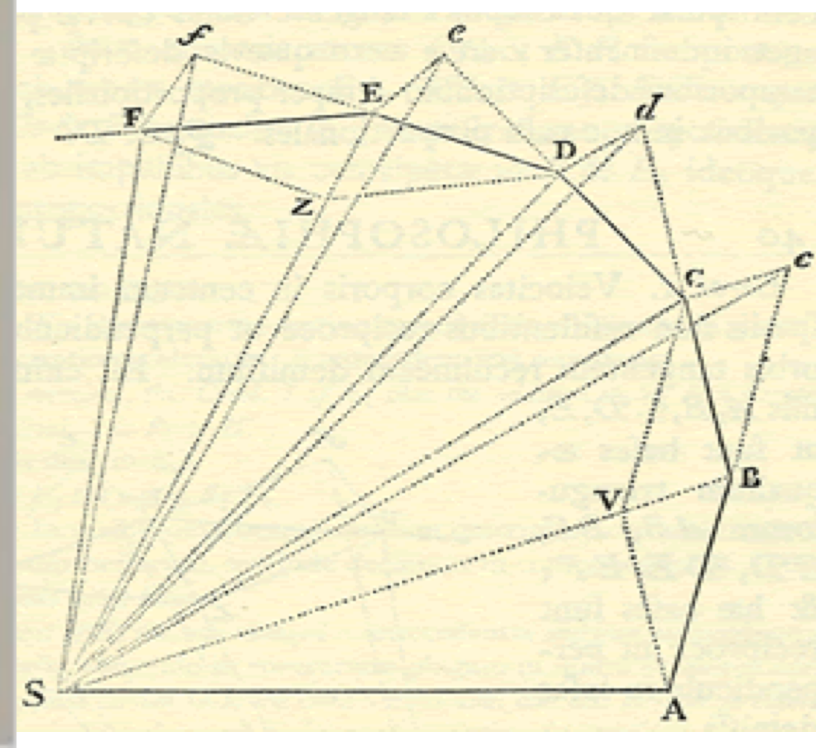
IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

1687

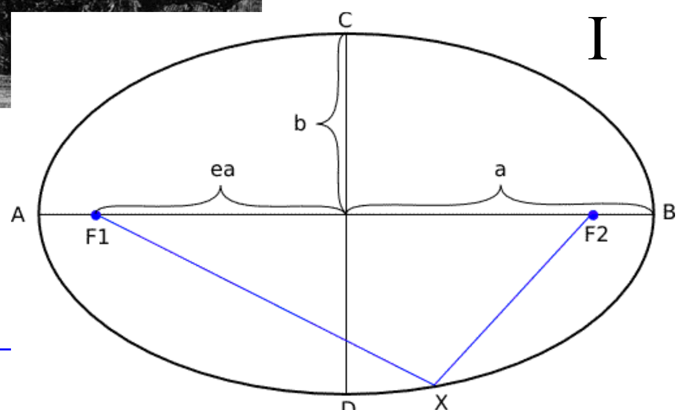
Newton's *Principia* today arguably remains the most important book in physical sciences



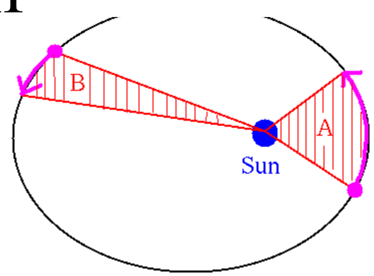
Gravity

J. Kepler (1571-1630)

I



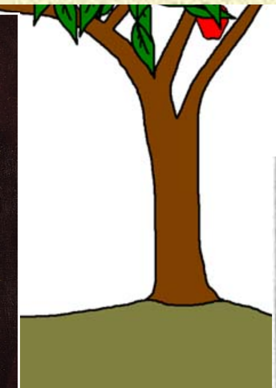
II



A = B

III

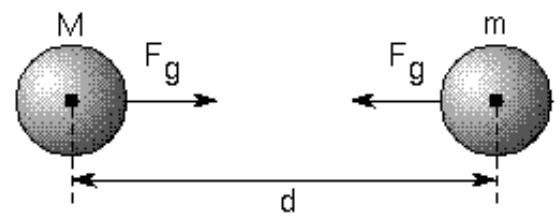
$$\frac{P^2}{a^3} = \text{constant}$$



?!

I. Newton (1643-1727)

R. Hook (1635-1703)



$$F_g = \frac{GMm}{d^2}$$

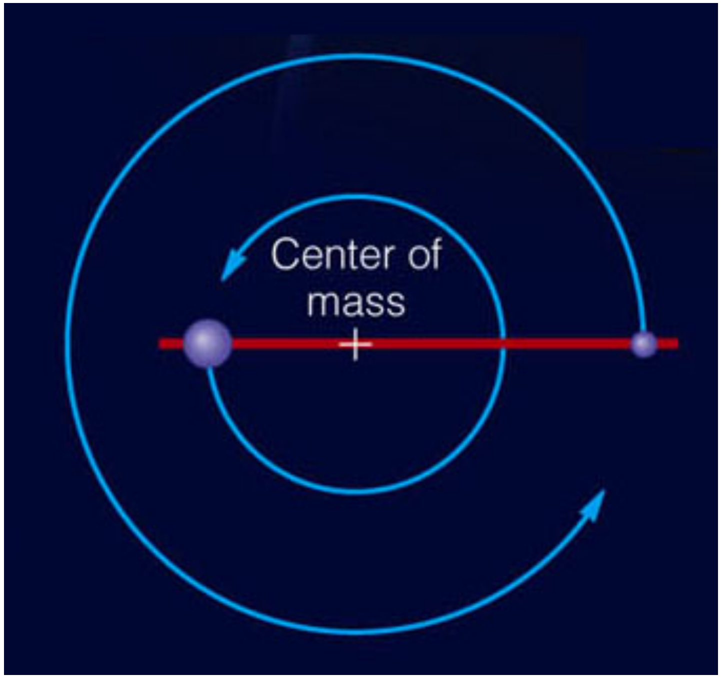
Orbital Motion

- Objects orbiting each other actually revolve around their mutual center of mass (C.M.)

Newton assumed that there is a center of the universe in our solar system, which is at rest (but never coincides with sun's center)

"Hypoth. IV. Centrum Systematis Mundani quiescere"
"Hypoth. IV. Center of the System of the World rests [is quiescent]"

- Thus we can detect and measure the mass of unseen, faint planets by looking at their much brighter stars, tugged by their planets.



The Universal Theory of Gravitation

Gravitational force of attraction between two objects depends on the product of the masses of the two objects.

- for example, doubling one of the masses (either m or M) would double the gravitational force F, and doubling both masses would quadruple the force.

$$F = - G M m / r^2$$

where G is a gravitational constant (measured in experiment)

- Gravity is universal. So, for instance:
  - Your mass affects Neptune, the galaxy M31, and every other object in the universe.
  - Their masses affect you – although not much, because they are so far away and your mass is relatively so small.

Newton's physics makes it possible to both understand why and how the Moon orbits Earth, the planets orbit the Sun, and why Kepler's laws work even in the furthest galaxies

- It explains why the pendulum swings, and also why galaxies look as they look (theory of spiral waves), and why they sometimes interact and merge.
- Einstein's theory (General Relativity) extended Newton's theory and

gave more correct description to the what causes the orbital motion

Orbital Motion around a point mass

Orbiting a planet is possible if you give an object enough speed

This is a type of illustration often found in books; it was first drawn by Newton.

An object in a stable orbit continuously falls toward the center of the planet but misses it because of its horizontal velocity and the curvature of the surface of the planet.

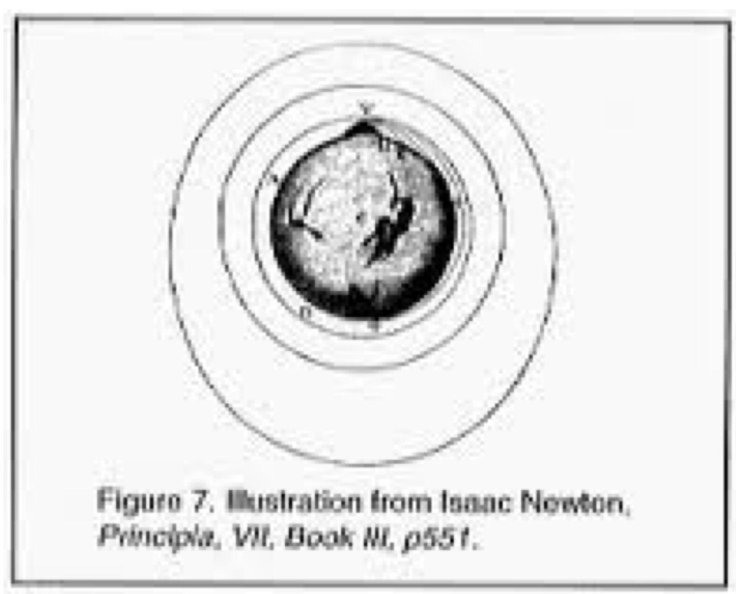


Figure 7. Illustration from Isaac Newton, *Principia, VII, Book III, p551.*