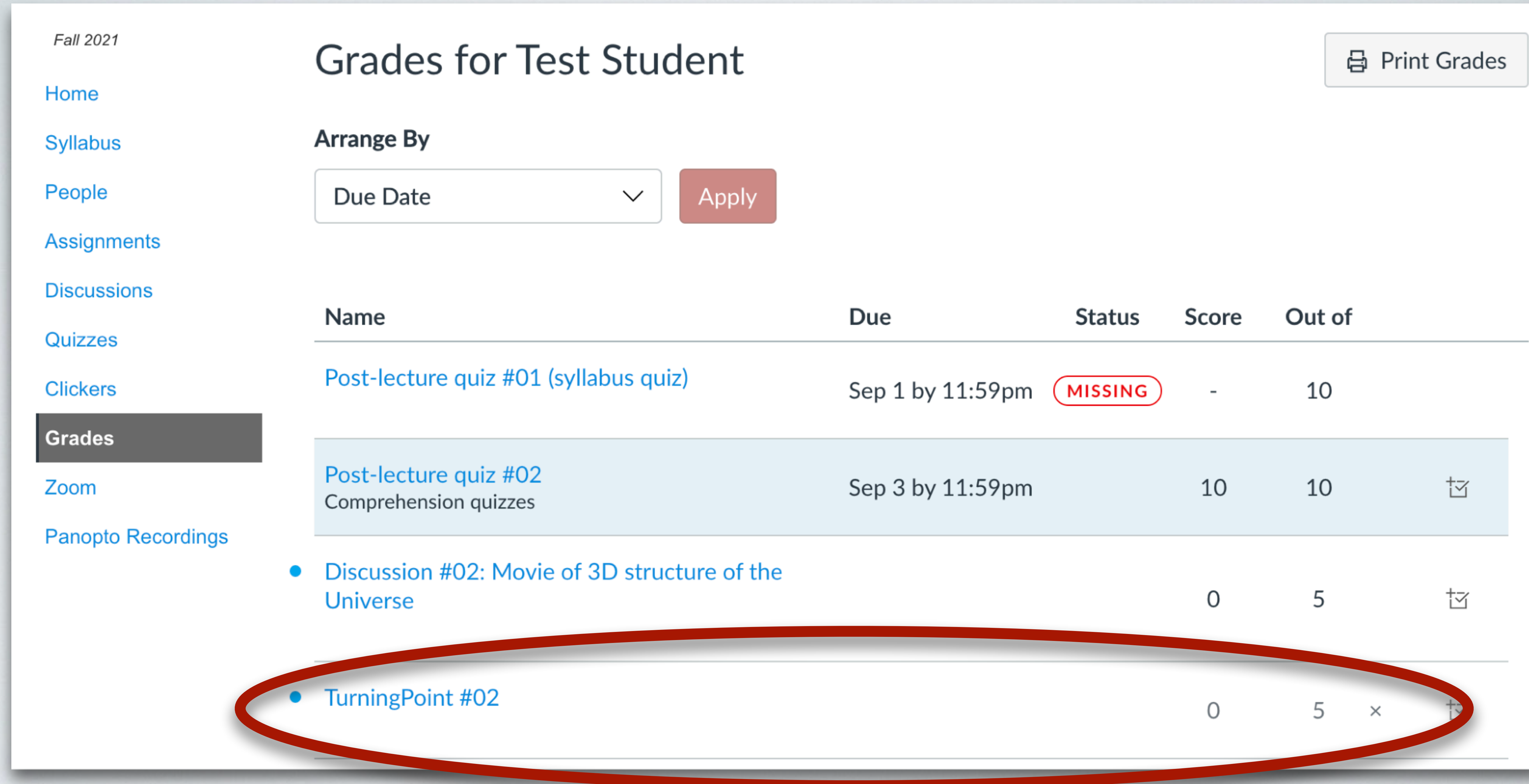
ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 3 • Self-centered cosmology: geocentric and heliocentric pictures

09/07/2021

Turning Point



Office hours

ASTR340 › ASTR340-0101: Origin of the Universe-Fall 2021 diemer

Fall 2021

- Home
- Syllabus
- People
- Assignments
- Discussions
- Quizzes
- Clickers
- Grades
- **Zoom**
- Panopto Recordings

zoom

Your current Time Zone and Language are (GMT-04:00) Eastern Time (US and Canada), English

Upcoming Meetings | **Previous Meetings** | **Cloud Recordings** | Ge

Start Time	Topic	Meeting ID		
Thu, Sep 9 (Recurring) 11:00 AM	Office hours (Thursday)	967 7017 6261	Join	Invitation
Wed, Sep 15 (Recurring) 3:00 PM	Office hours (Wednesday)	982 2957 2426	Join	Invitation
Thu, Sep 16 (Recurring) 11:00 AM	Office hours (Thursday)	967 7017 6261	Join	Invitation
Wed, Sep 22 (Recurring) 3:00 PM	Office hours (Wednesday)	982 2957 2426	Join	Invitation
Thu, Sep 23 (Recurring) 11:00 AM	Office hours (Thursday)	967 7017 6261	Join	Invitation

Quiz grading

Question 3 **2 pts**

Eudoxus, Aristotle, and Ptolemy are some of the main developers of the predominant cosmological model until the Renaissance. Their model matched the motions of the known celestial bodies well but could be said to fail as a scientific hypothesis because they are not particularly...

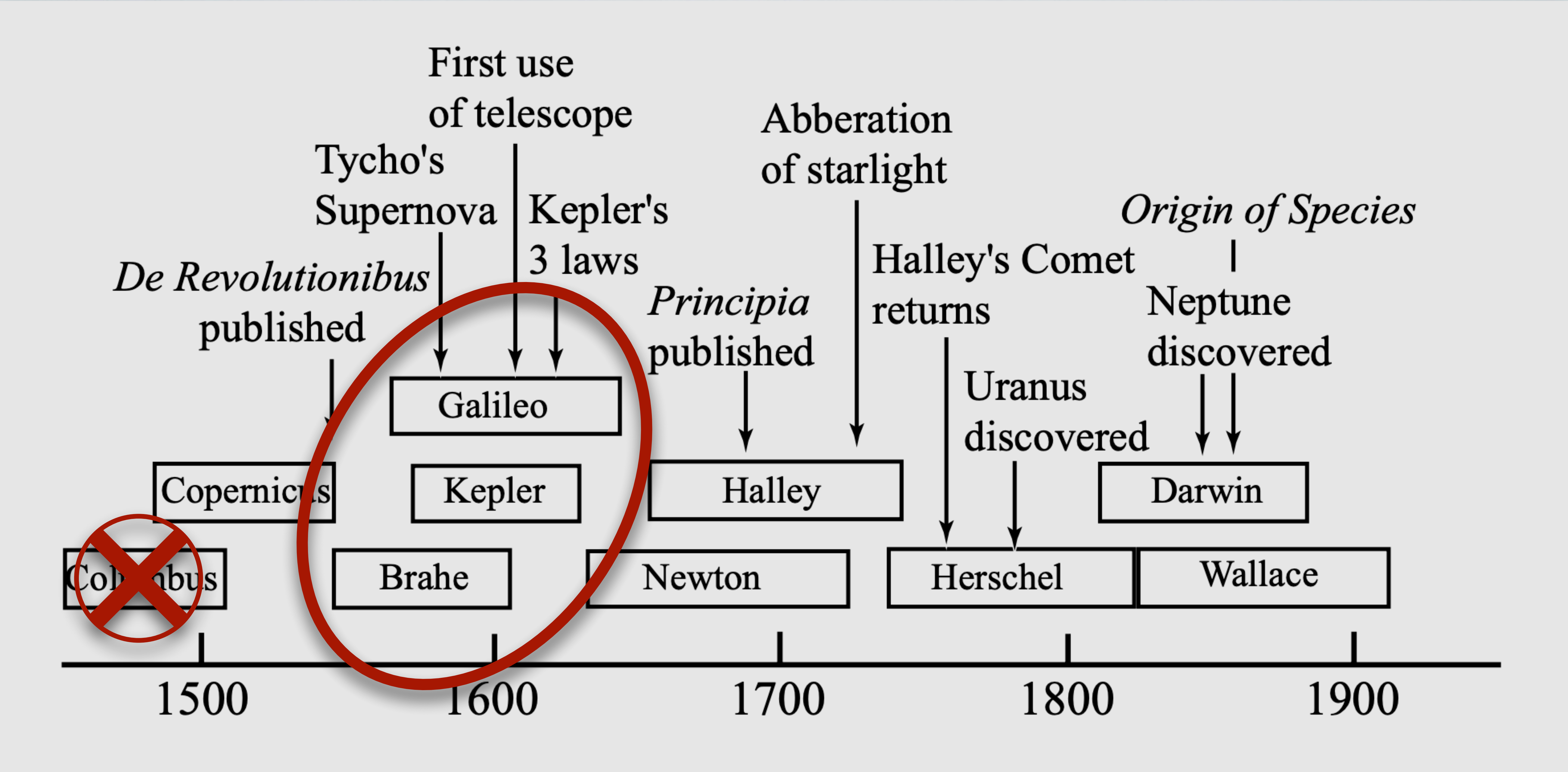
(pick 3 out of the 5 options)

- ☐ Simple (55 spheres for 7 objects, are you kidding me??)
- ☐ Predictive (the motion of any new body can be explained by more spheres)
- ☐ Testable (we cannot see their imaginary spheres in the sky)
- ☐ Relevant (they didn't talk about the celestial objects of interest)
- ☐ Consistent (they assumed different physics for the Earth and the heavens)

eBOSS video discussion

- **Top-voted unclear concepts:**
  - Dark energy (why is it so hard to observe if it's important?)
  - Cosmic microwave background (why is it depicted as a sphere?)
  - Expansion (how can it proceed if there is no center to the universe?)
  - Acceleration of the expansion
  - Dark matter (why do we need to prove its existence?)
  - Why are some areas invisible, and can we still build a model of the entire universe without them?
  - What is meant by the "observable" or "entire" universe?
  - Quasars
  - Redshift
- **Quick comments on:**
  - Detecting distances, generating 3D map
  - Milky Way obscuring certain areas of the sky

Today



Hawley & Holcomb, Foundations of Modern Cosmology

Participation: Favorite Greek scientist

Respond to the poll on TurningPoint

Session ID: diemer

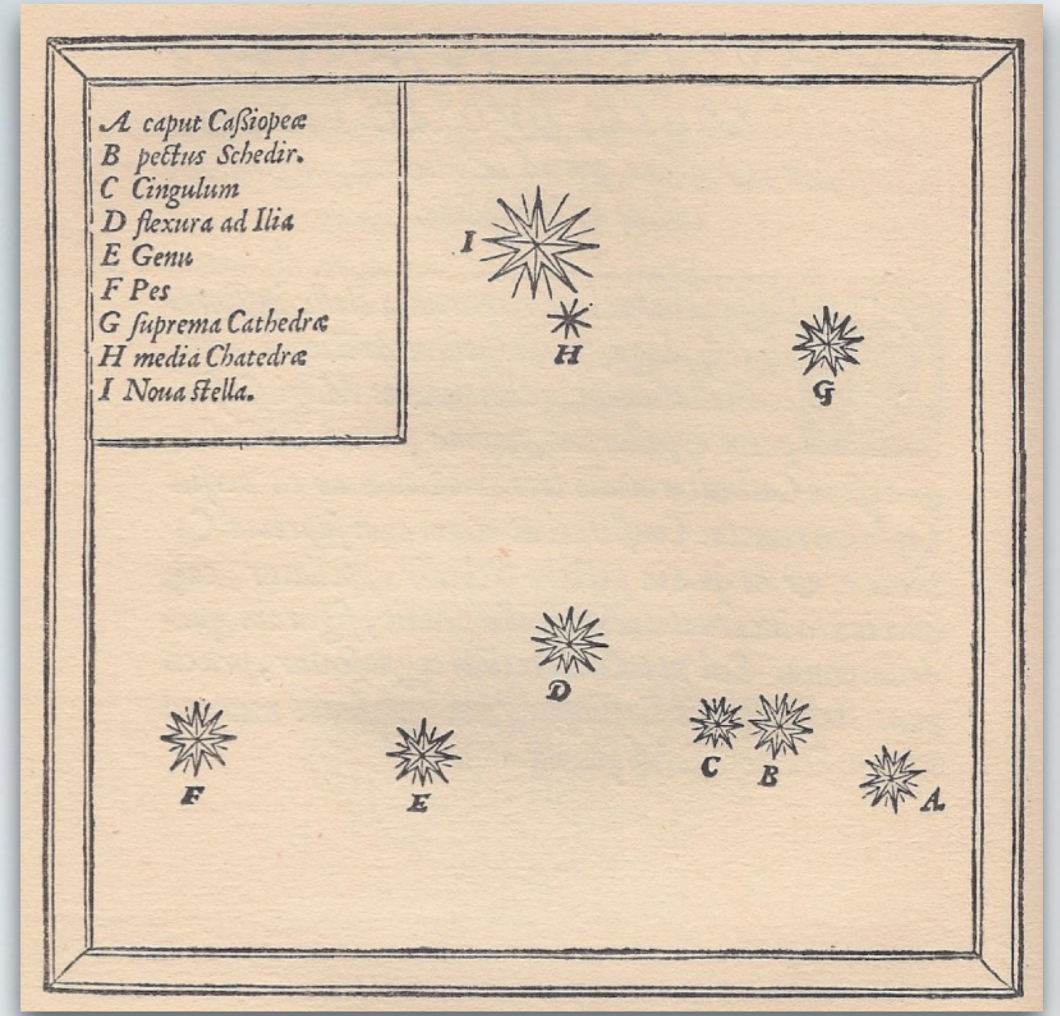
30 seconds

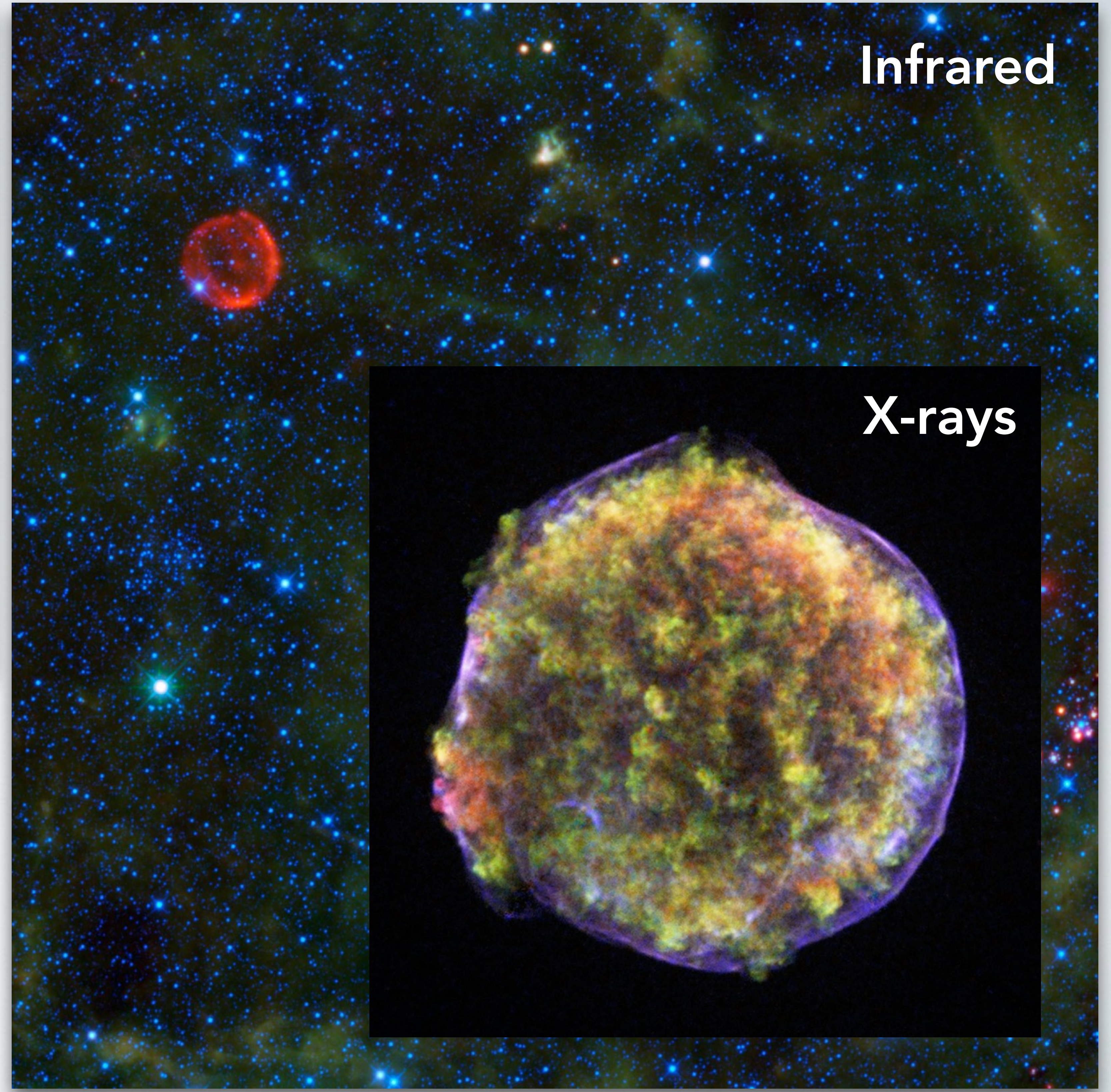
Part 1: Tycho Brahe

Tycho Brahe (1546-1601)

- Flamboyant and **tyrannical aristocrat**, but devoted to science
  - Lived and observed on an island (Ven) off the coast of Denmark
  - Last of the great "naked eye" observers
- Made planetary observations much more **accurate** than any previous
- Observed "new star" (**Tycho's supernova**) in 1572
- Demonstrated that a comet was beyond Moon's orbit
- From parallax observations of new star, comet:
  - knew they were not in Earth's atmosphere
  - evidence that heavens were **not immutable**

Tycho’s Supernova (SN1572)

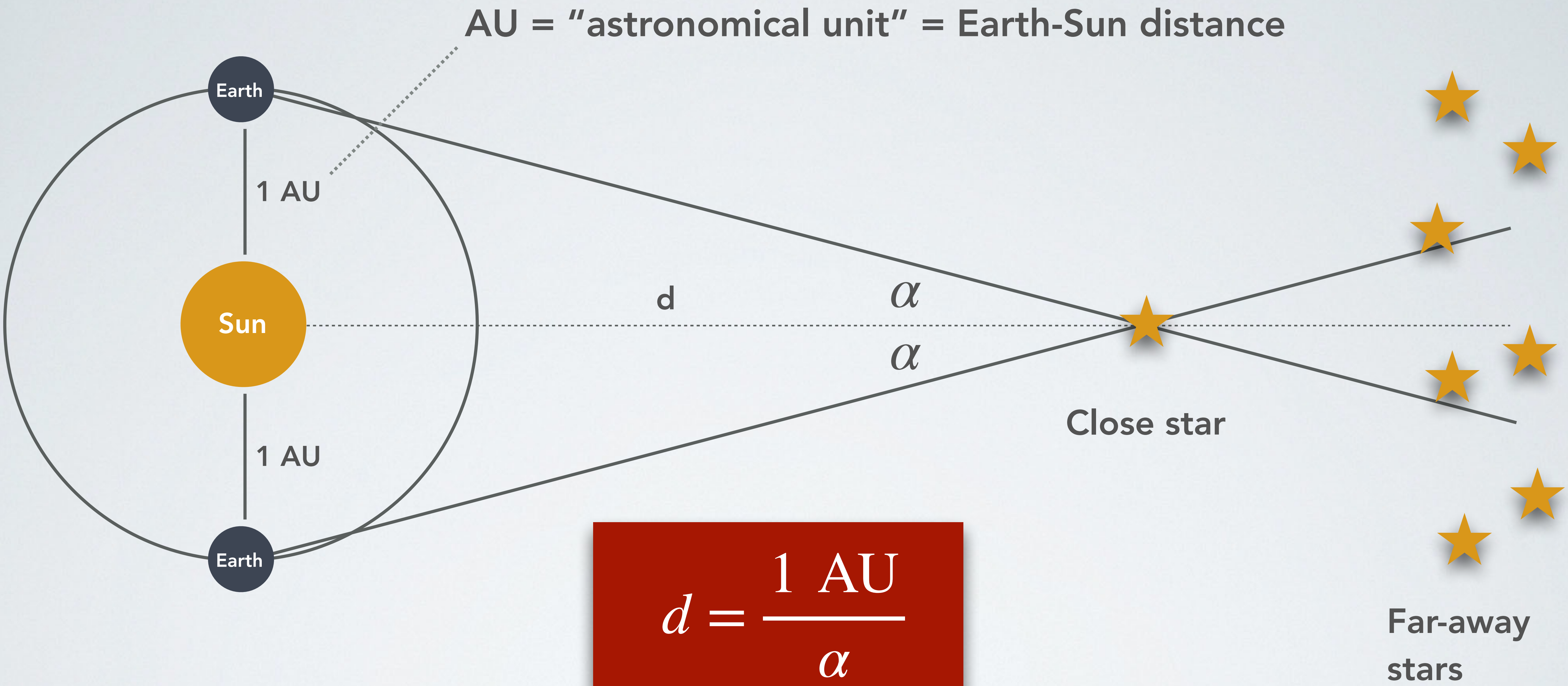




Images: WISE, Chandra

Large quadrant at Uraniborg

Parallax



$$d = \frac{1\ \mathrm{AU}}{\alpha}$$

- Angles are expressed in radians
- sin(small angle) ~ small angle

Tycho's cosmological model

- Tycho **could not detect** any significant parallax (~100 times too small for naked-eye observations)
  - Concluded Earth is stationary
  - Settled on combined geo/heliocentric model: Sun orbits Earth, planets orbit sun
- Measured **large deviations of Mars** from Copernican model

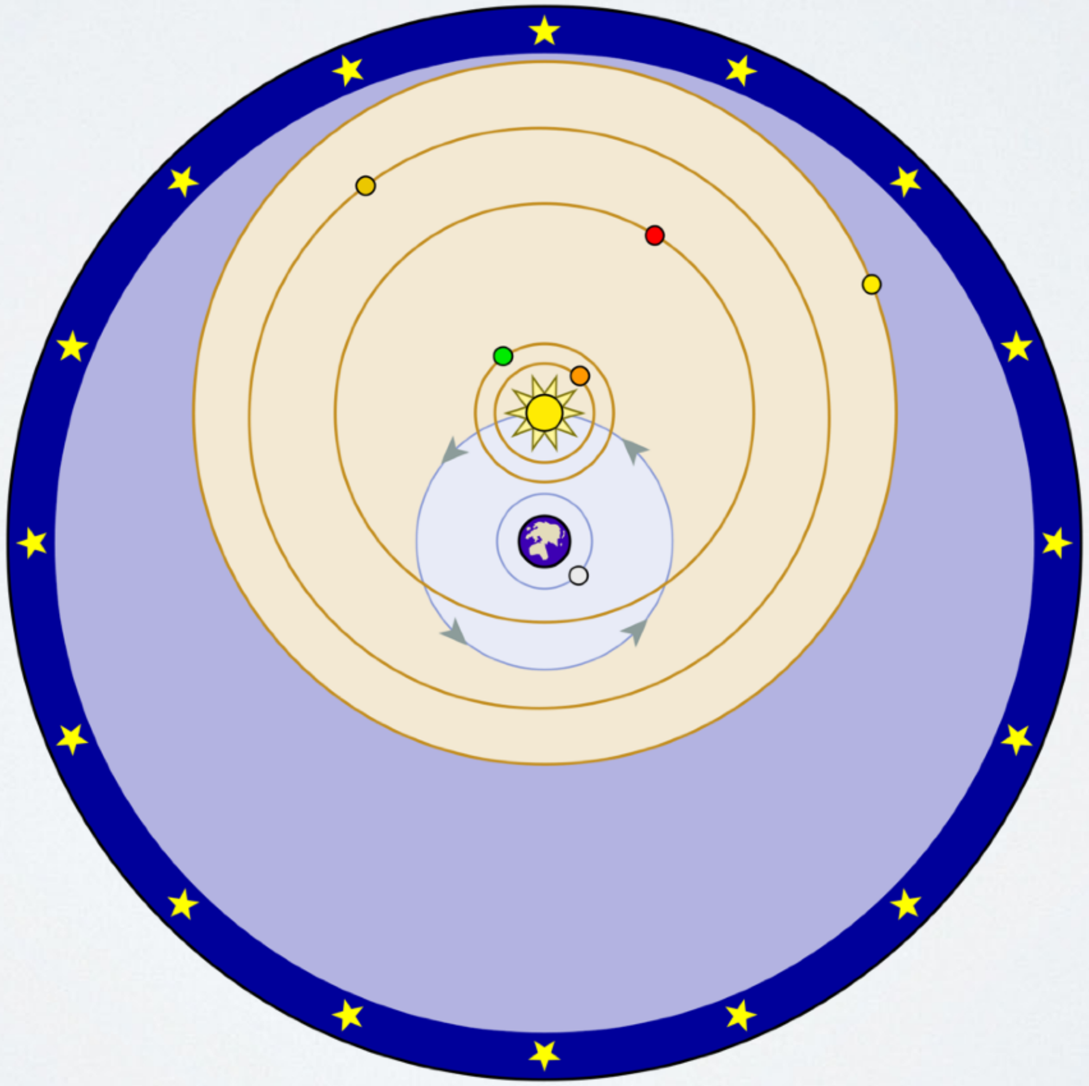


Image: FastFission / Wikipedia

Part 2: Kepler’s Laws

Johannes Kepler (1571-1630)

- Born in Germany
- Got into astronomy as a child after seeing the **Great Comet of 1577**
- Childhood smallpox **damaged his vision**
- Quite **religious**
  - Originally planned to be ordained as Lutheran minister
  - Convinced God made the Universe according to a mathematical plan
  - Saw his Christian duty as understanding works God had created

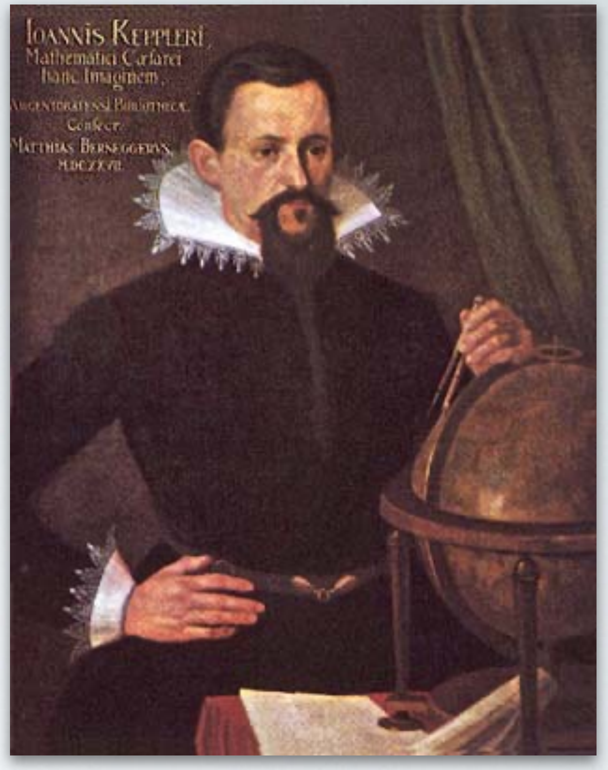
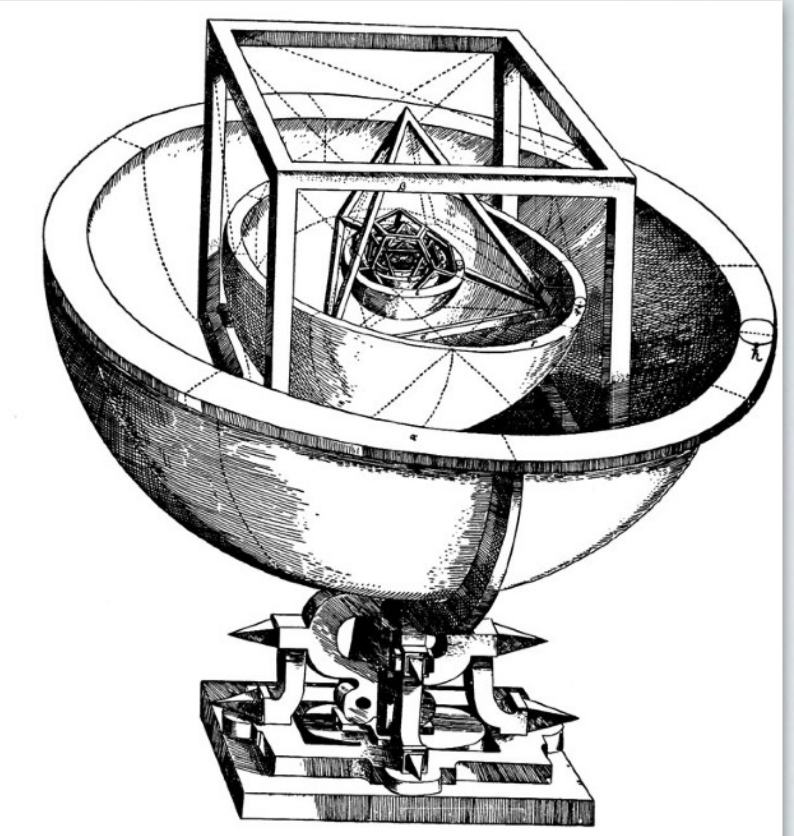


Image: Jiri Daschitzky / Wikipedia

Johannes Kepler (1571-1630)

- Studied mathematics
- Published in 1596 his **Mystery of the Cosmos** proposing that planetary orbits lie in spheres nested within a series of the **Platonic solids** (wrong!)
- Was hired as **Tycho Brahe's assistant** in Prague; his job was to make sense of Brahe's extremely accurate observations of Mars
- Kepler became **Imperial Mathematician** after Brahe's death (1601)



The Polyhedra inscribed into the planetary orbits. Kepler's drawing is a pure geometrical fancy, but it is meant to correspond to the actual relation between the radii of the planetary orbits. Most important here is the cube, fitted into the outermost sphere of Saturn.

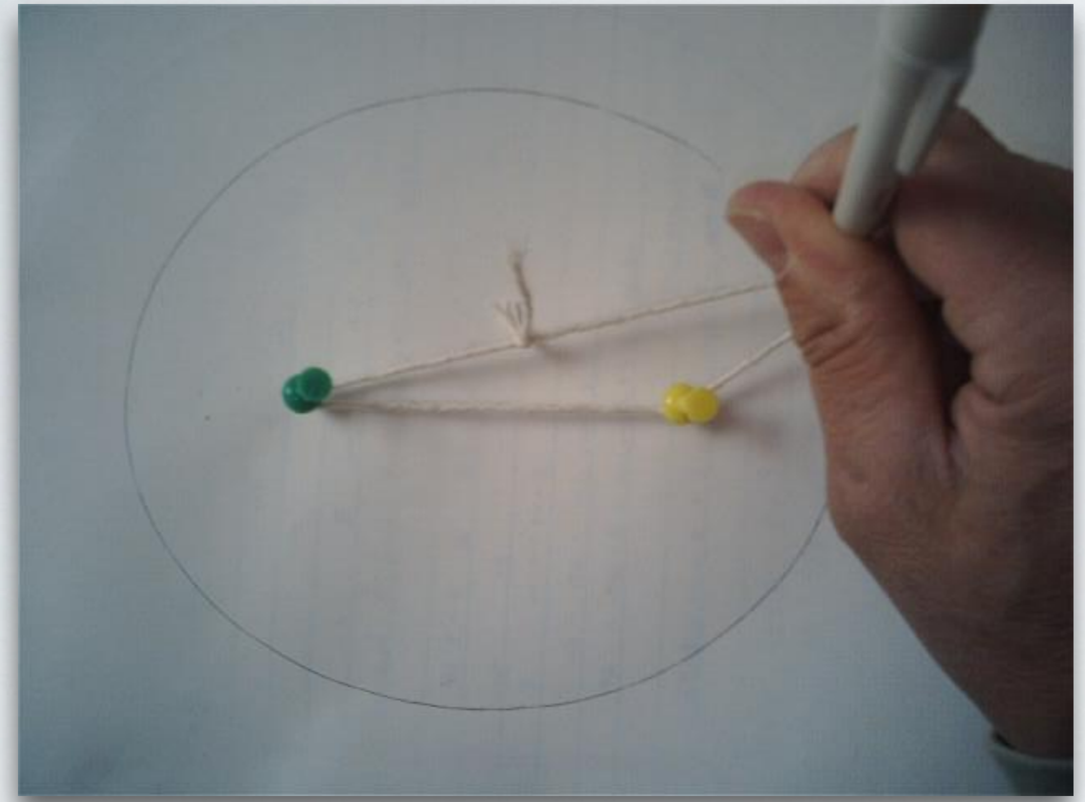
Law vs. Theory

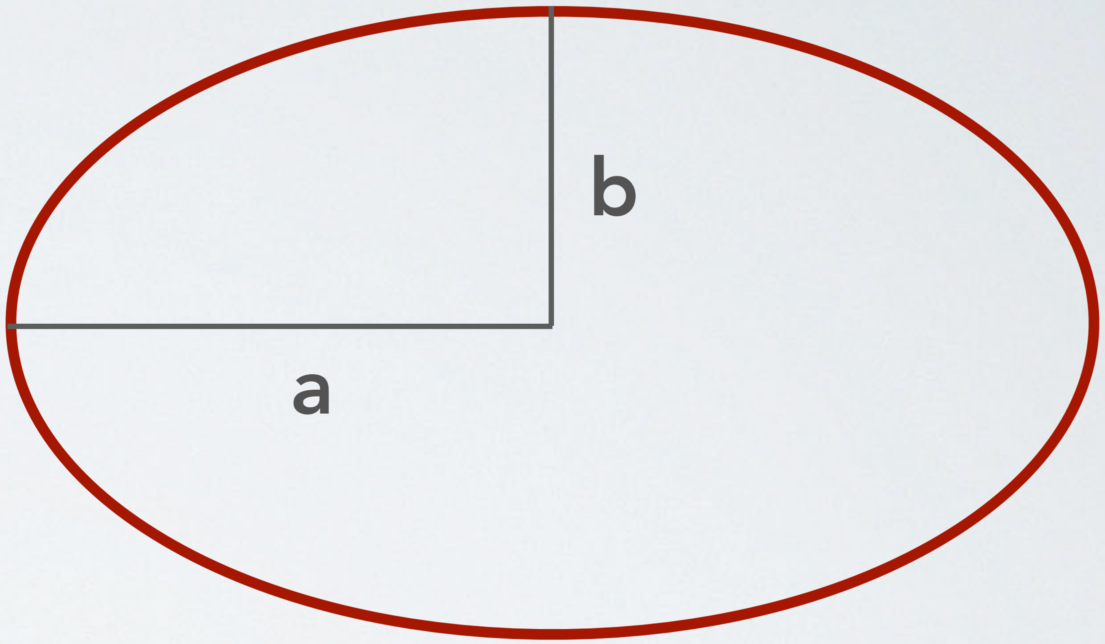
- **Law:** Descriptive statement of observation
- **Theory:** Explanation of observed phenomena

Kepler’s three laws (imprecise)

- **Law 1:** Orbits are not circular
- **Law 2:** A planet changes speed along its orbit
- **Law 3:** Relation between period and distance

Kepler's 1st law





Ellipse: $$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

Ellipticity: $$\epsilon = \sqrt{1 - \frac{b^2}{a^2}}$$

Participation: Perihelion date

Respond to the poll on TurningPoint

Session ID: diemer

30 seconds

Kepler's 1st law

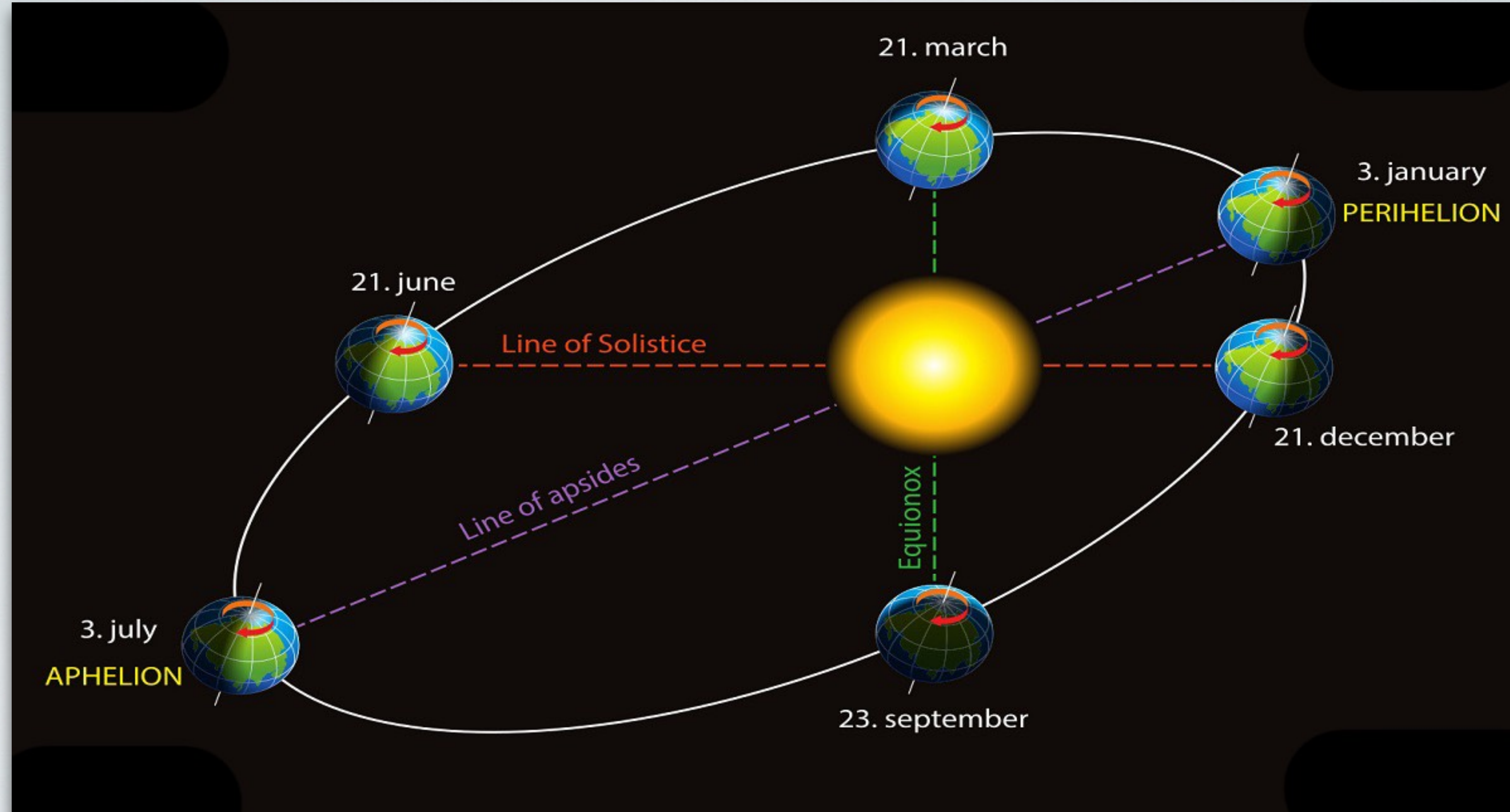
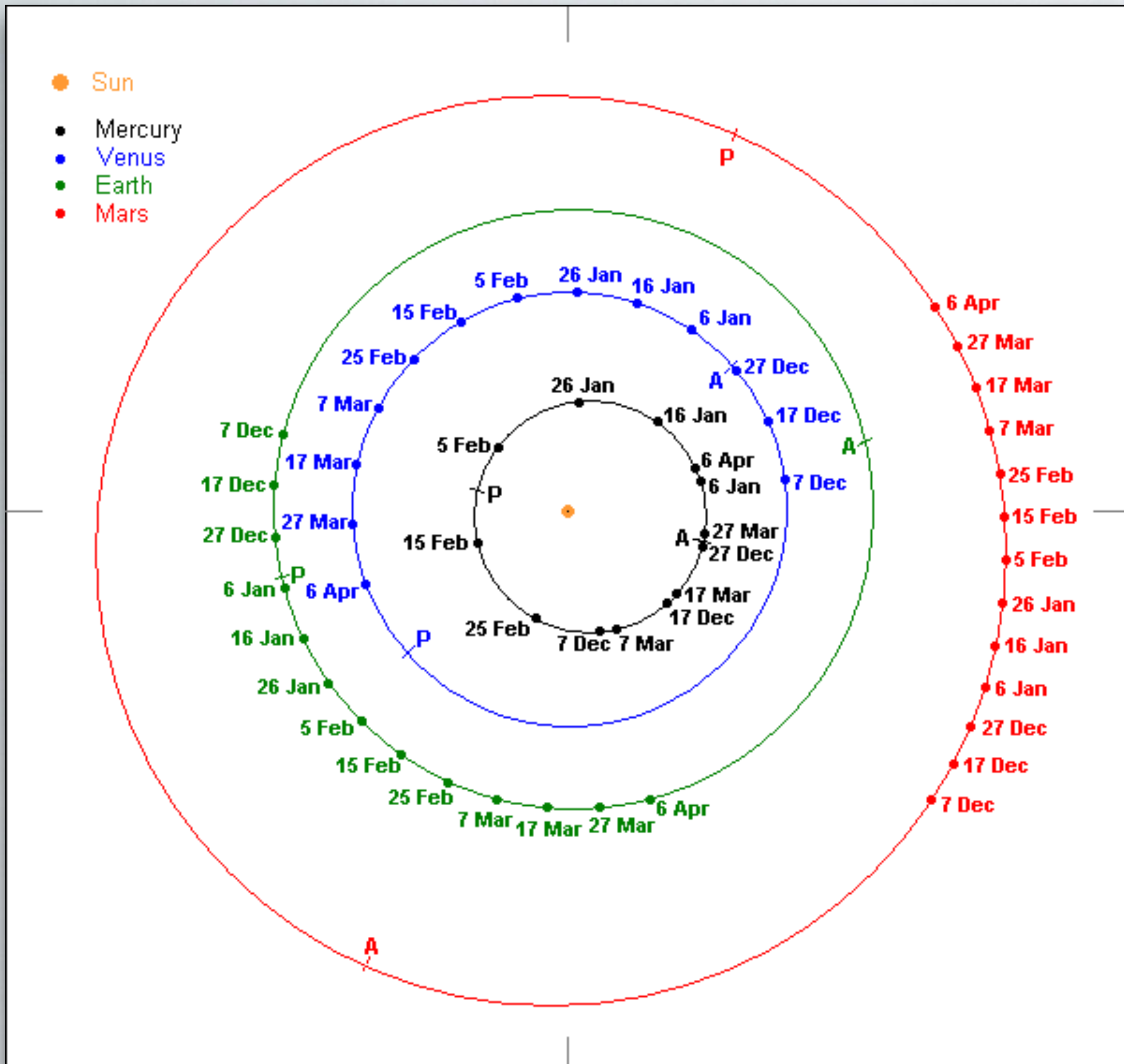


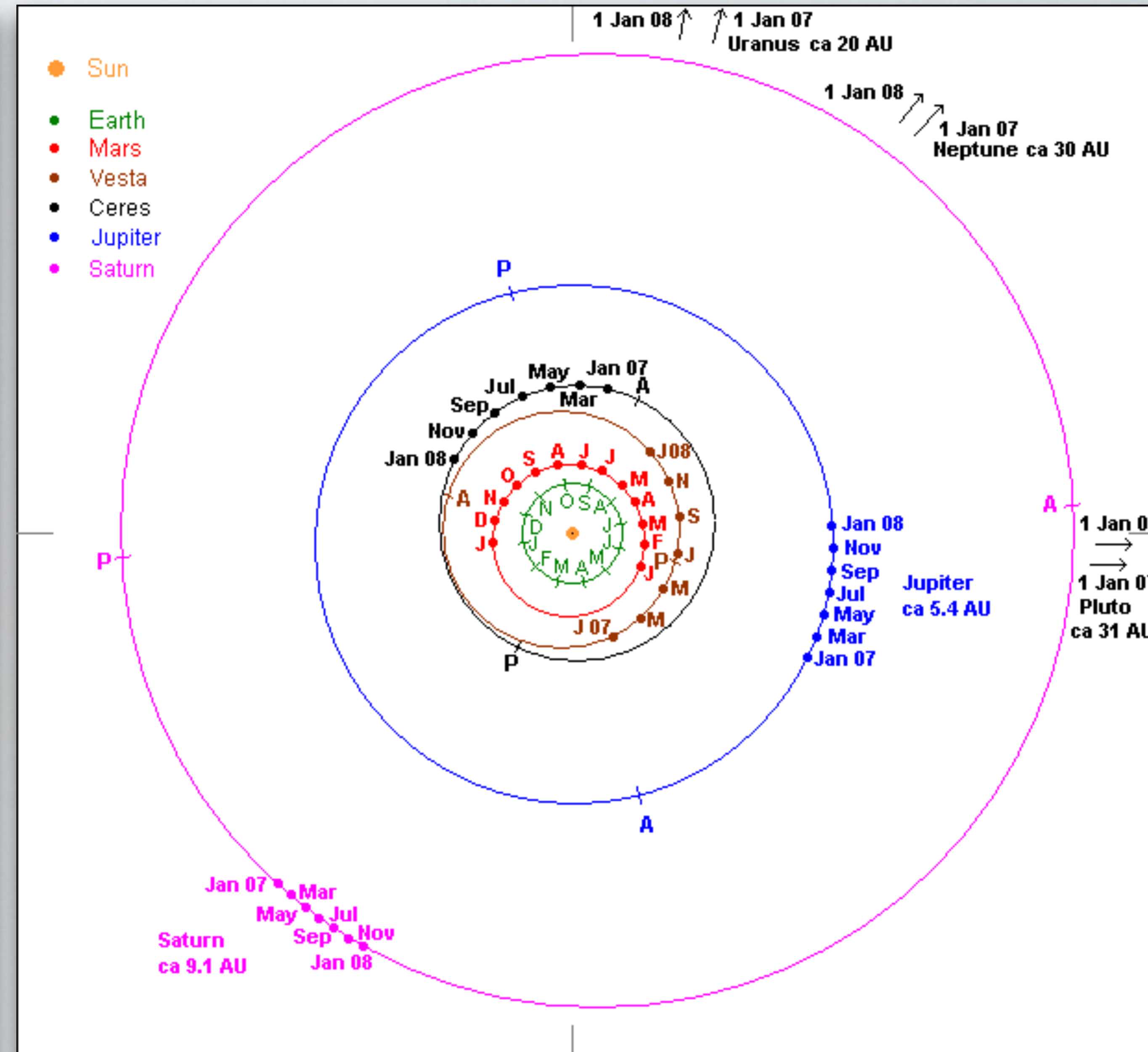
Image: NoPainNoGain / Shutterstock

Solar system orbits

Inner planets



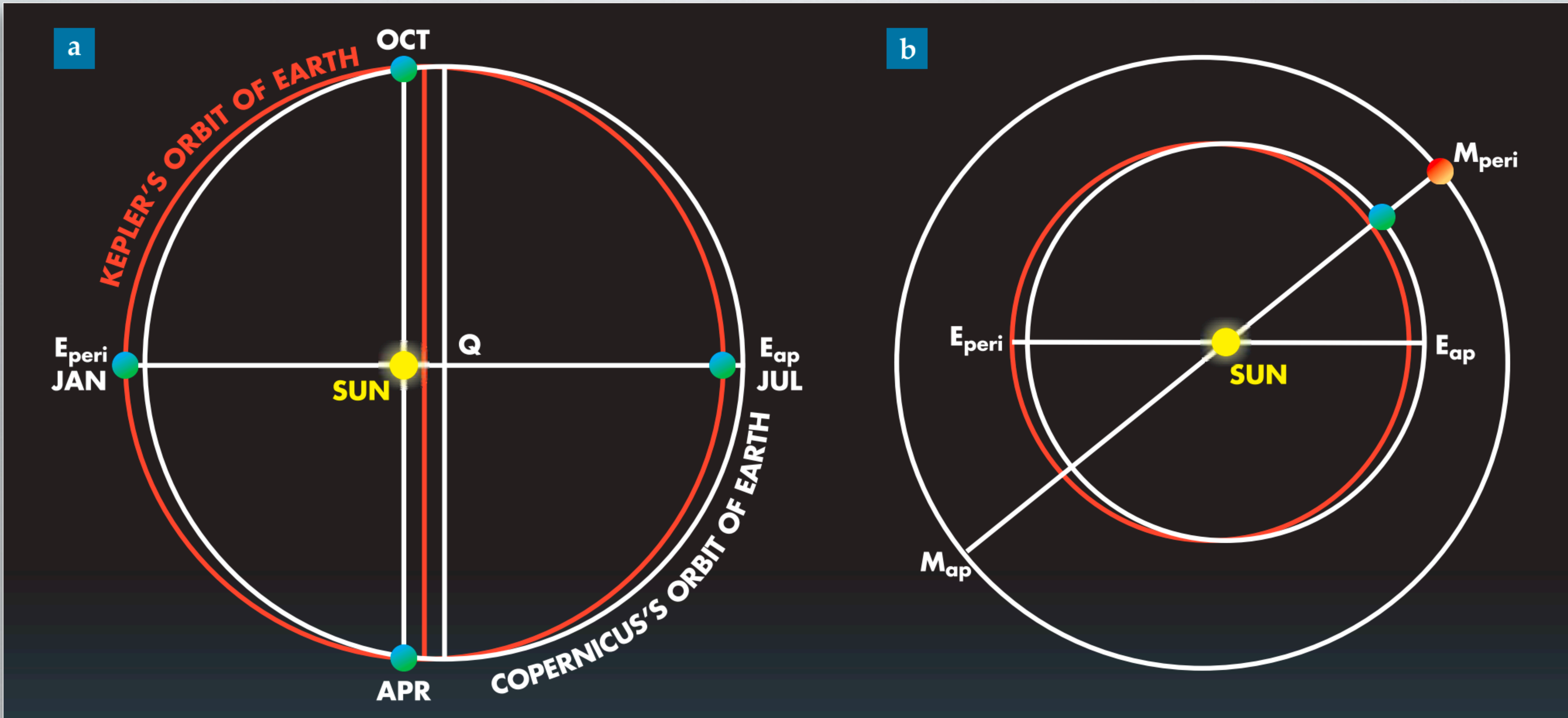
Outer planets



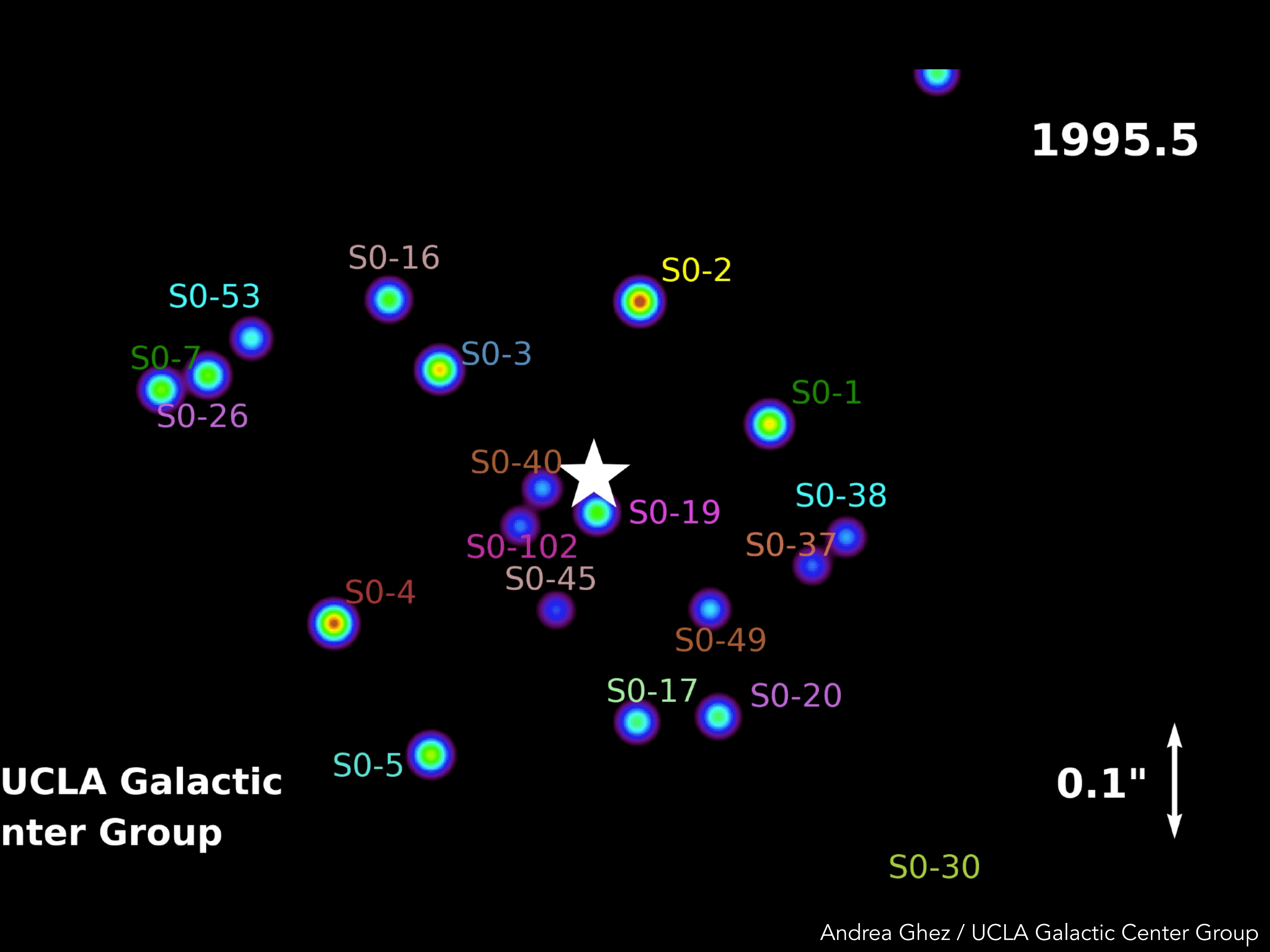
Solar system eccentricities are small!

Images: www.rasnz.org.nz

Kepler vs. Copernicus: The "war with Mars"



Gingerich 2011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S0-45
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Andrea Ghez / UCLA Galactic Center Group

Participation: Black hole mass

Respond to the poll on TurningPoint

Session ID: diemer

30 seconds

Kepler's 2nd law

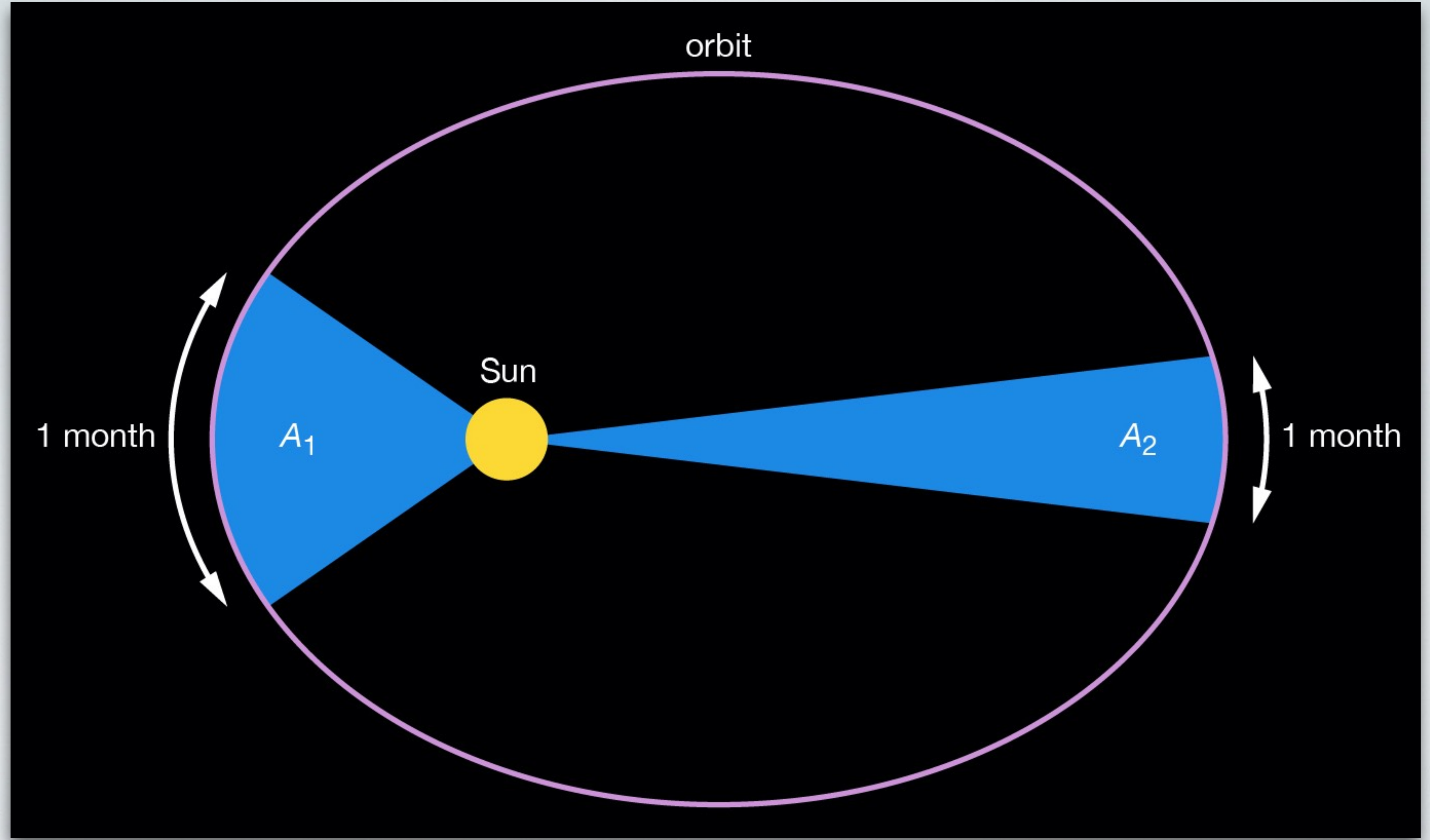


Image: Encyclopedia Britannica

Kepler's 3rd law

$$P^2 \propto a^3$$

- **P: period** = time it takes for planet to complete one orbit
- **a: semi-major axis** = half of the length of the "long" (i.e. major) axis of the ellipse.

Knowing Earth data:

$$\left(\frac{P}{\mathrm{yr}}\right)^2 = \left(\frac{a}{\mathrm{AU}}\right)^3$$

- **yr: year** = 3×10^7 seconds
- **AU: astronomical unit** = earth-sun distance = 150 million km

Knowing Newton's laws:

$$P^2 = \frac{4\pi^2}{G(M+m)}a^3$$

- **G: gravitational const** = $6.67 \times 10^{-11} \frac{m^3}{\mathrm{kg}\ s^2}$
- **M: mass of first body** (e.g., Sun)
- **m: mass of second body** (e.g., Earth)

Kepler's three laws (precise)

- **Law 1:** The orbits of planets are ellipses
- **Law 2:** A line between the sun and planet sweeps out a constant area per time
- **Law 3:** Period^2 is proportional to distance^3

Kepler in perspective

- Based on **Tycho Brahe's accurate observations**, Kepler calculated and thought his way to a major breakthrough in cosmology
- Kepler's three laws of planetary motion
    - Represented a **very simple** (and correct!) model of the solar system
    - Swept away thousands of years of **prejudice** (circular orbits, his own previous pet theory)
    - Were driven fundamentally by the data, including Tycho's **error estimates**
- Kepler's Laws had **predictive power**, consistent with modern idea of a meaningful scientific theory

Kepler's 3rd law

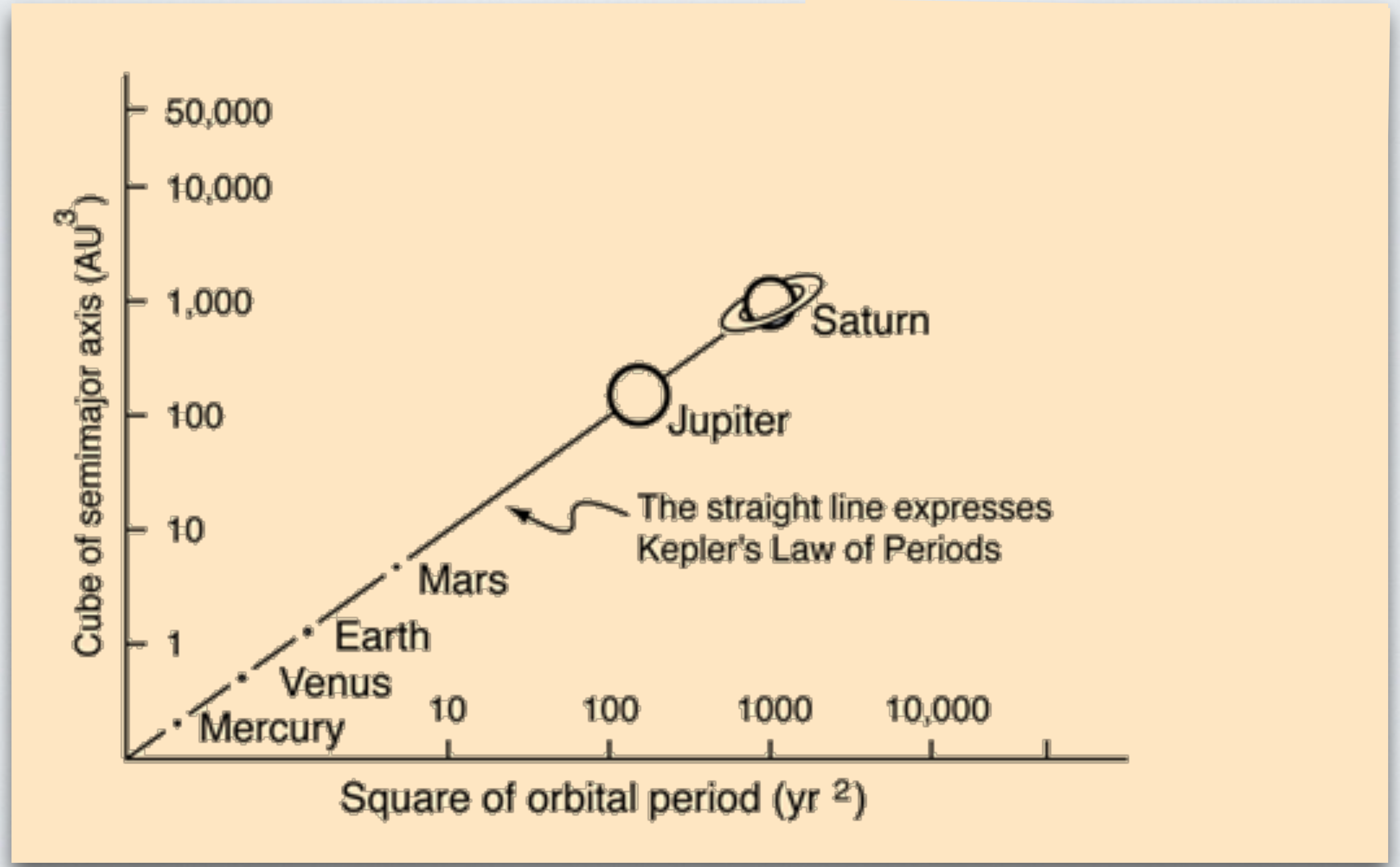
	Distance to Sun	Period
Mercury	0.4 AU	88 Earth days
Venus	0.72 AU	225 Earth days
Mars	1.5 AU	687 Earth days
Jupiter	5.2 AU	4332 Earth days

Table: Peter Behroozi

Kepler's 3rd law

$$\left(\frac{P}{\mathrm{yr}}\right)^2 = \left(\frac{a}{\mathrm{AU}}\right)^3 \quad \rightarrow 2\log_{10}\left(\frac{P}{\mathrm{yr}}\right) = 3\log_{10}\left(\frac{a}{\mathrm{AU}}\right)$$

$$\rightarrow \log_{10}\left(\frac{P}{\mathrm{yr}}\right) = \frac{3}{2}\log_{10}\left(\frac{a}{\mathrm{AU}}\right)$$



Plot: hyperphysics.phy-astr.gsu.edu

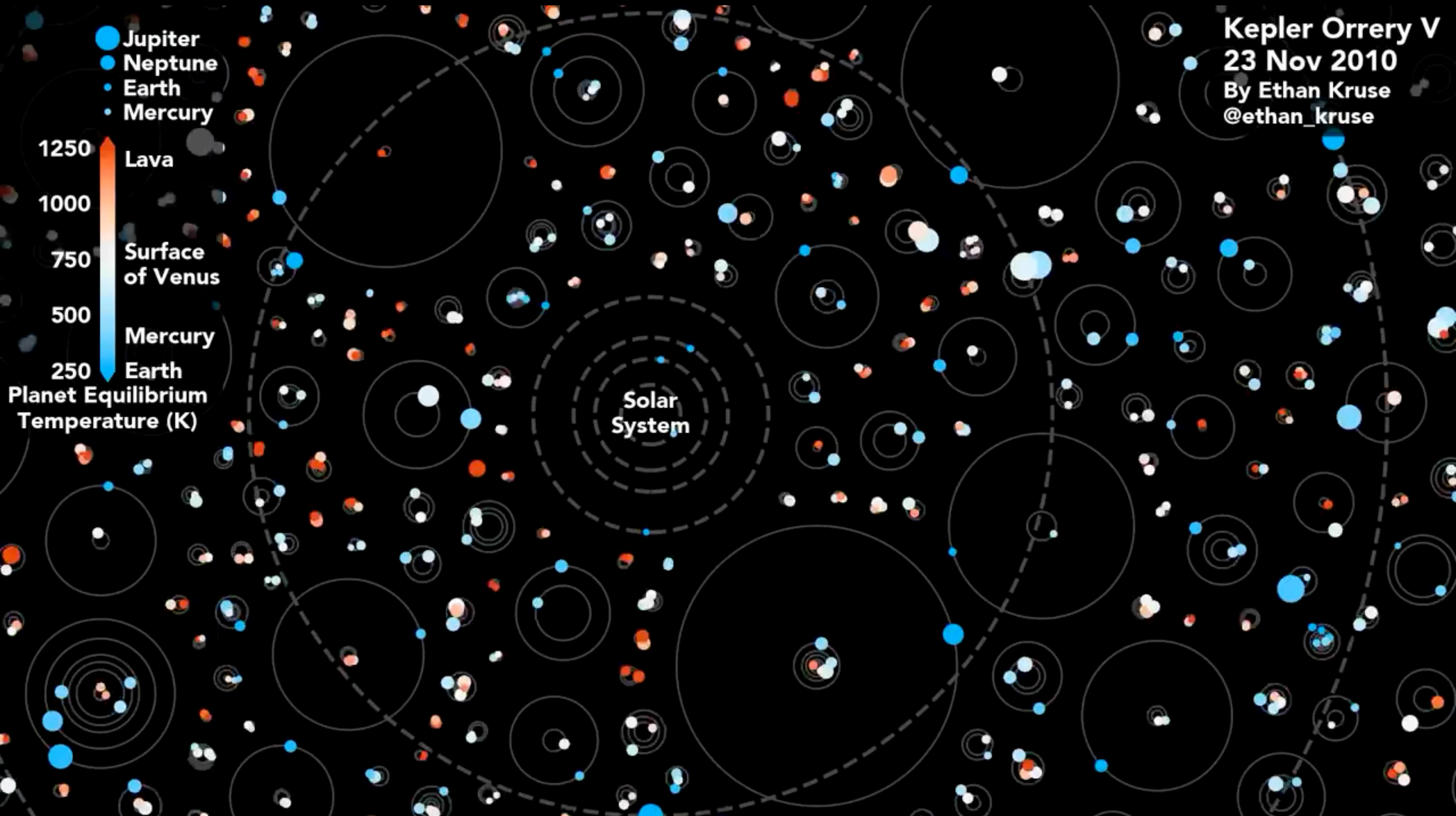
Participation: How many exoplanets?

Respond to the poll on TurningPoint

Session ID: diemer

30 seconds

Exoplanets discovered by the Kepler observatory



Participation: Group discussion #3

In this group discussion, we will explore the concept of **free parameters**. Almost any theory will leave some numbers unexplained, which must then be found experimentally. In your discussion post, please consider the following questions:

- Roughly **how many free parameters** are needed to describe the motion of the planets (say, out to Saturn) in each of the following systems? The exact number depends on the subtleties of each model; here, it's more important that you have an explanation for your estimate. (Hint: consider the free parameters needed for each sphere/orbit)
    - Aristotle (55 spheres)
    - Ptolemy (assume orbits with one epicycle and offset ("equant") for each body
    - Copernicus (including equants)
    - Kepler (assuming all planets orbit in the same plane)
- How is the number of free parameters related to the **scientific method?** Think about the five criteria for a valid hypothesis.

12 minutes

Participation: Group discussion #3

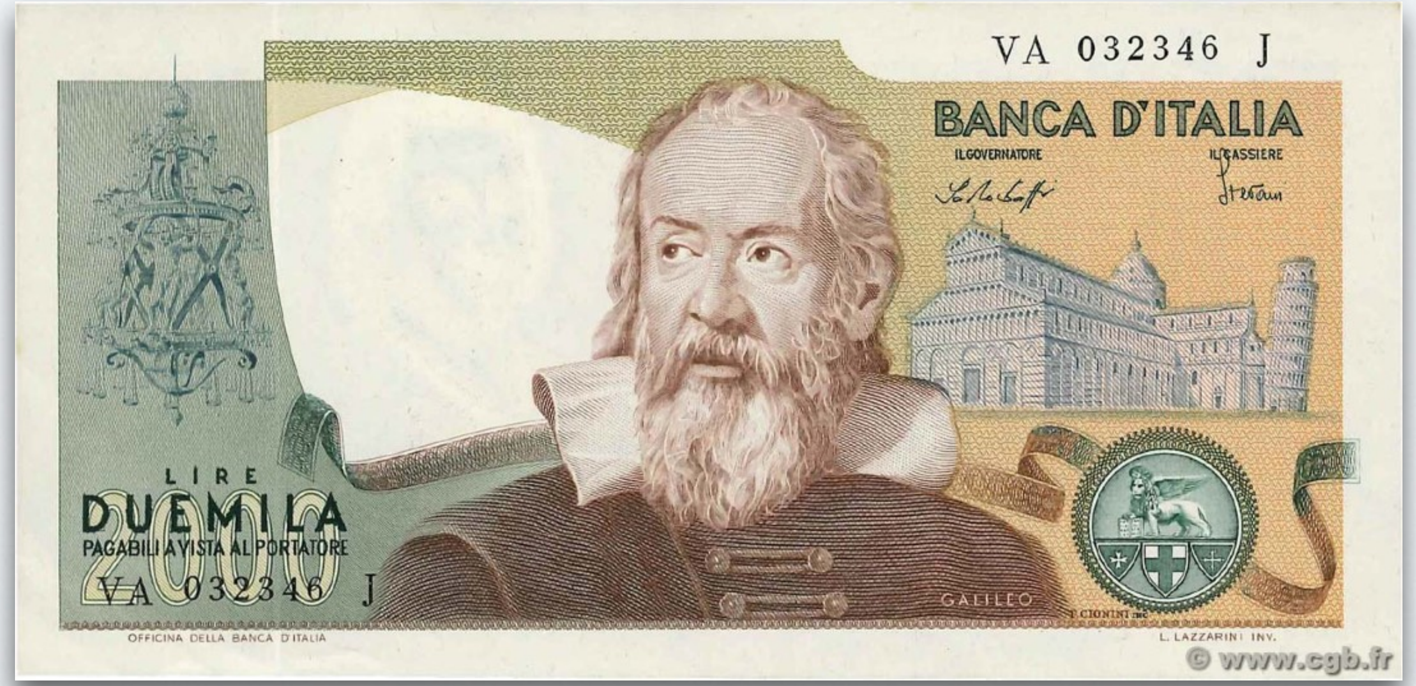
- **Aristotle:**
  - For each sphere, need radius, direction of rotation (2 angles), speed = 4 parameters -> up to **220 parameters**
- **Ptolemy:**
  - For each body, need radius of orbit and epicycle, speeds (2), equant and eccentric (3) = 7 parameters x 7 bodies = about **49 parameters** (more complicated in detail)
- **Copernicus:**
  - For each planet, need radius, period, equant (2) = 4 parameters x 7 bodies = about **28 parameters**
- **Kepler:**
  - For each planet, need period (or distance), ellipticity, direction of ellipse = 3 parameters x 7 bodes = about **21 parameters**

Not exactly correct! Full models are more complicated

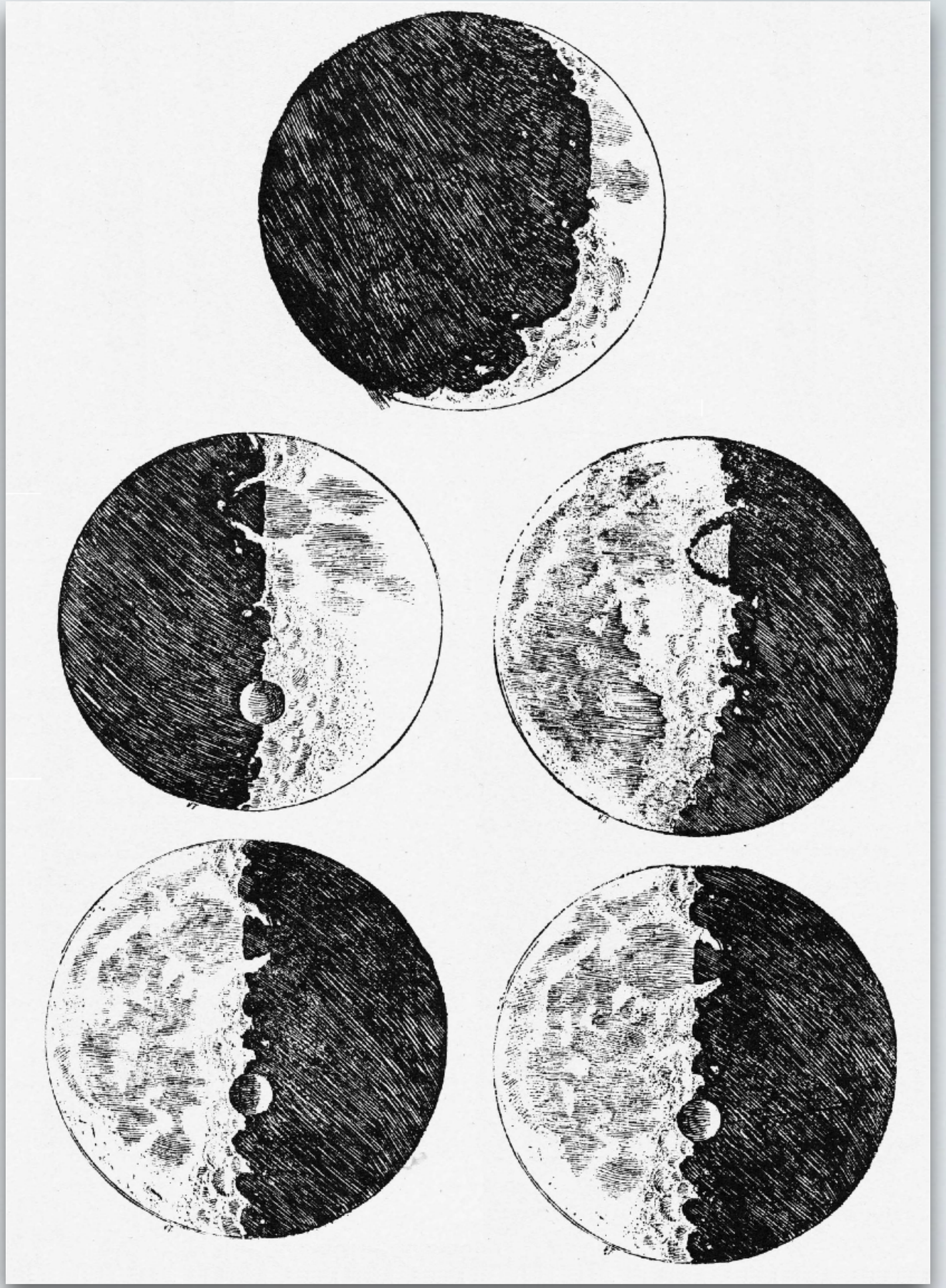
Part 3: Galileo Galilei

Galileo Galilei (1564-1642)

- Born in Pisa; worked as professor of mathematics
- Built one of the **first telescopes** in 1609
- Telescopic observations (some published in *The Starry Messenger, 1610)*
    - Saw craters and mountains on the **Moon**
    - Realized **sunspots** were on surface, not foreground; rotated with Sun
    - Identified four **satellites of Jupiter** ("Galilean moons")
    - Saw **rings of Saturn**
    - Resolved the **diffuse Milky Way** into many faint stars
    - Observed **phases of Venus** including gibbous and full

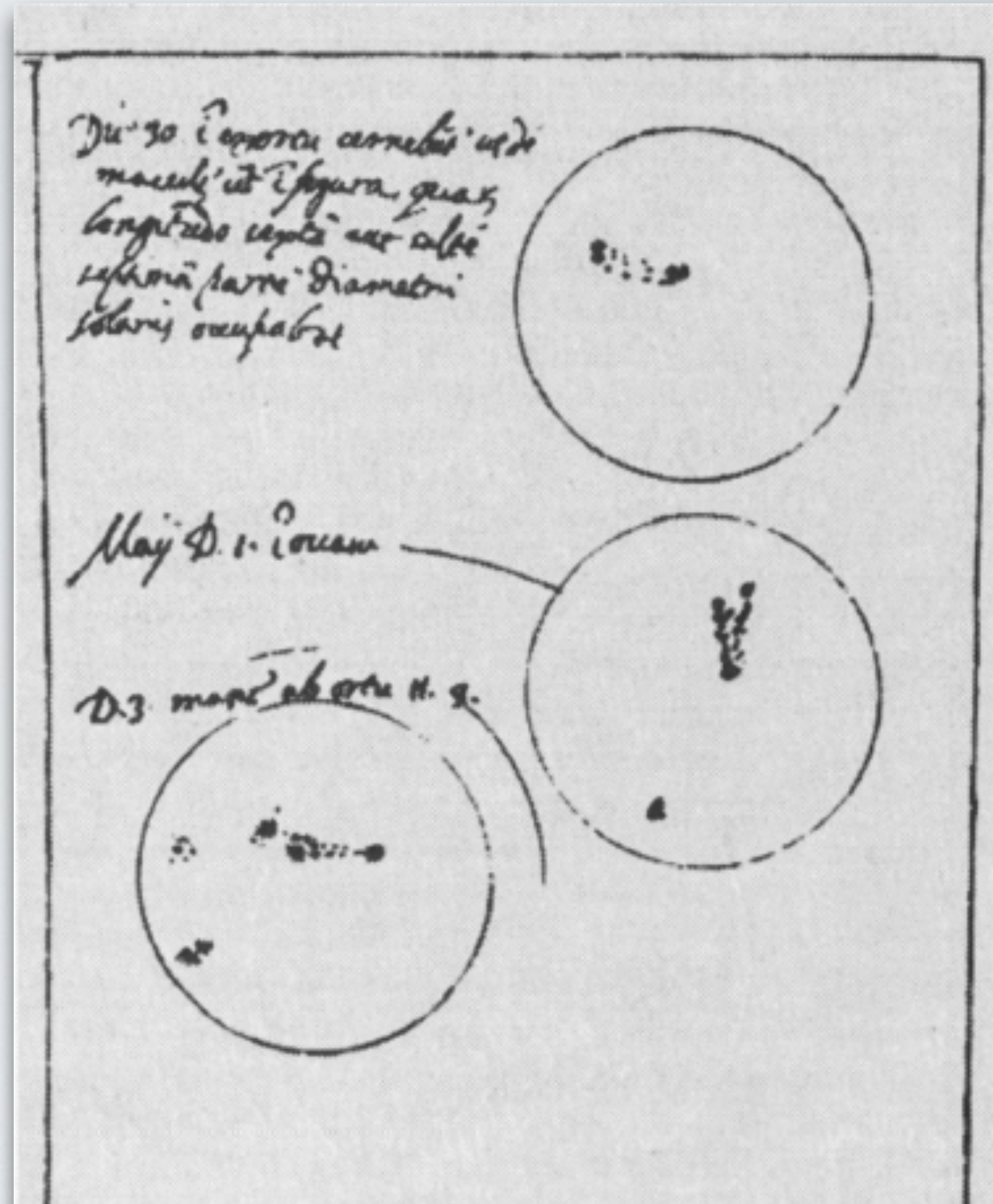


Galileo’s observations: The Moon

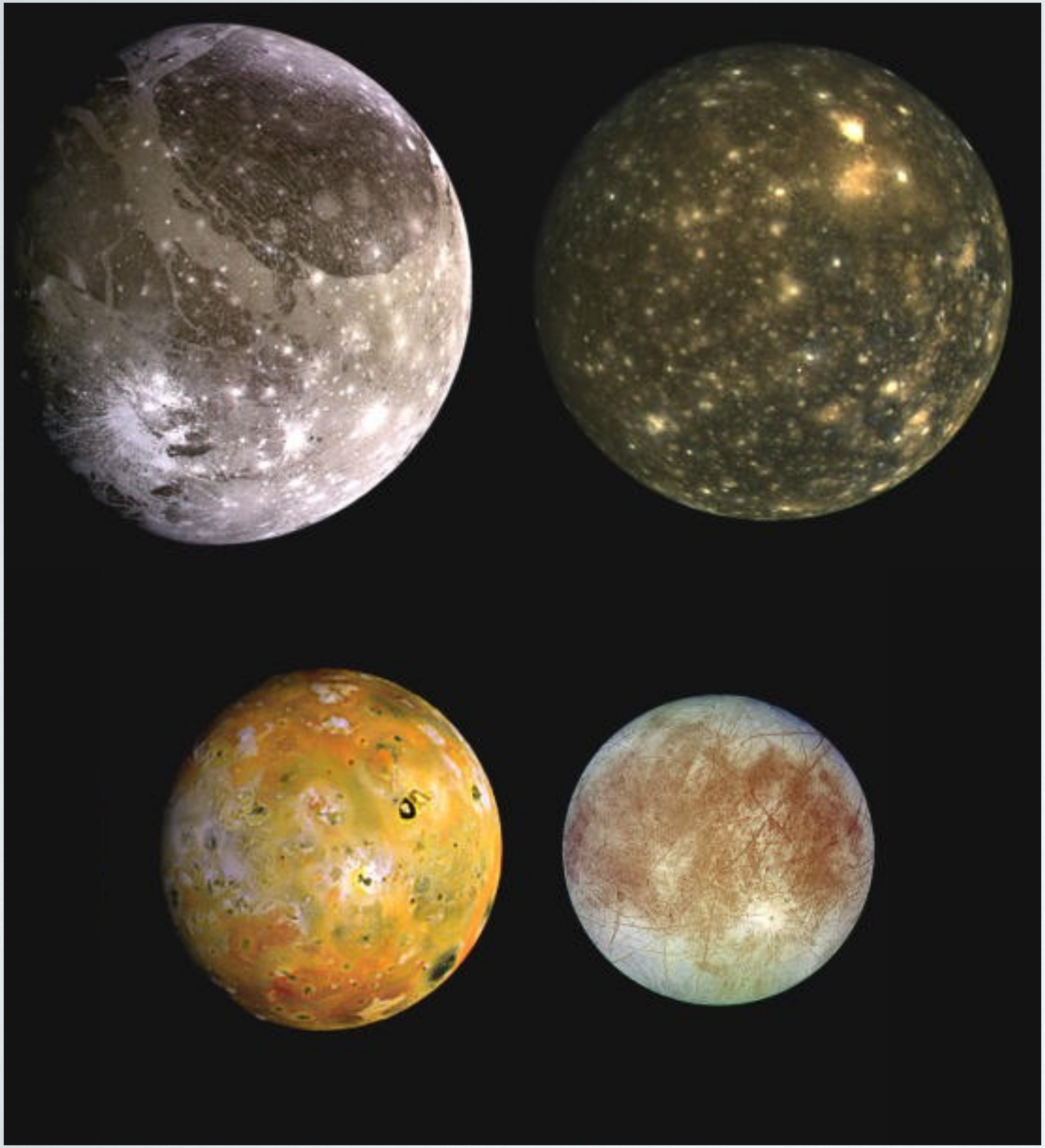


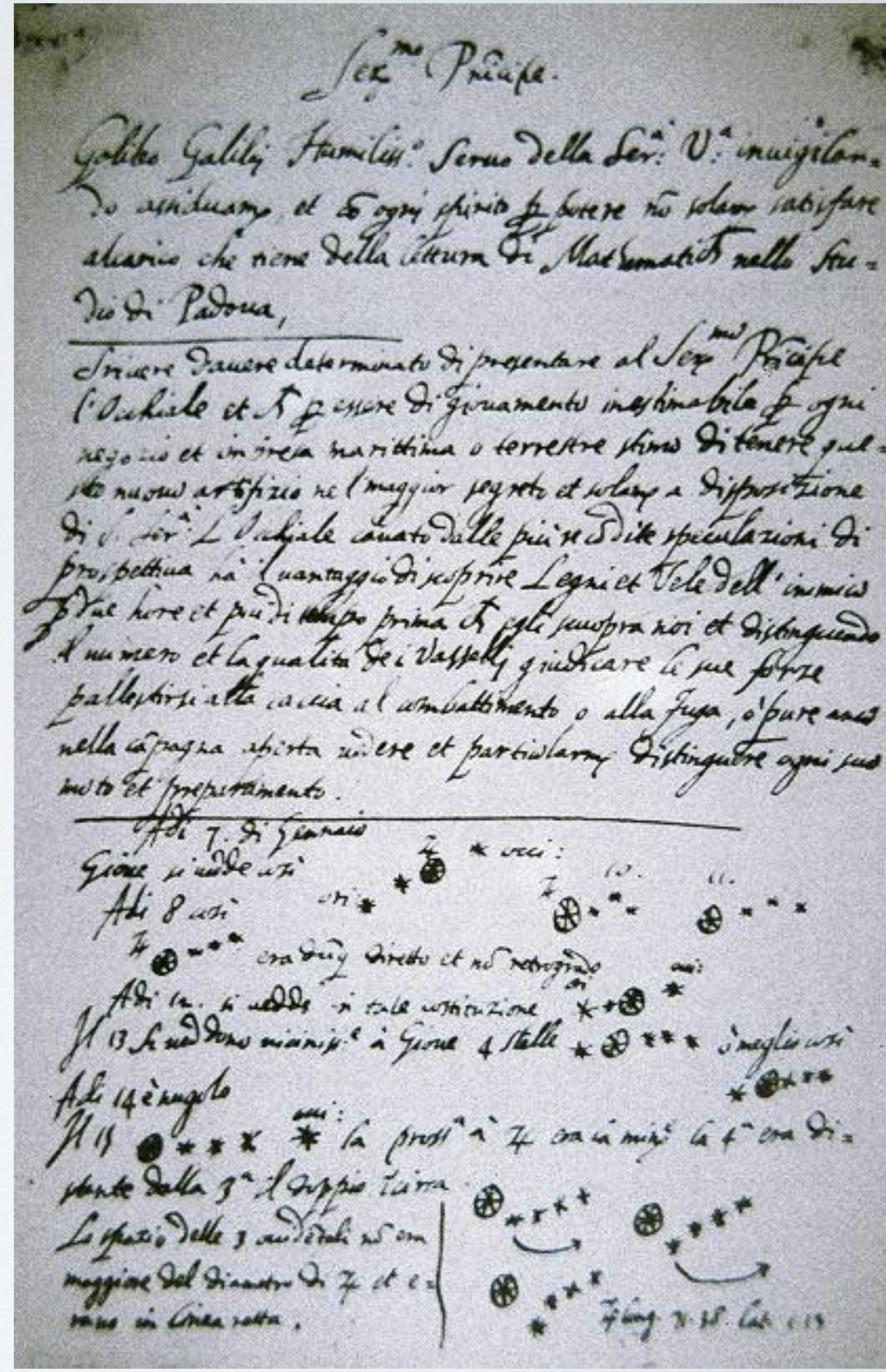
Images: astromax.org, Siderius Nuncius

Galileo's observations: Sunspots



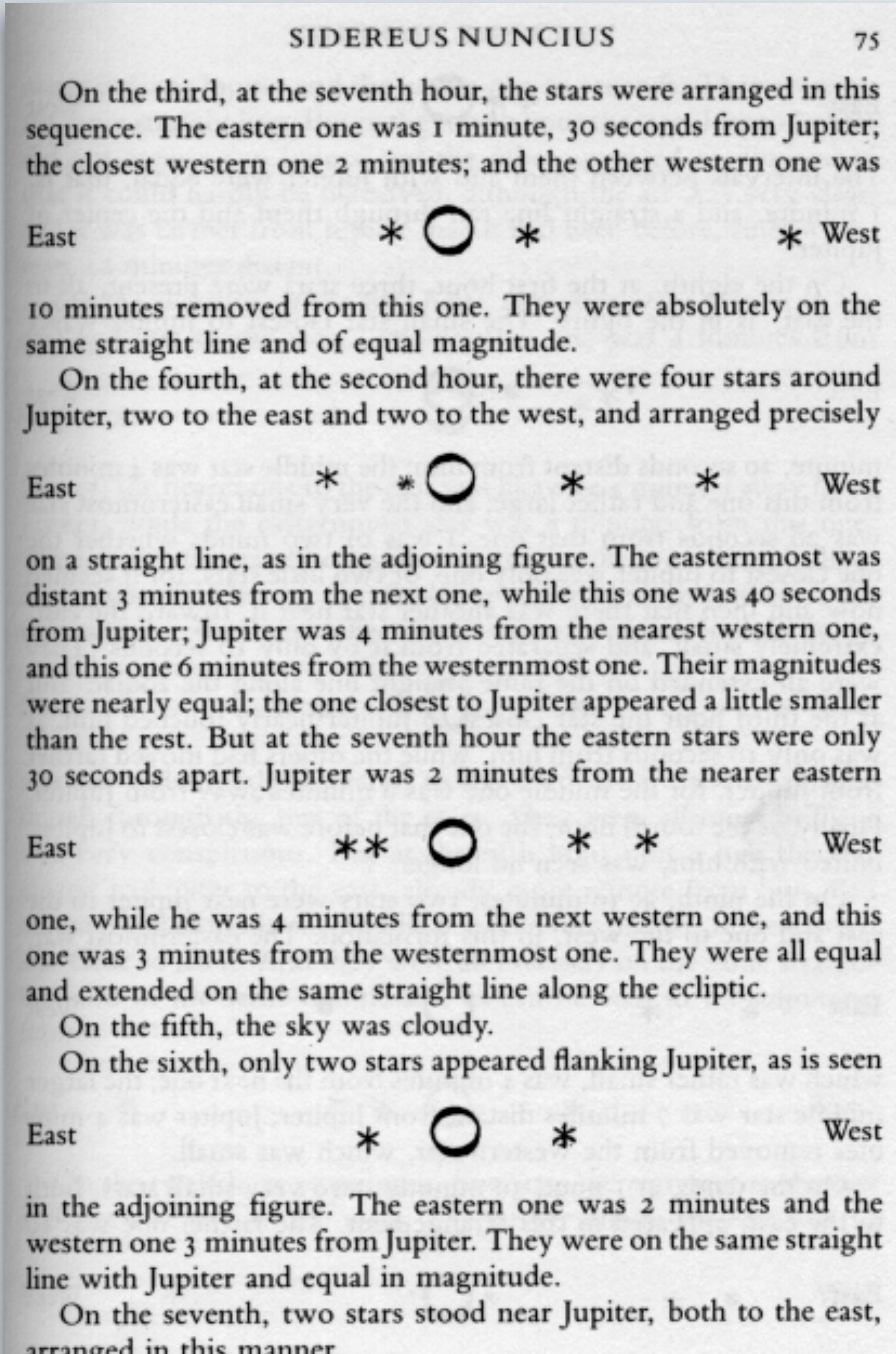
Galileo’s observations: Jupiter moons





Images: NASA, Wikipedia

Galileo’s observations: Jupiter moons



On the third, at the seventh hour, the stars were arranged in this sequence. The eastern one was 1 minute, 30 seconds from Jupiter; the closest western one 2 minutes; and the other western one was

East * ○ * * West

10 minutes removed from this one. They were absolutely on the same straight line and of equal magnitude.

On the fourth, at the second hour, there were four stars around Jupiter, two to the east and two to the west, and arranged precisely

East * * ○ * * West

on a straight line, as in the adjoining figure. The easternmost was distant 3 minutes from the next one, while this one was 40 seconds from Jupiter; Jupiter was 4 minutes from the nearest western one, and this one 6 minutes from the westernmost one. Their magnitudes were nearly equal; the one closest to Jupiter appeared a little smaller than the rest. But at the seventh hour the eastern stars were only 30 seconds apart. Jupiter was 2 minutes from the nearer eastern

East ** ○ * * West

one, while he was 4 minutes from the next western one, and this one was 3 minutes from the westernmost one. They were all equal and extended on the same straight line along the ecliptic.

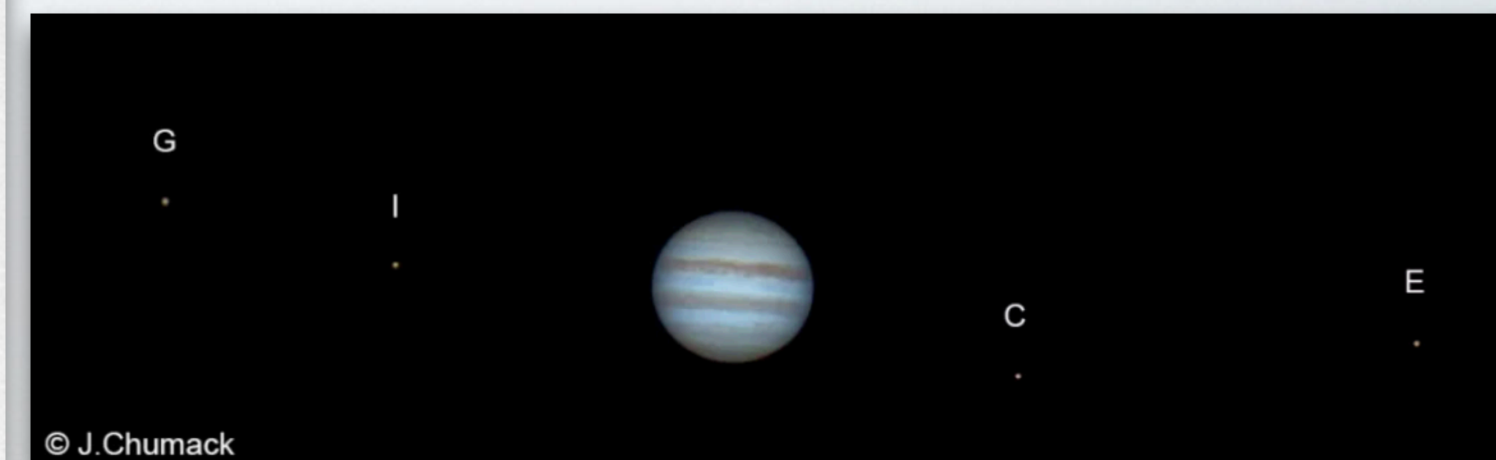
On the fifth, the sky was cloudy.

On the sixth, only two stars appeared flanking Jupiter, as is seen

East * ○ * West

in the adjoining figure. The eastern one was 2 minutes and the western one 3 minutes from Jupiter. They were on the same straight line with Jupiter and equal in magnitude.

On the seventh, two stars stood near Jupiter, both to the east, arranged in this manner.



Images: Siderius Nuncius

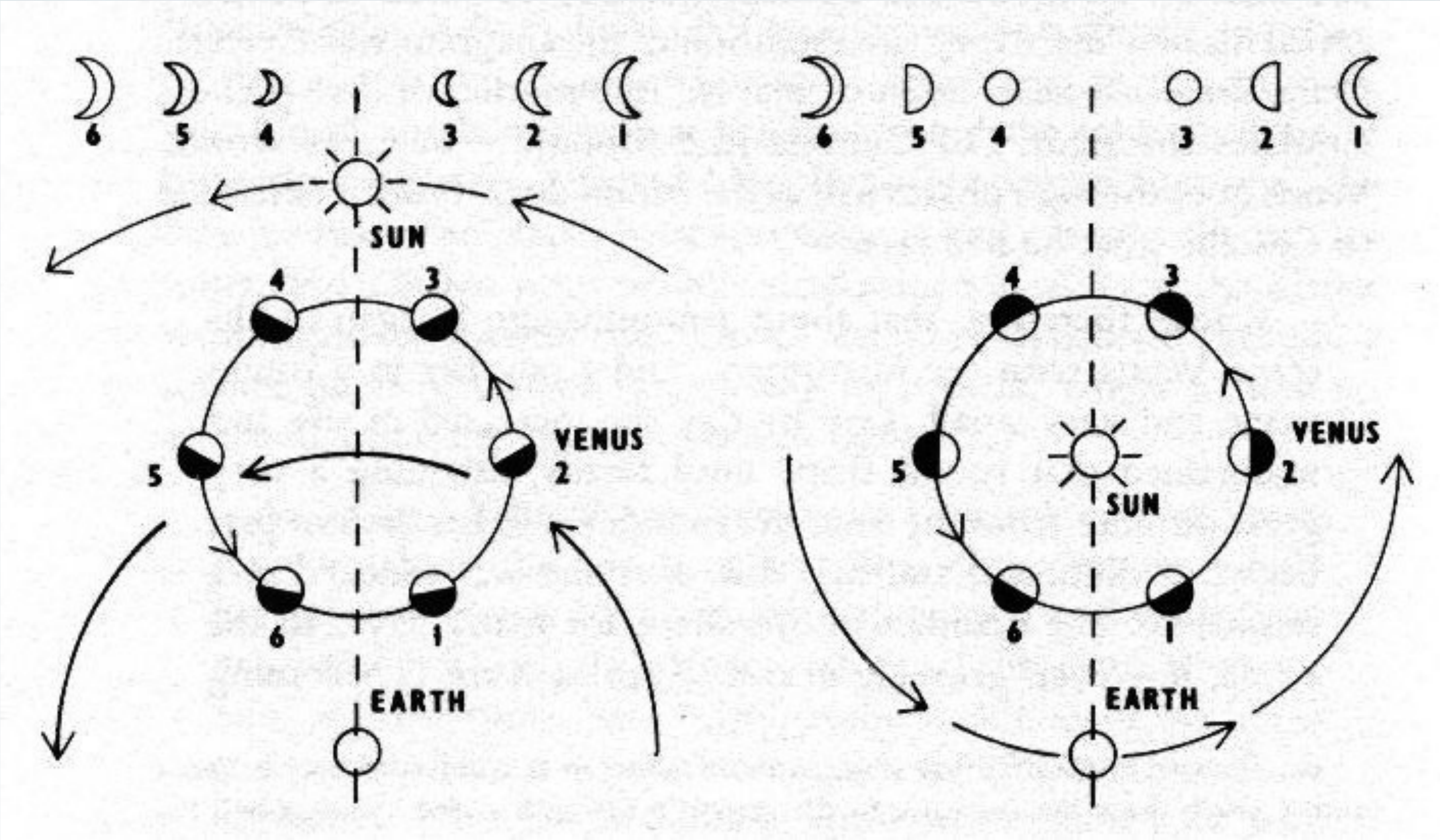
Galileo's lens

Galileo's… WHAT?

Galileo’s impact

- Chipping away at Aristotelian point of view:
  - Features on Sun, Moon, Saturn showed they are **not “perfect” orbs**
  - Faint stars resolved in Milky Way indicate **different distances** rather than a single sphere
  - Moons of Jupiter showed that **Earth is not sole center of motion**

Galileo’s observations: Phases of Venus



- **To Kepler:**
  Haec immatura a me iam frustra leguntur o.y.
  These are now too young to be read by me
- **Decoded version:**
  Cynthiae figuras aemulatur mater amorum
  The mother of love imitates the shape of Cynthia

Galileo's impact

- Phases of Venus **rule out Ptolemaic model**
  - Observation supported **Copernican or Tycho's model**
  - Galileo became ardent supporter of Copernican viewpoint
- In 1632, published dialogue concerning the Ptolemaic and Copernican systems
  - The **Inquisition** banned the book
  - Galileo was found guilty of **heresy** in supporting Copernican view
  - Sentenced to **house arrest**

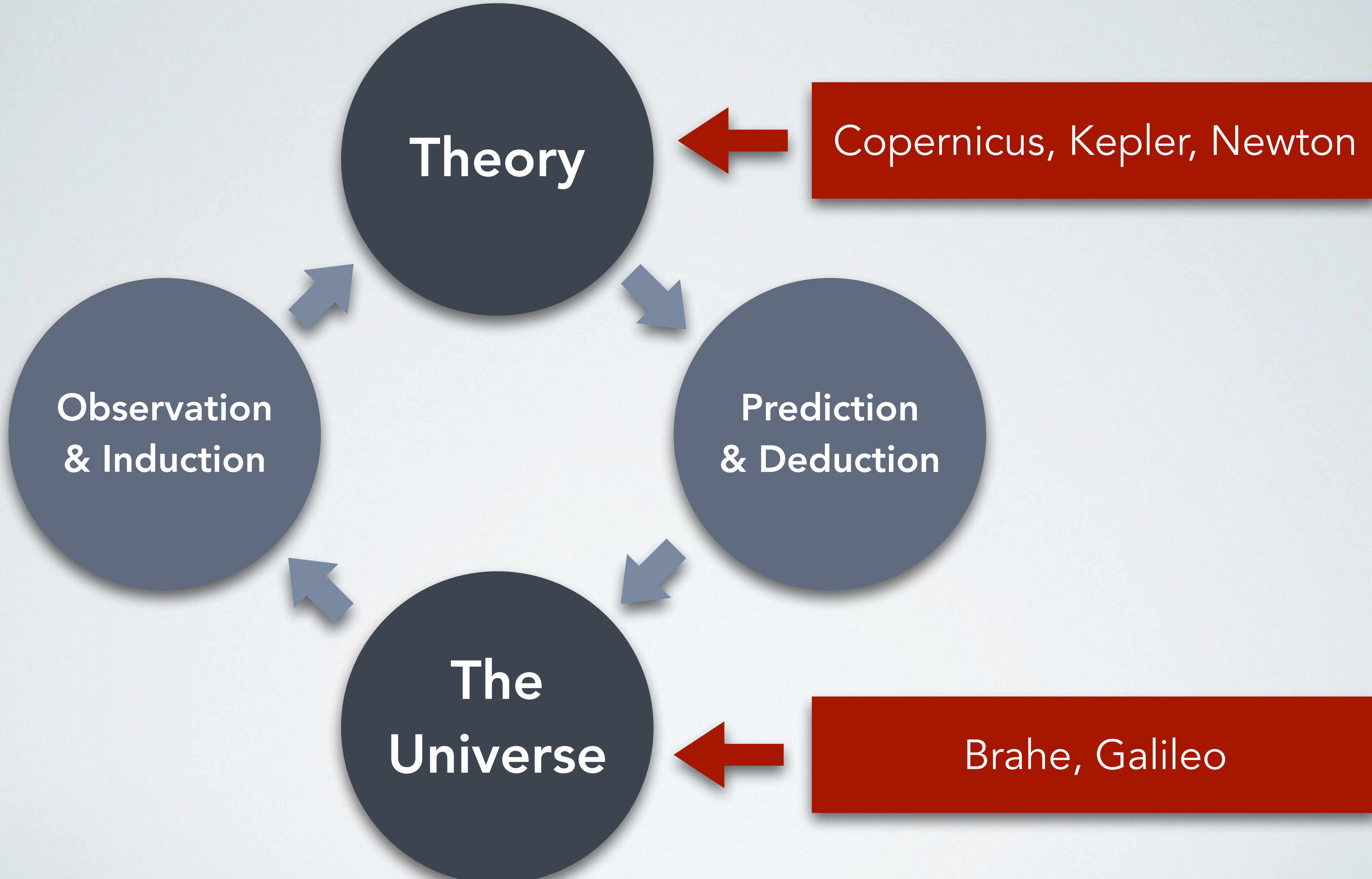
Participation: Favorite Renaissance scientist

Respond to the poll on TurningPoint

Session ID: diemer

30 seconds

The scientific method



Take-aways

- **Renaissance observers** measured orbits in great detail and eventually found proof of the Copernican picture
- **Renaissance theorists** created the foundation of modern physics and astronomy
- The orbits of the planets are **elliptical**

Next time…

We'll talk about:

- Newton, Newton, Newton

Assignments

- Post-lecture quiz (by tomorrow night)

Reading:

- H&H Chapter 3