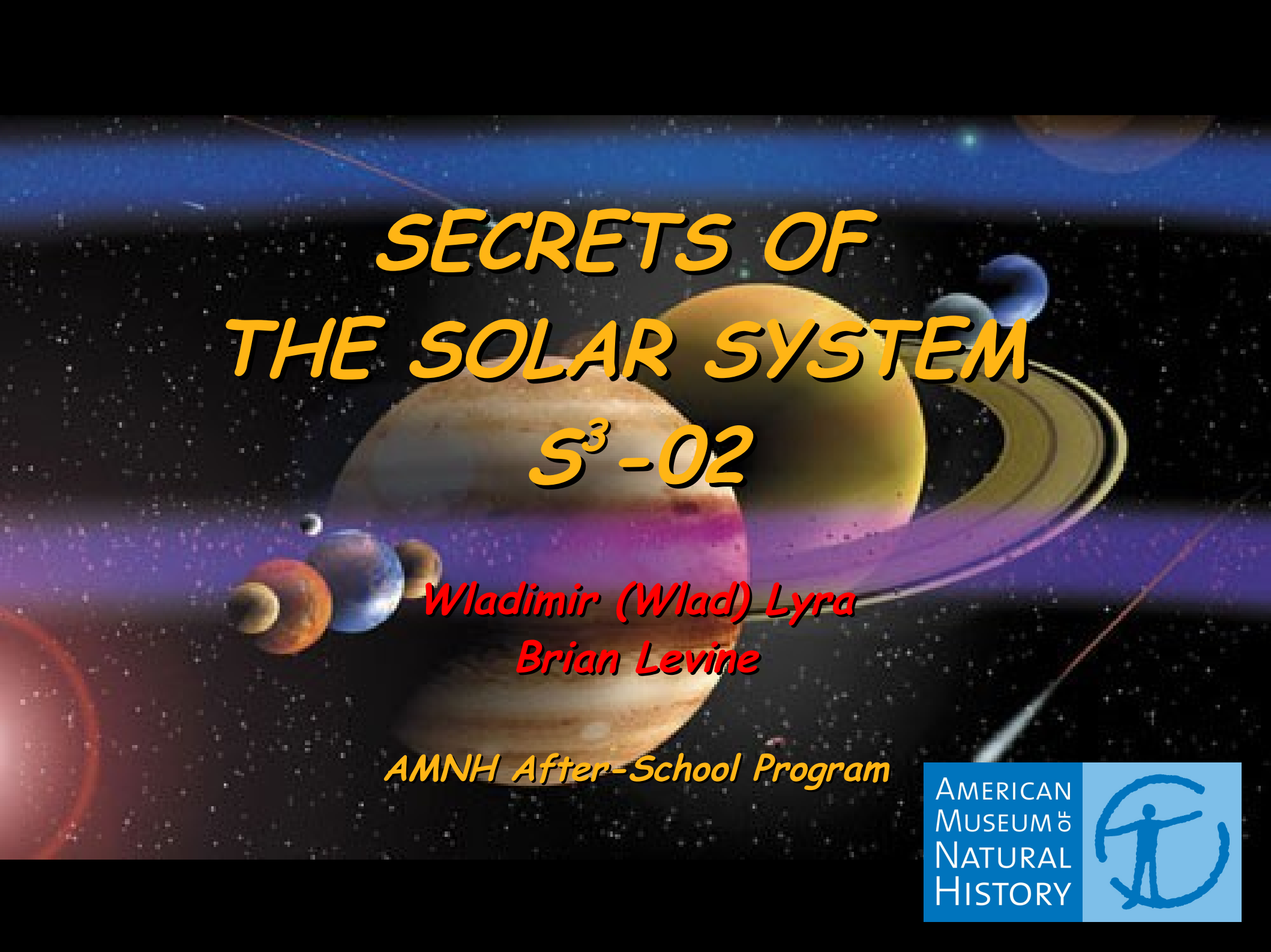


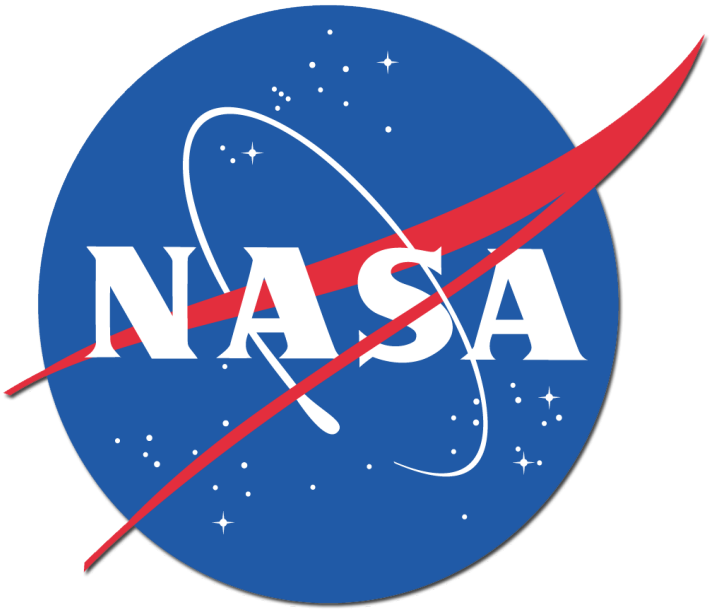
SECRETS OF THE SOLAR SYSTEM S^3-02

Wladimir (Wlad) Lyra
Brian Levine

AMNH After-School Program

American Museum of Natural History

This class is brought to you by funding provided by NASA, and is part of the AMNH After-School Program and Science Research Mentoring Program. The material contained in this course is based upon work supported by NASA under grant award Number NNX09AL36G. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NASA.

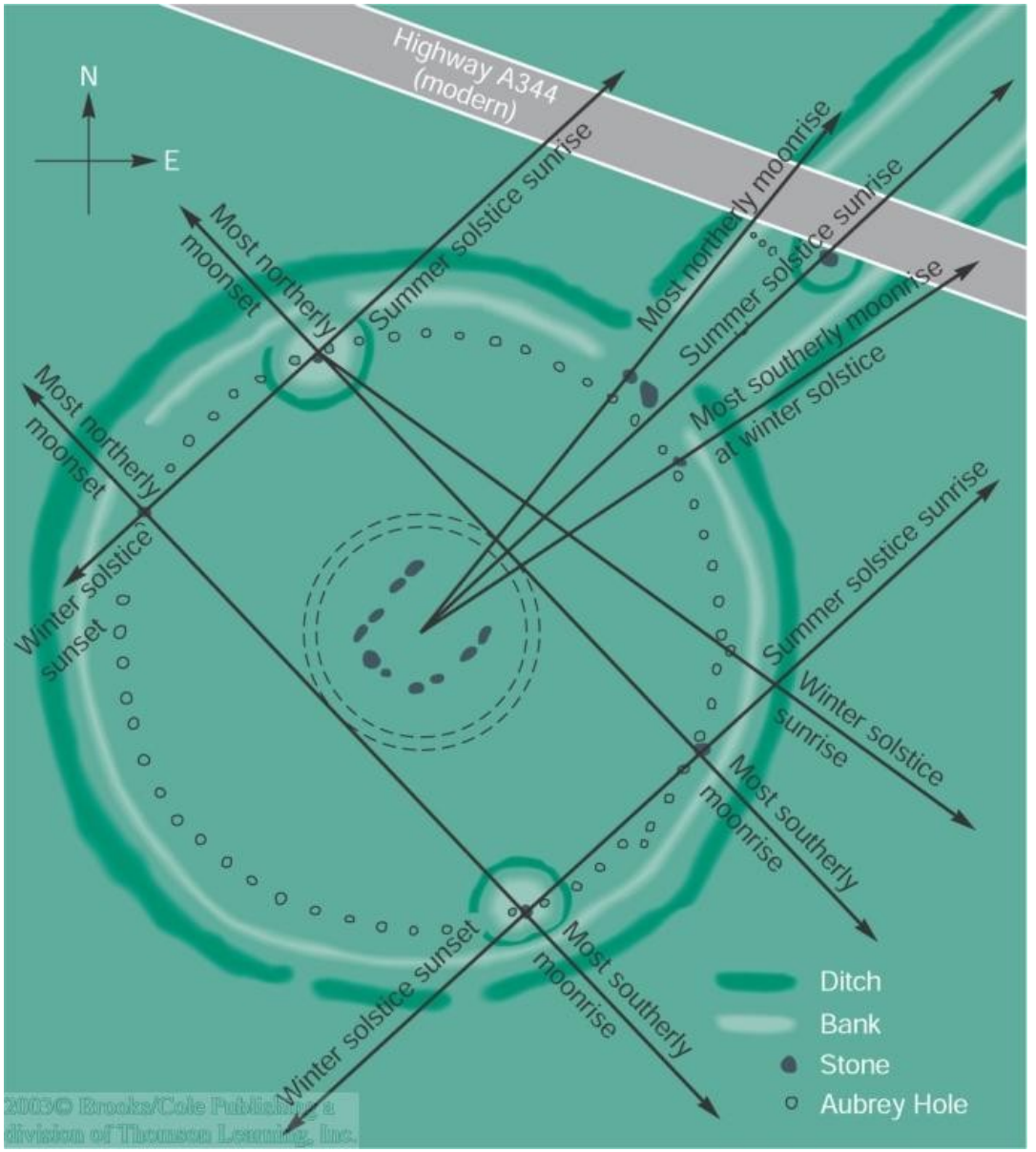


Outline

History of Western Astronomy

Pre-history Astronomy: Stonehenge

- Constructed 3000 – 1800 B.C. in Great Britain
- Alignments with locations of sunset, sunrise, moonset and moonrise at summer and winter solstices
- Probably used as calendar.



Stonehenge Today

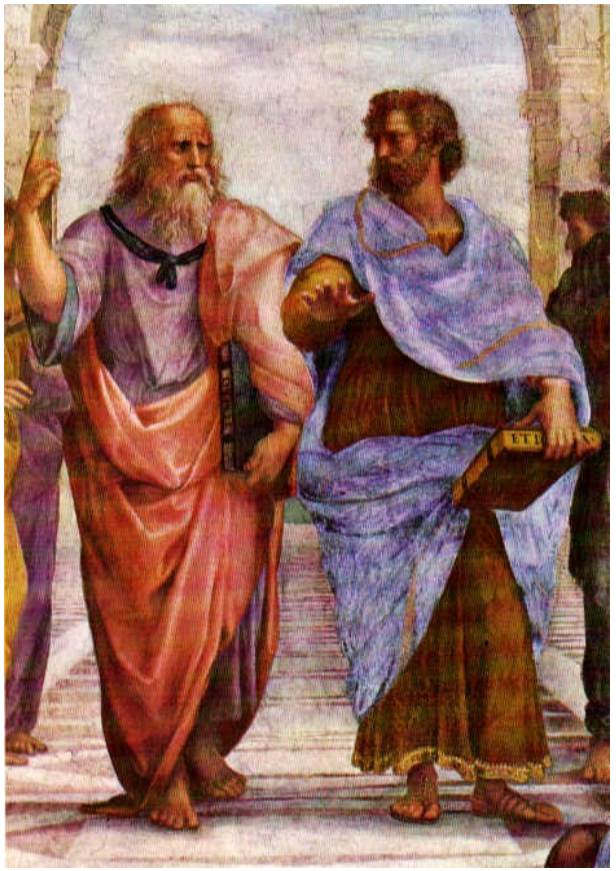
Stonehenge Today

Stonehenge Today

1st millenium BC: Ancient Greece

Raphael's
"**School of Athens**"

Aristotle 384-322 BC



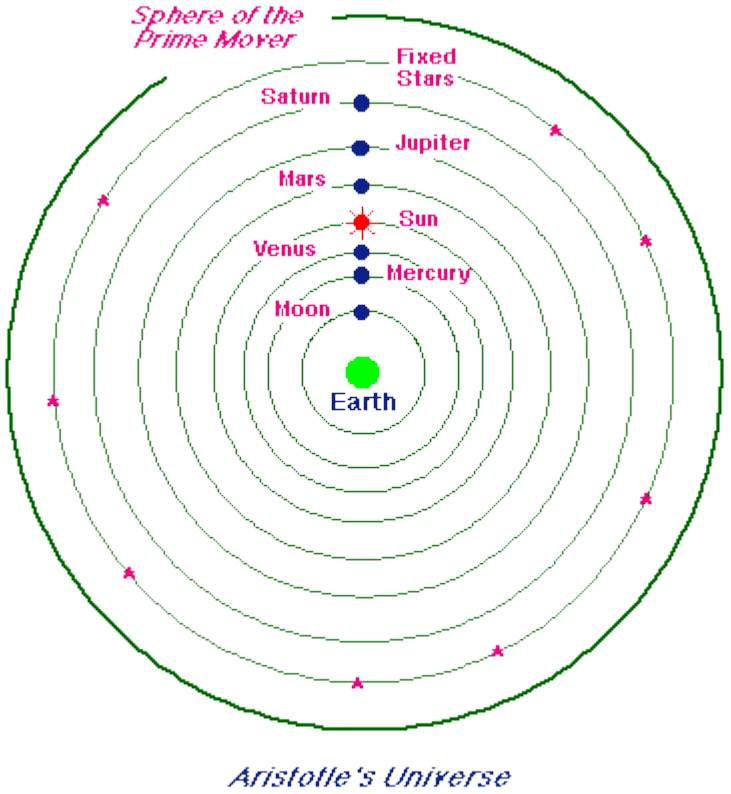
There are four elements. Everything is composed of different proportions of the four.

Earth, Air, Water, Fire

They seek their natural places. Evidence?

- Rain (water) falls from the sky
- Rocks (earth) fall when thrown
- Smoke (air) rises.
- Flames (fire) rise.

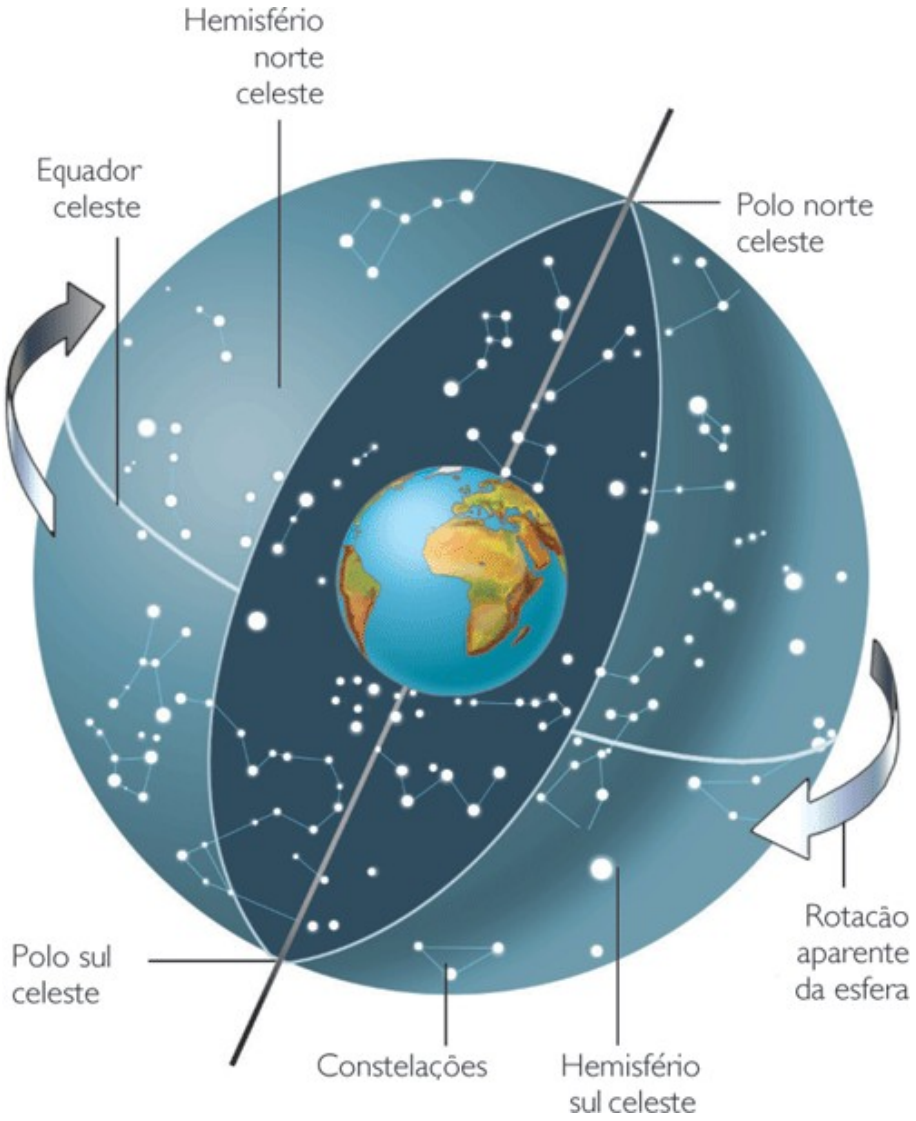
How about the stars and planets, Aristotle?



Aristotle's Universe

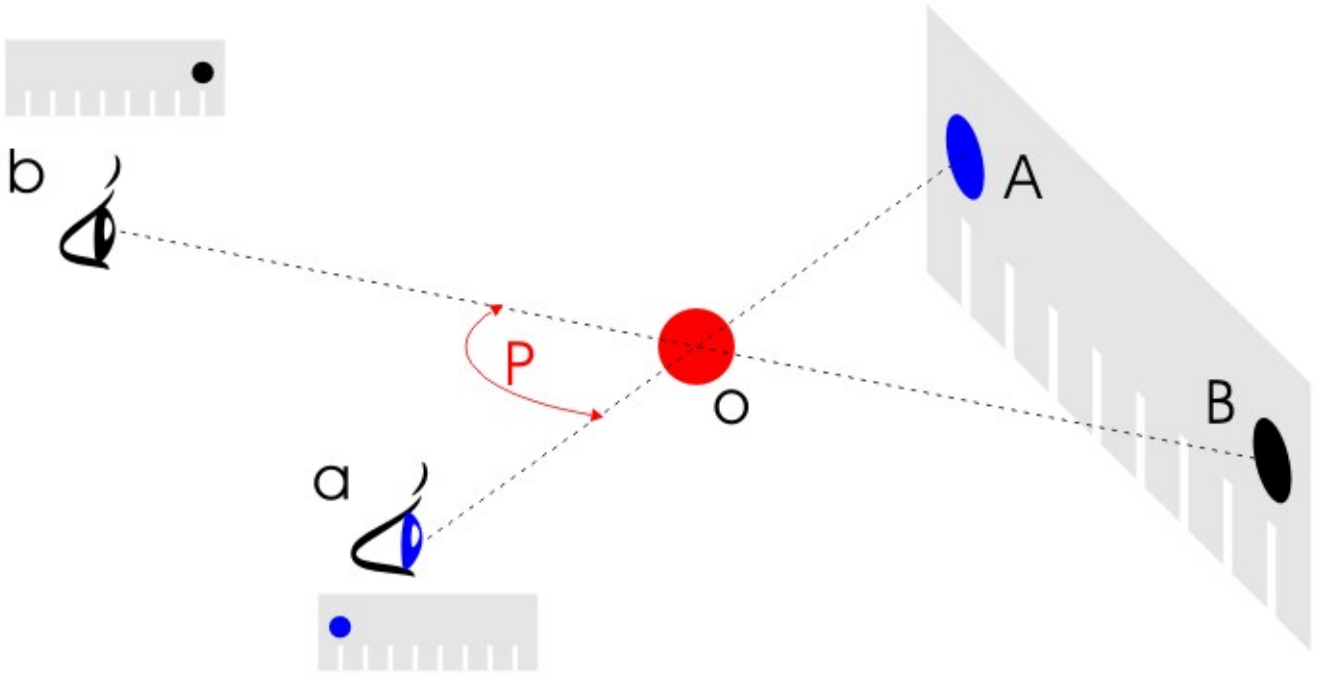
- Their motion is so regular and perfect, they cannot be made by the same corruptible and "blendable" elements. They must be made by something else, a fifth element, that he calls "**Aether**".
- Therefore, the Universe has "sub-lunar" (The Earth) and "super-lunar" (The Heavens) physics.
- Motions in the heavens occur in perfect geometry: circles.
- Imperfect, immobile Earth at center of Universe.

The celestial sphere



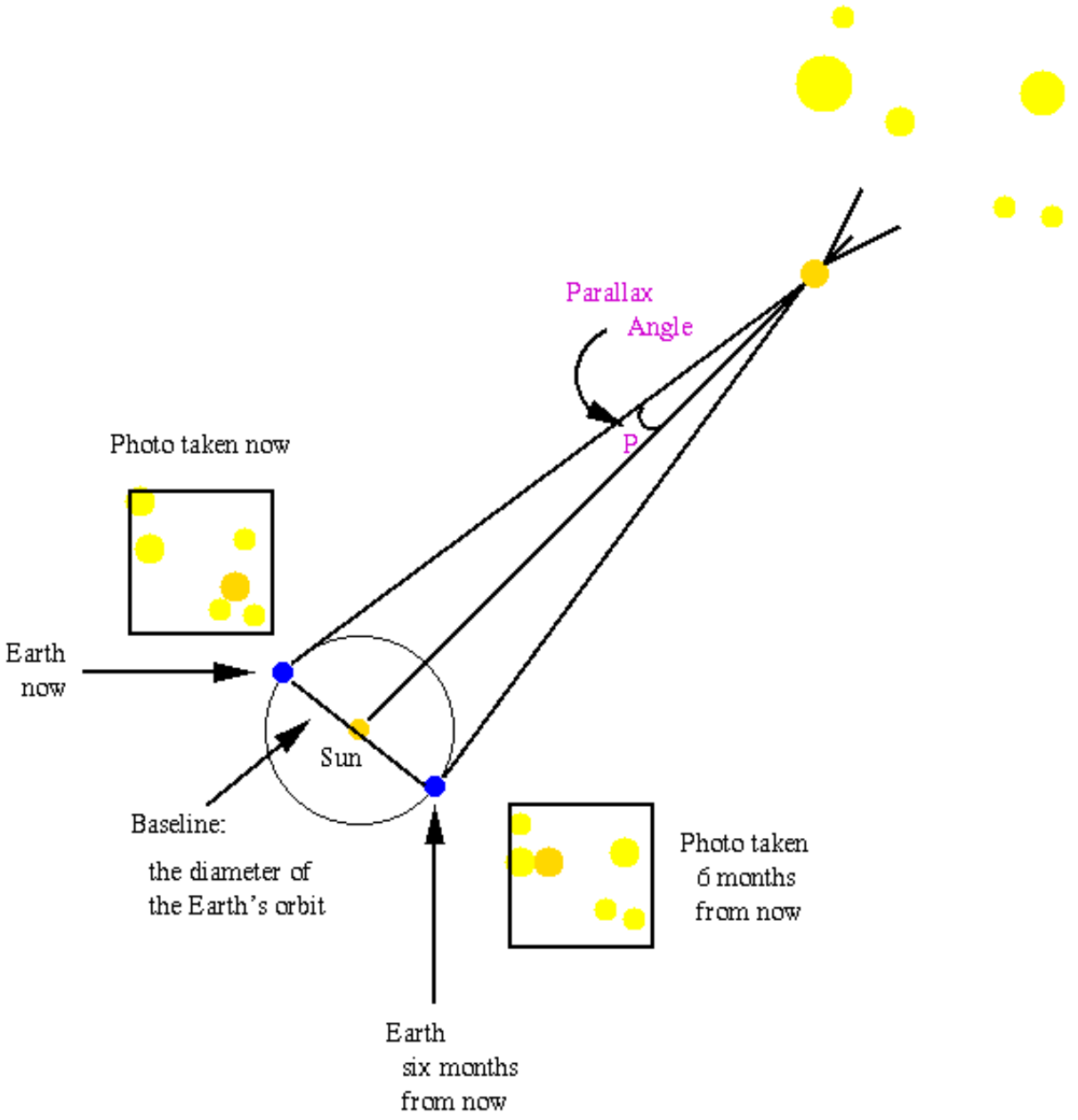
Evidence for Geocentrism

Parallax



Evidence for geocentrism

If the Earth moved, the fixed stars should show a parallax.

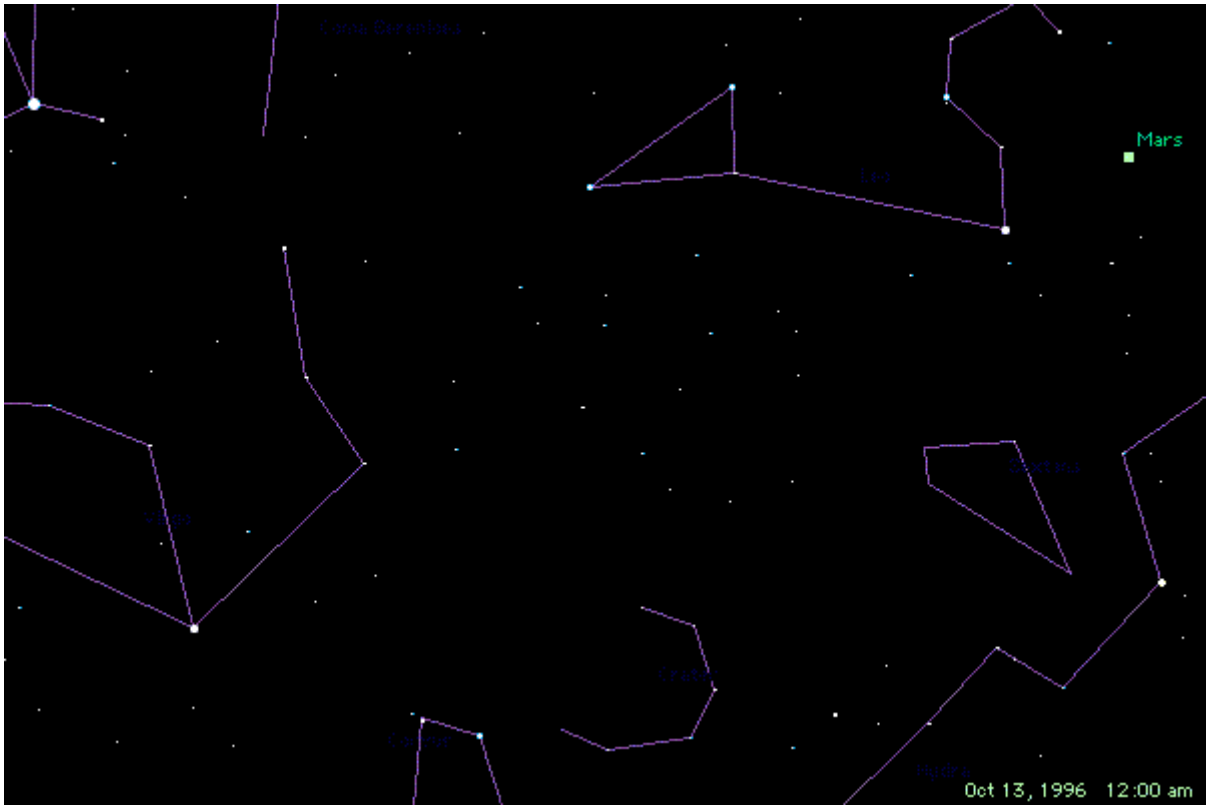


Ptolemy 85-165 AD

A great astronomer with the wrong theory.

He described the geocentric model mathematically nearly to perfection, thus able to correctly predict the position of the planets.

Retrograde Motion

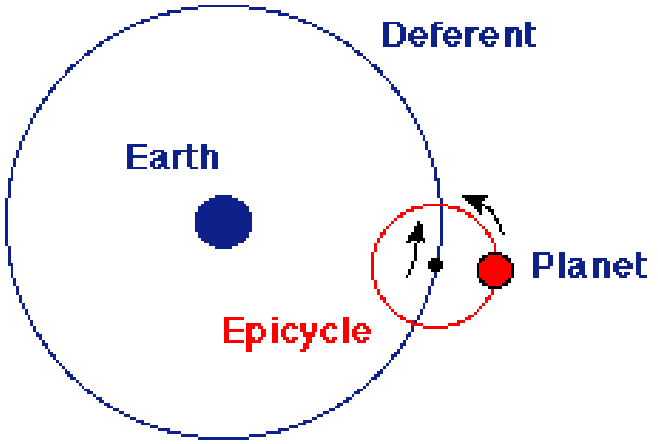


Retrograde Motion

Retrograde motion of Mars, in 2005.

All motion in the aether is supposed to be uniform and circular, so what is going on?

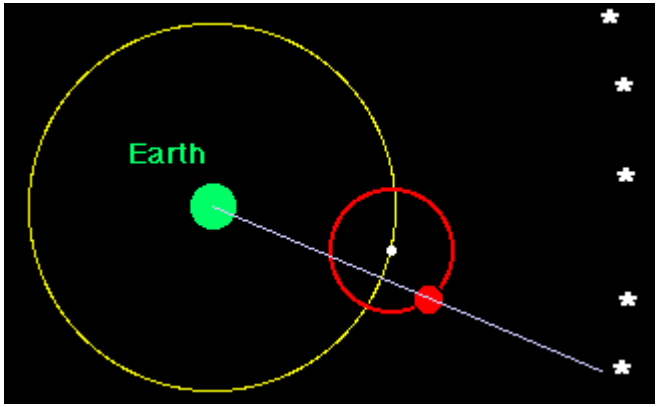
An ingenious idea: Epicycles



Two circles, not just one!

The planet executes an orbit (epicycle) around a point
This point executes an orbit (deferent) around Earth.

An ingenious idea: Epicycles



Two circles, not just one!

The planet executes an orbit (epicycle) around a point
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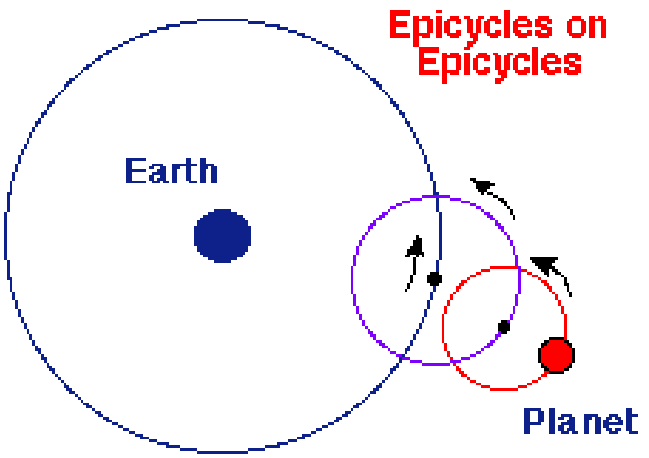
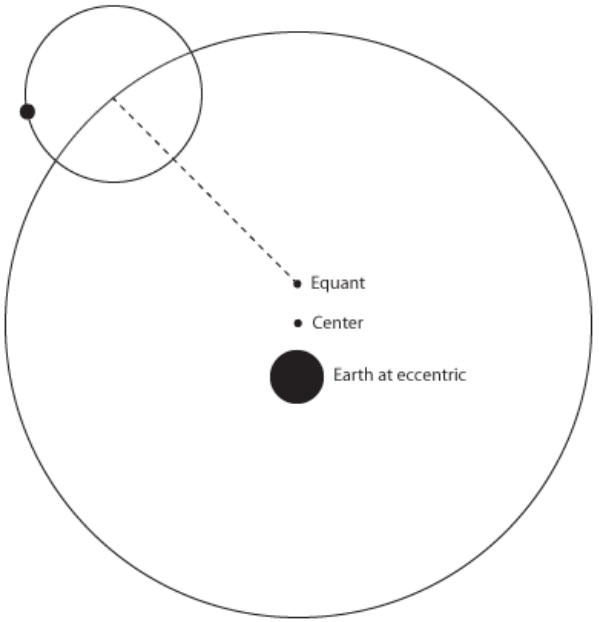
Sophistications



Sometimes more epicycles were needed
to accurately predict the position of the planets.

Sophistications: The Equant.



Earth is at an "eccentric" point, off the center of the deferent.
The center of the epicycle moves with constant speed
around the Equant.
Note that the motion of the center of the epicycle around the deferent
is therefore not circular uniform...

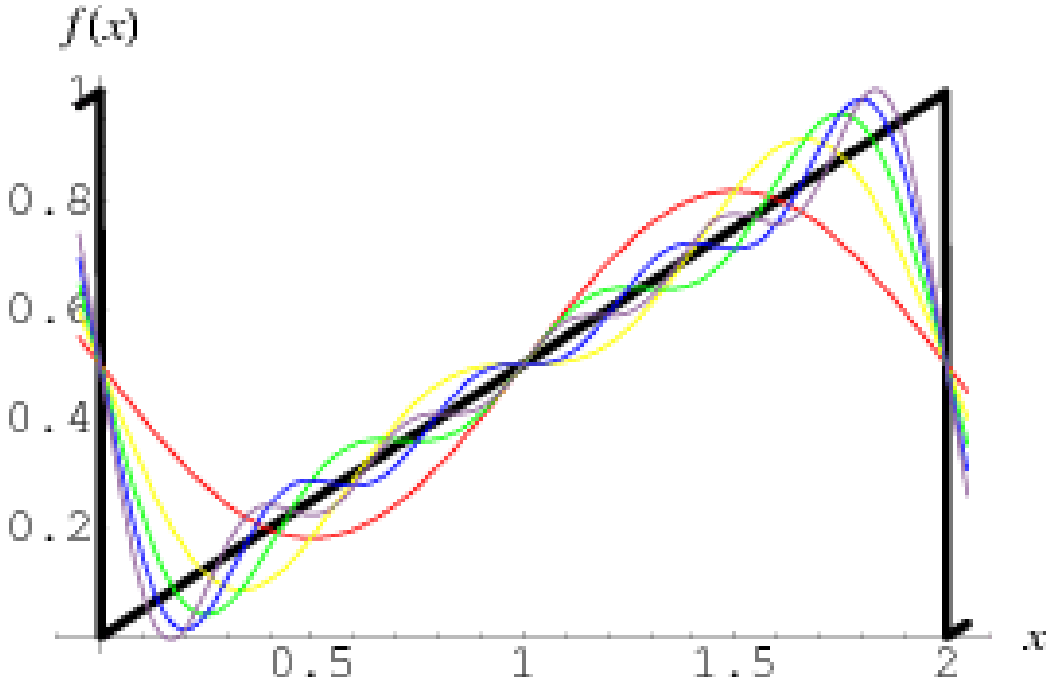
Why does the geocentric model work?

A proof from the 19th century. Any periodic function can be approximated by a sum of sines and co-sines, called Fourier series.

$$f(x) = \frac{a_0}{2} + \sum_{1}^{\infty} a_n \cos(nx) + \sum_{1}^{\infty} b_n \sin(nx)$$

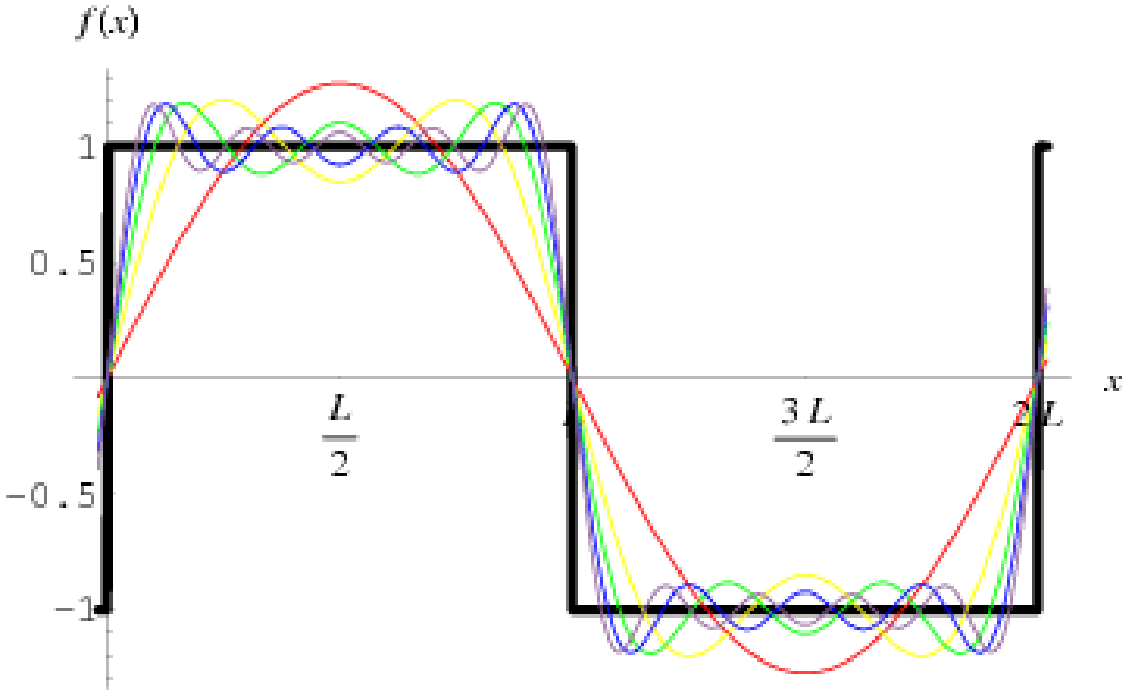
$$f(x)=\frac{a_0}{2}+\sum_1^\infty a_n\cos(nx)+\sum_1^\infty b_n\sin(nx)$$

Example:



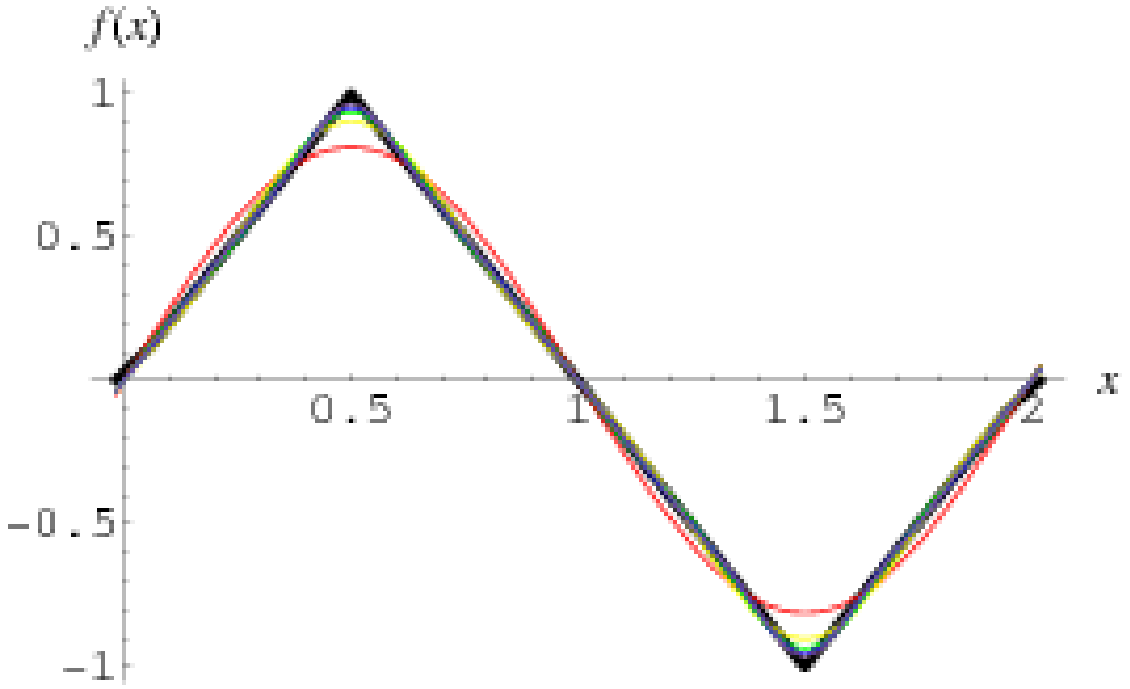
$$f(x)=\frac{a_0}{2}+\sum_{1}^{\infty} a_n \cos(nx)+\sum_{1}^{\infty} b_n \sin(nx)$$

Example:



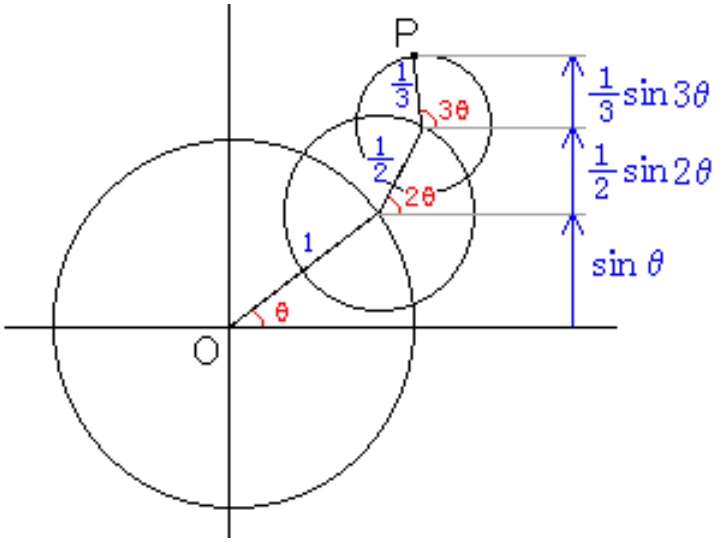
$$f(x)=\frac{a_0}{2}+\sum_{1}^{\infty} a_n \cos(nx)+\sum_{1}^{\infty} b_n \sin(nx)$$

Example:



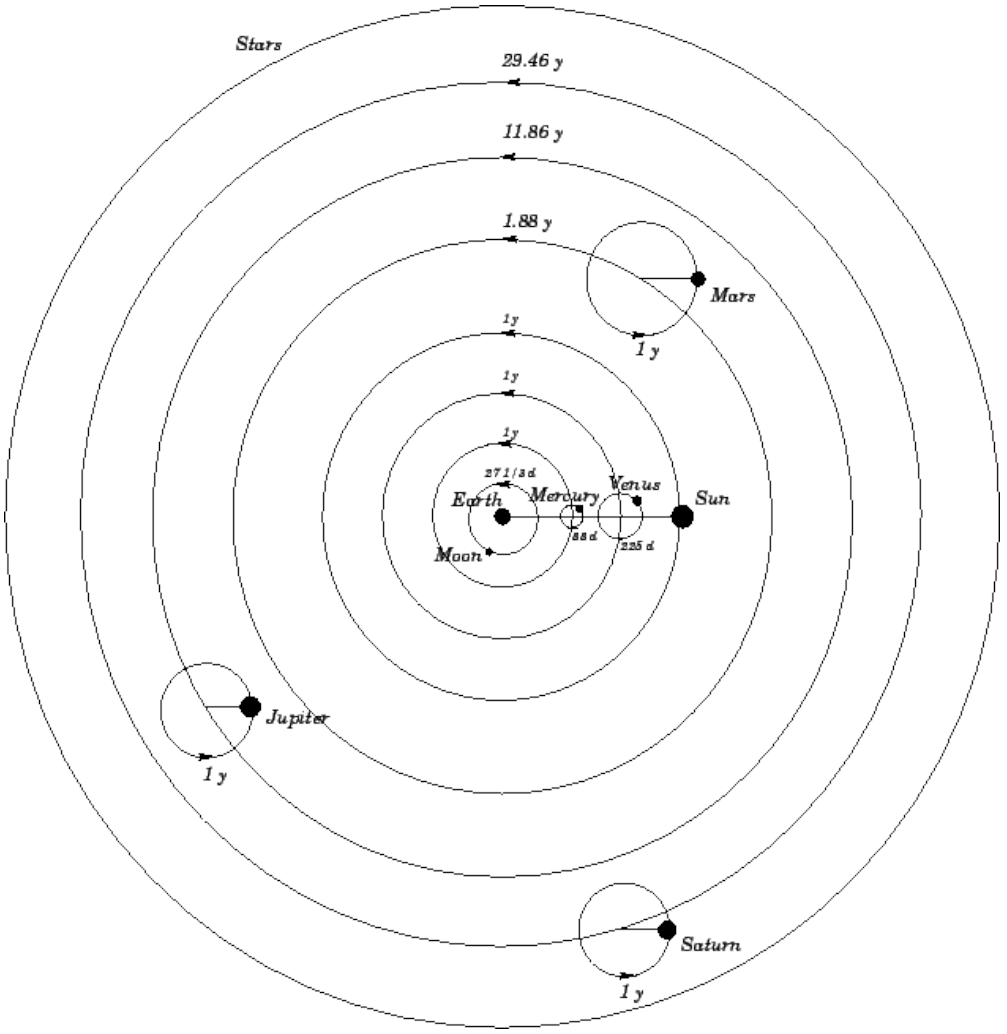
Geometric interpretation

$$f(x)=\frac{a_0}{2}+\sum_1^\infty a_n\cos(nx)+\sum_1^\infty b_n\sin(nx)$$



Epicycles!

The geocentric model



- Ptolemy summed up Greek thoughts on astronomy.
- Round Earth at the center.
- Surrounded by spheres
- Could predict motions, eclipses fairly well

- It is **so good** it is used today in planetaria all around the world to simulate planet motion. Gears and motors substitute epicycles.

Then came the "Dark Ages"...

- The growing influence of the Church meant a revision on the worldview.
- Catholic scholars, mainly Augustine and Thomas Aquinas, embarked on the ambitious project of merging "Reason and Faith". That is, Greek knowledge with Christian theology.
- The geocentric model was in accordance to scripture, since it placed the Earth in the center of "creation".
- Aristotle's "Prime Mover" was identified with "God".

1500 years later...

- The geocentric model worked, but growing precision in observations were making the need to add more and more epicycles to the model, effectively raising the accuracy.

- By the late 1400s, the system had **92 epicycles**.

- The church was having troubles calculating the date of Easter.

- Astronomers knew that the Geocentric model had some intrinsic problems (nobody liked that the motion in the deferent was not uniform). Even though some already spoused the idea of heliocentrism, **no "simple" heliocentric model competed in mathematical accuracy with the "complicated" geocentric model.**

Regiomontanus (1463- 1476)

- Gifted mathematician, dedicated astronomer, knew Greek, translated the Almagest into Latin.
- Tremendous work to bring the Ptolemaic predictions up to date. Published monumental work, "Ephemerides", predicting the positions of the planets for every day from January 1, 1475 to December 31, 1506.
- Got convinced the system needed a reform. The error accumulated in 1500 years meant that something was not correct...
- This mentality permeated the rest of the late 1400 and early 1500. People **knew** of the **heliocentric model**, but **no one could do the task of getting the model to be as accurate as Ptolemy's epicycles on epicycles....**

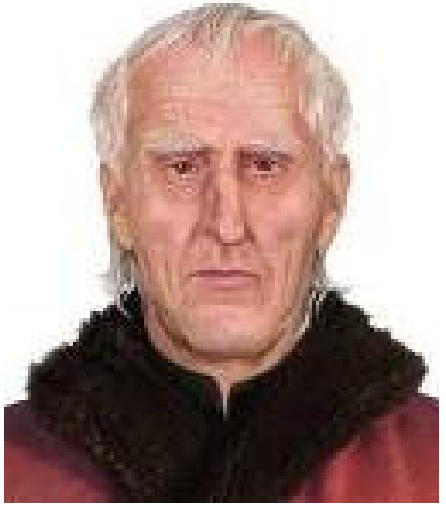
Johannes Müller von Könisberg (Regiomontanus)

Two generations later...

The planet **theories of Ptolemy** and most other astronomers, although consistent with numerical data, seemed likewise to **present no small difficulty**. For these theories were not adequate unless certain **equants** were also conceived; it then appeared that a planet moved with uniform velocity neither on its deferent (main orbit) nor about the center of its epicycle (second orbit). Hence, a system of this sort seemed **neither sufficiently uniform nor sufficiently pleasing to the mind**. I often considered whether there could perhaps be found **a more reasonable arrangement of circles**, where everything would move uniformly about its proper center.

Copernicus, *Commentariolus*, 1514

Nicolaus Copernicus (1473 - 1543)



Nicolaus Copernicus (1473 - 1543)

Pope Clement VII was very pleased with the promises of a heliocentric theory. A Cardinal writes back to Copernicus:

> **Word reached me concerning your proficiency**, of which everybody constantly spoke. […] For I had learned **that you had** not merely mastered the discoveries of the ancient astronomers uncommonly well but had also **formulated a new cosmology**. In it you maintain **that the earth moves**, that the **sun occupies** the lowest, and thus **the central place**, in the Universe [...] I have also learned that you have written an exposition of the whole system of astronomy, **and have computed the planetary motions and set them down in tables**, to the greatest admiration of all. Therefore with the utmost earnestness **I entreat you, to communicate this discovery of yours to scholars** […] If you gratify my desire, you will see that you are dealing with a man who is zealous for your reputation and eager to do justice to so fine a talent.

Cardinal Nicolas Schönberg
November 1st, 1533

Nicolaus Copernicus (1473 - 1543)

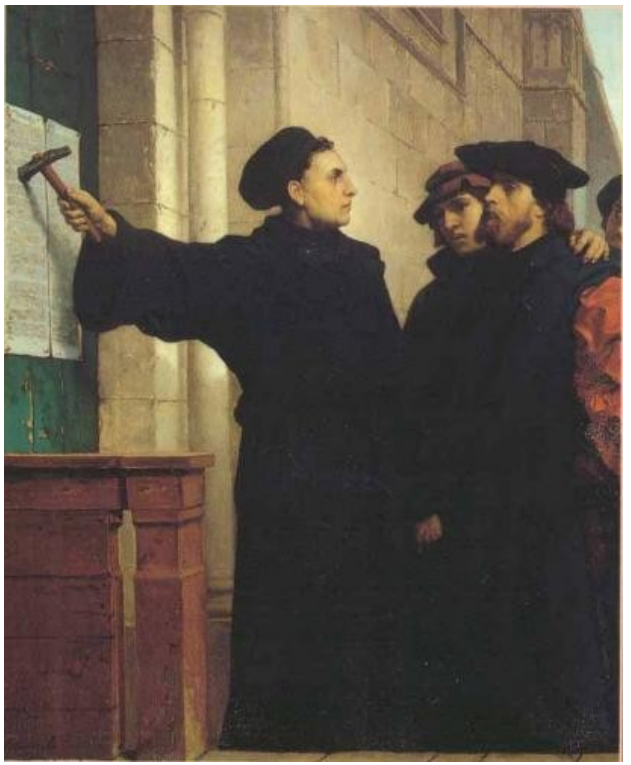
This man whose work I am now treating is in every field of knowledge and in mastery of astronomy not inferior to Regiomontanus. **I rather compare him with Ptolemy...**

Georg Joachim Rethicus, *Narratio Prima*, 1540

Luther on Copernicus

There is mention of a certain new astrologer who wanted to prove that the earth moves and not the sky, the sun, and the moon […] **The fool wishes to subvert the whole science of Astronomy.** […] I believe the holy scriptures, for Joshua commanded the sun to stand still, and not the earth.

Martin Luther



“that Polish astronomer”...

Many hold it for an excellent idea to praise such an absurd matter, like that Polish astronomer, who moves the earth and lets the sun stand still.

Rethicus' boss.

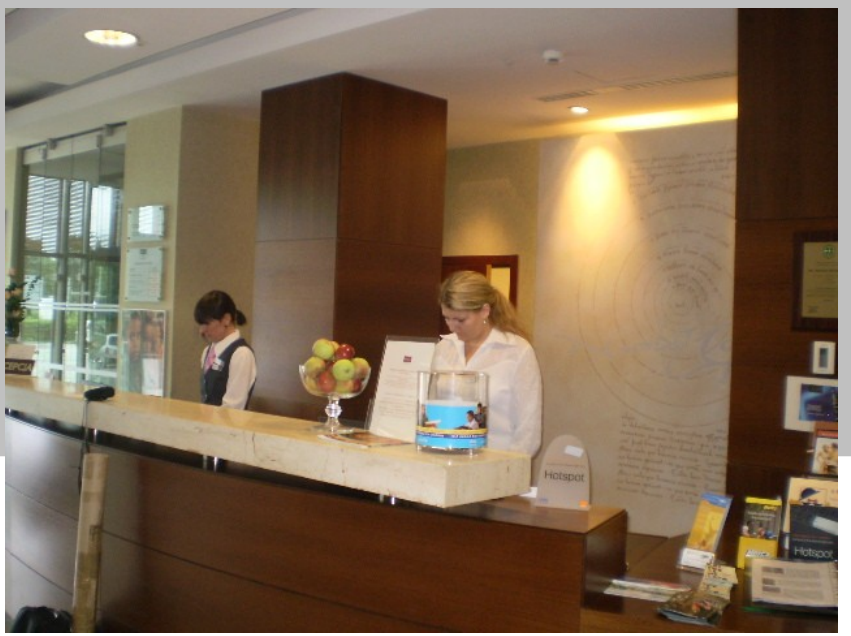
Toruń

NICOLAUS COPERNICUS
THORUNENSIS
TERRAE MOTOR
SOLIS CAELIQUE STATOR

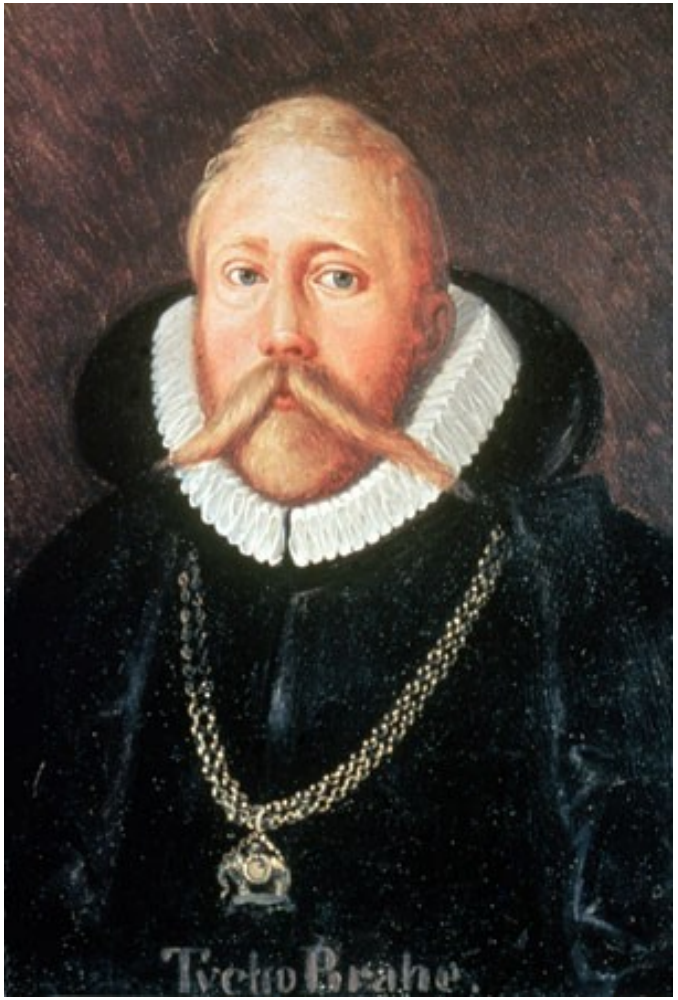
Baltic Sea
Torun
POLAND
Warsaw
CZECH REP.
1992 MAGELLAN Geographix, Santa Barbara, CA

Toruń
porusza
775-lecie
Torunia

Kopernika

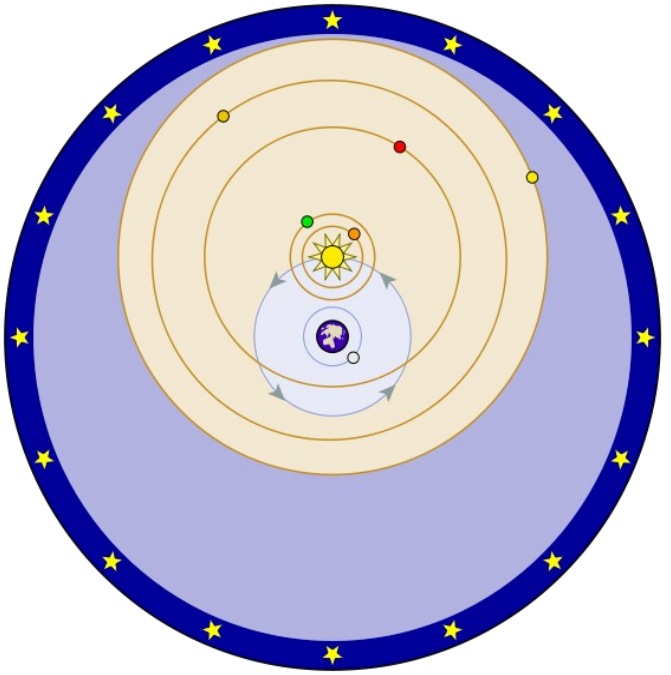


Tycho Brahe (1546-1601)



Hybrid (geo-heliocentric) model

- Planets orbit the Sun
- Sun orbits the Earth



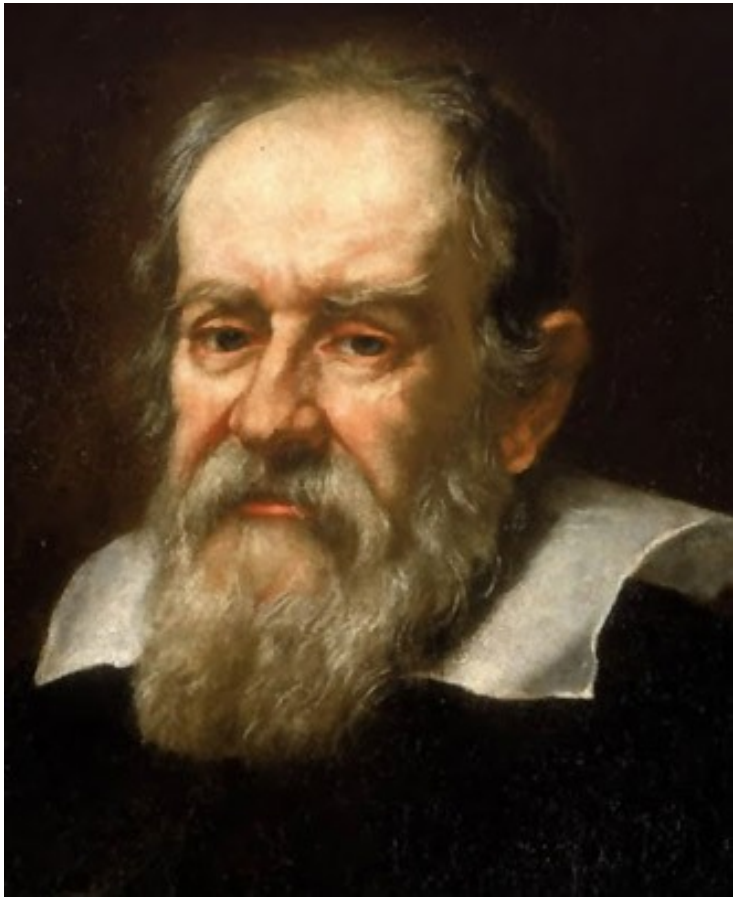
Tycho's model

Very popular in the 1600's

"A safe synthesis of ancient and modern"

One generation later, two giants!

Johannes Kepler
1571-1630



Galileo Galilei
1564-1642

Galileo-Kepler correspondence

[Galileo to Kepler, 1597]

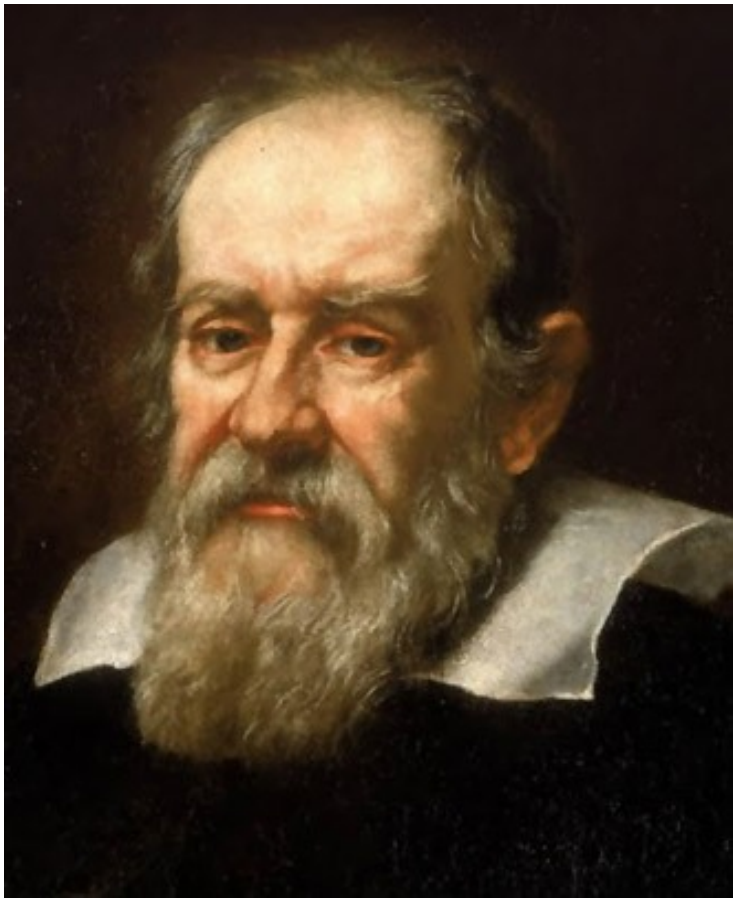
....**Like you, I accepted the Copernican position several years ago** and discovered from thence the causes of many natural effects which are doubtless inexplicable by the current theories. **I have written up many of my reasons and refutations on the subject, but I have not dared until now to bring them into the open, being warned by the fortunes of Copernicus himself**, our master, who procured immortal fame among a few but stepped down among the great crowd (for the foolish are numerous), only to be derided and dishonored. **I would dare publish my thoughts if there were many like you**; but, since there are not, I shall forebear....

[Kepler to Galileo, 1597]

....**I could only have wished that you, who have so profound an insight, would choose another way**. You advise us, by your personal example, and in discreetly veiled fashion, to retreat before the general ignorance and not to expose ourselves or heedlessly to oppose the violent attacks of the mob of scholars (and in this you follow Plato and Pythagoras, our true perceptors). But after a tremendous task has been begun in our time, first by Copernicus and then by many very learned mathematicians, and when the assertion that the Earth moves can no longer be considered something new, would it not be much better to pull the wagon to its goal by our joint efforts, now that we have got it under way, and gradually, with powerful voices, to shout down the common herd, which really does not weigh the arguments very carefully? Thus perhaps by cleverness we may bring it to a knowledge of the truth. **With your arguments you would at the same time help your comrades who endure so many unjust judgments**, for they would obtain either comfort from your agreement or protection from your influential position. **It is not only your Italians who cannot believe that they move if they do not feel it**, but we in Germany also do not by any means endear ourselves with this idea. Yet there are ways by which we protect ourselves against these difficulties....

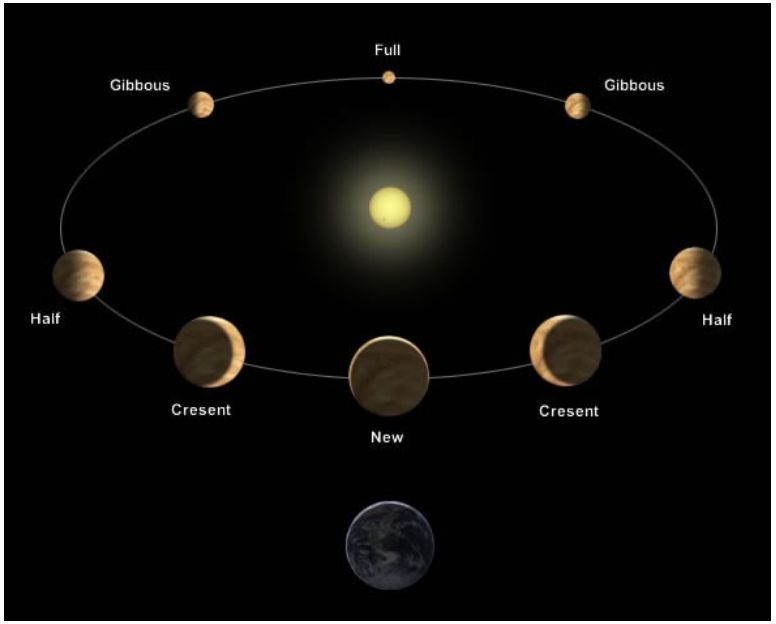
Be of good cheer, Galileo, and come out publicly. If I judge correctly, there are only a few of the distinguished mathematicians of Europe who would part company with us, so great is the power of truth. If Italy seems a less favorable place for your publication, and if you look for difficulties there, perhaps Germany will allow us this freedom.

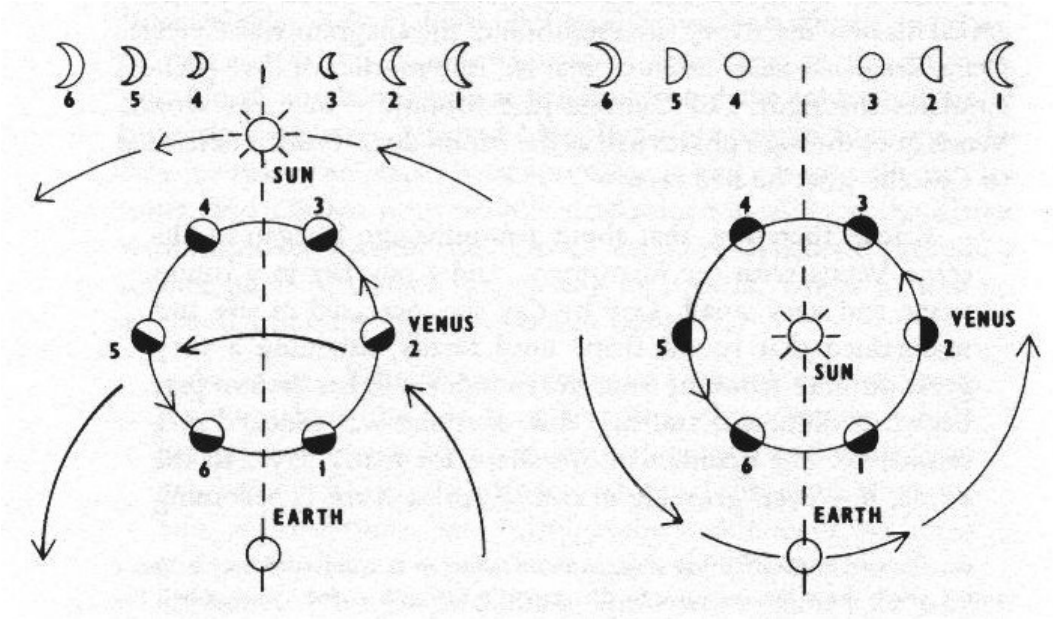
Galileo



First to use telescope (then a toy) to look at the night sky. Many discoveries....

Phases of Venus





Haec immatura a me iam frustra leguntur o.y.

[These are present too young to be read by me]

Cynthiae figuras aemulatur mater amorum

[The mother of love (Venus) imitates the shape of Cynthia (the Moon)]

Moons of Jupiter

Moons of Jupiter

- Activity:
  - What is the orbital period of each Galilean moon?

Moons of Jupiter

- Activity:
  - What is the orbital period of each Galilean moon?

- Reflection:
  - What was the hardest part of the analysis?
  - How's that different from what Galileo did?

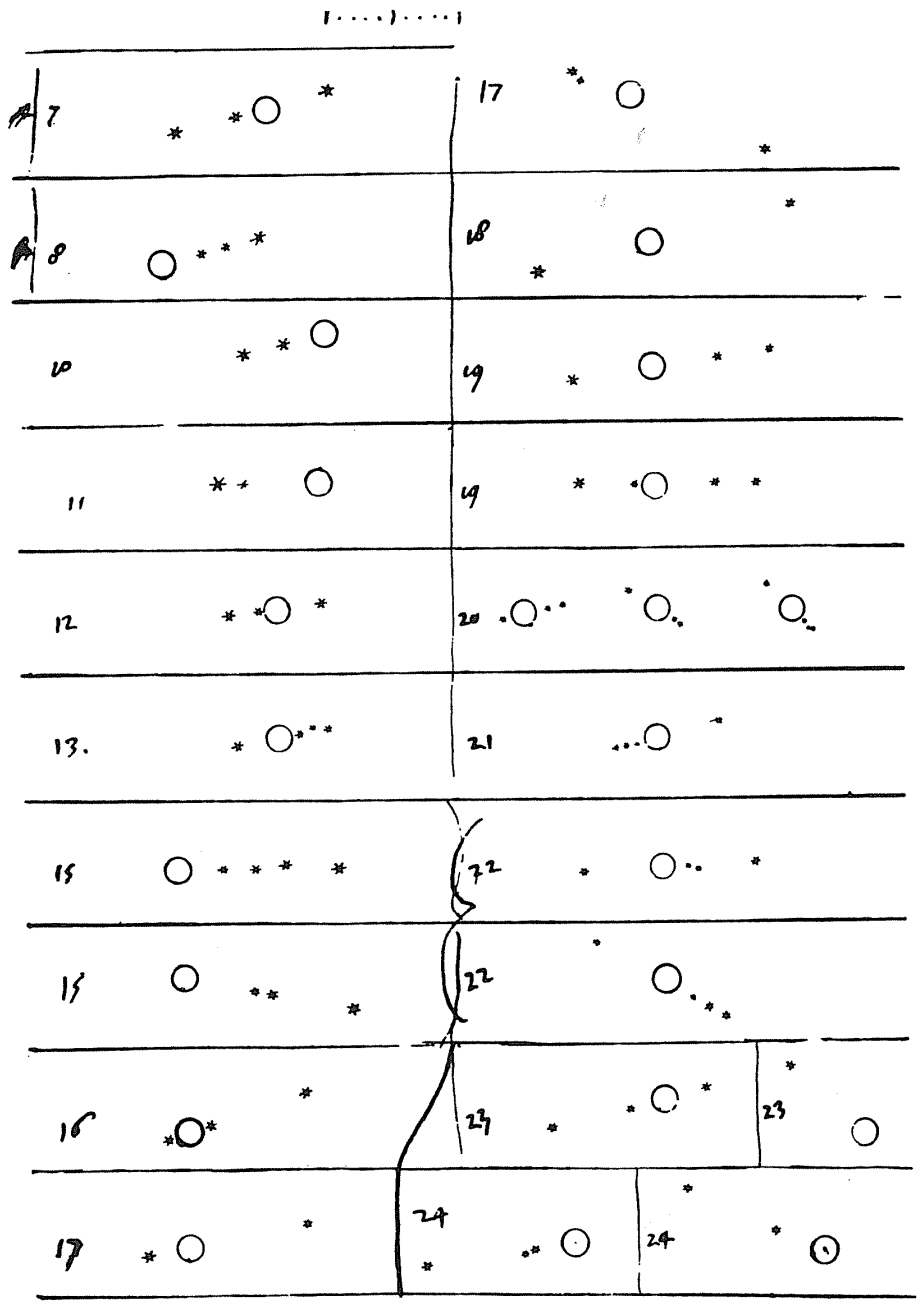
Moons of Jupiter

- Actual data:

Moon	Orbital Period	Orbital Distance
Io	1.8 days	422,000 km
Europa	3.6 days	670,900 km
Ganymede	7.2 days	1,070,000 km
Callisto	16.7 days	1,833,000 km

Moons of Jupiter

You just completed the same type of analysis that Galileo did!



Drawings made by Galileo for use in printing *Sidereus Nuncius* illustrations of satellite positions. Reduced facsimiles from Edizione Nazionale of Galileo's *Opere*; concerning his scale at top, see ensuing *Discussion*.

mè: & Stella Ioui vicinior reliquis duabus ſequentibus minor apparebat; omneſque in eadem recta exquiſite dixpoſitæ videbantur.

Die vigeſima tertia hora 0. min: 40. ab occaſu, in hũc fermè modum Stellarum conſtitutio ſe habuit: erant

Ori. * * ○ * Occ.

tres Stellæ cum Ioue in recta linea ſecundum Zodiaci longitudinem; veluti ſemper fuerunt: Orientales erant duæ, vna verò occidentalis. Orientalior aberat à ſequenti min: pr: 7. hæc verò à Ioue min. 2. ſec:40. Iuppiter ab occidentali min: 3. ſec:20. erantque omnes magnitudine ferè æquales. Sed hora quinta, duæ Stellæ, quæ prius Ioui erant proximæ amplius non cernebantur, ſub Ioue vt arbitror latitantes fuitque talis aſpectus.

Ori. * ○ Occ.

Die vigeſimaquarta tres Stellæ orientales omnes viſæ ſunt, ac ferè in eadem cum Ioue recta linea; me-

Ori. * ** ○ Occ.

dia enim modicè in auſtrum deflectebat. Ioui propinquior diſtabat ab eo min: 2. ſequens ab hac min: 0. ſec: 30. ab hac verò aberat orientalior min: 9. erantq; omnes admodum ſplendidæ. Hora verò ſexta, duæ

Ori. * ○ Occ.

Moons of Jupiter

- Modern astronomers
  - Calculate the positions of the moons
  - Often represent the paths similarly
  - Below - July 2007, Astronomy Magazine

Johannes Kepler (1571-1630)

- Inherited Tycho's data when he died in 1601
  - Briefly worked as Tycho's assistant
  - Analysis of data on Mars
  - Had problems fitting Mars' orbit around the Sun to a circle

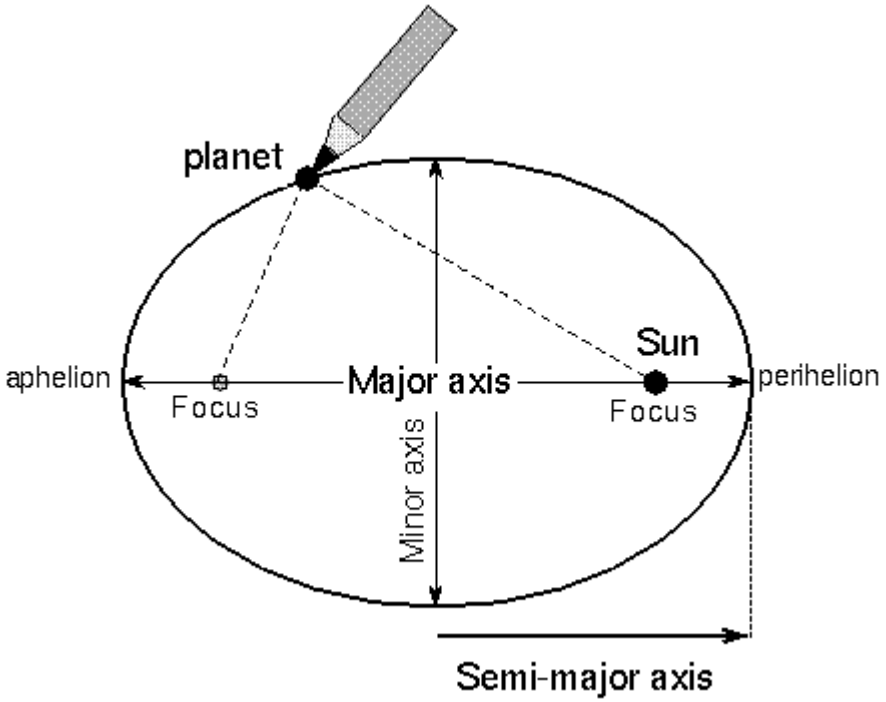
Kepler and Tycho's monument in Prague

Ellipses

- Kepler tried many times to fit the orbit of Mars to a circle, with epicycles, with the observed data that Tycho had taken.
- He couldn't.
- Radical idea - maybe it's not a circle, but is an ellipse!

Ellipses

- Elements
  - a = semimajor axis
  - b = semiminor axis
  - f = focal distance
  - Eccentricity = e = f/a
    - Ranges from 0 (circle) to 1 (straight line)



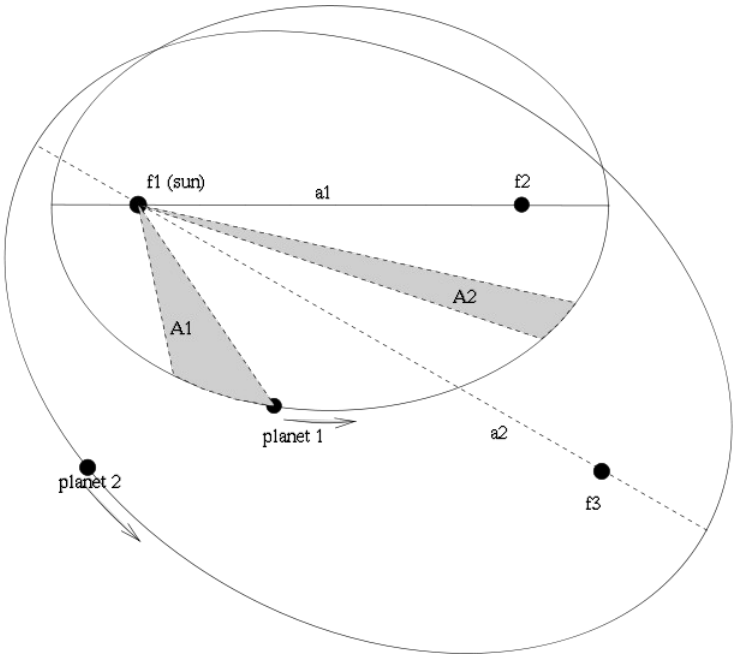
Kepler's Laws of Planetary Motion

1. The orbit of every planet is an ellipse with the Sun in one of the two foci.

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

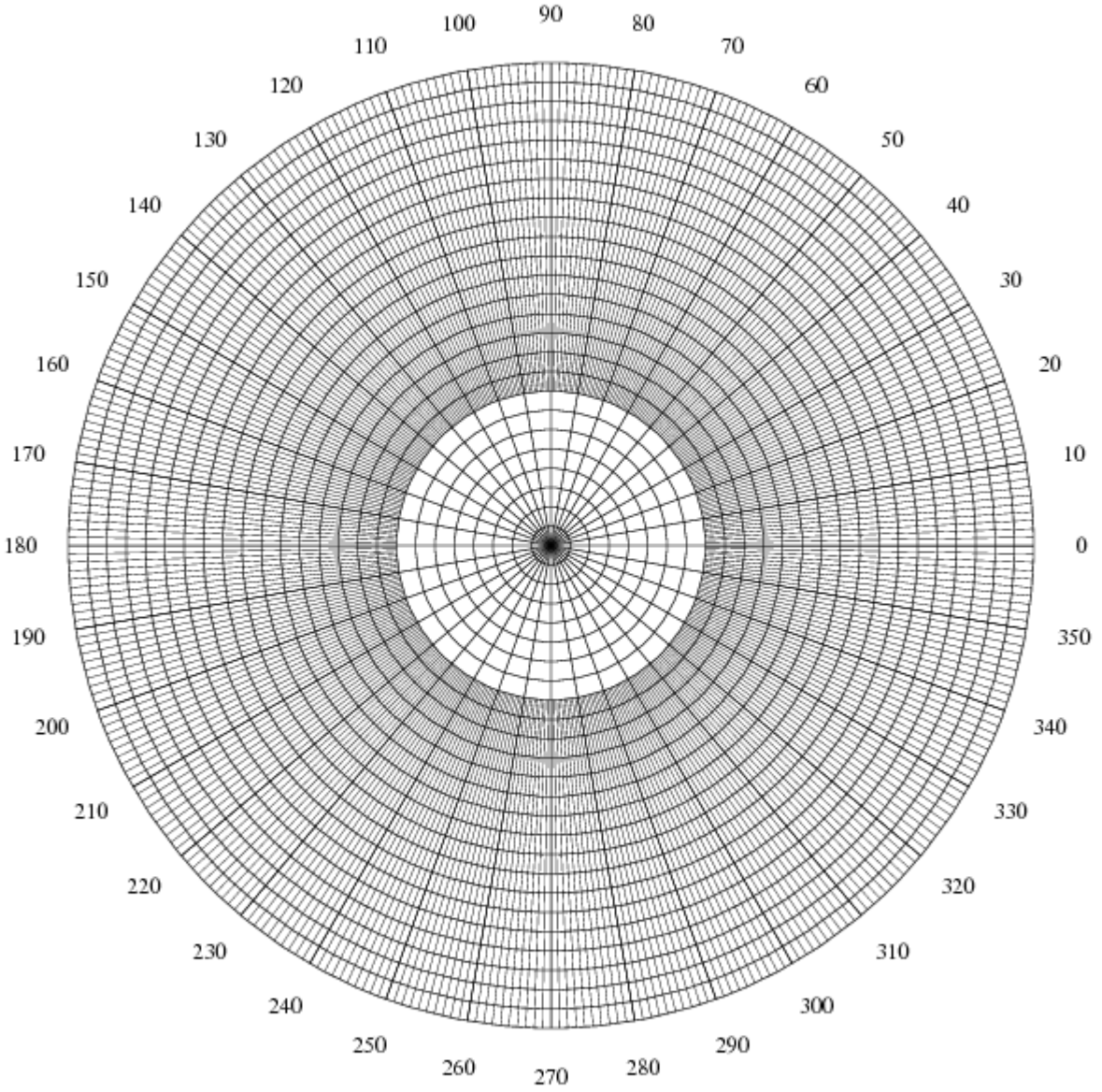
3. The square of the orbital period is directly proportional to the cube of the semi-major axis of its orbit.

$$T^2 = k r^3$$



Elliptical Orbits

- Kepler worked on Mars… we will work with Mercury
- Instructions on lab sheets
- If you have time - calculate the eccentricity of Mercury's orbit

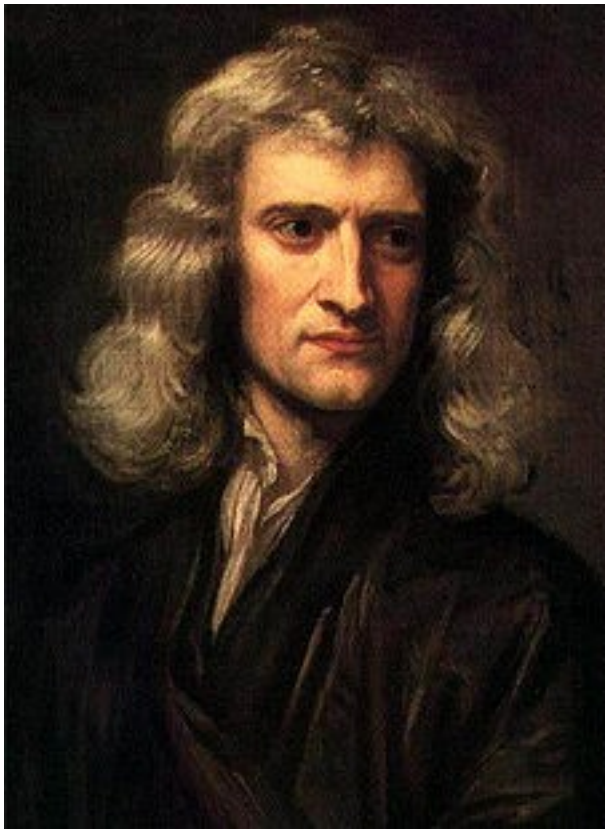


Free Polar Graph Paper from http://incompetech.com/graphpaper/polar/

Elliptical Orbits

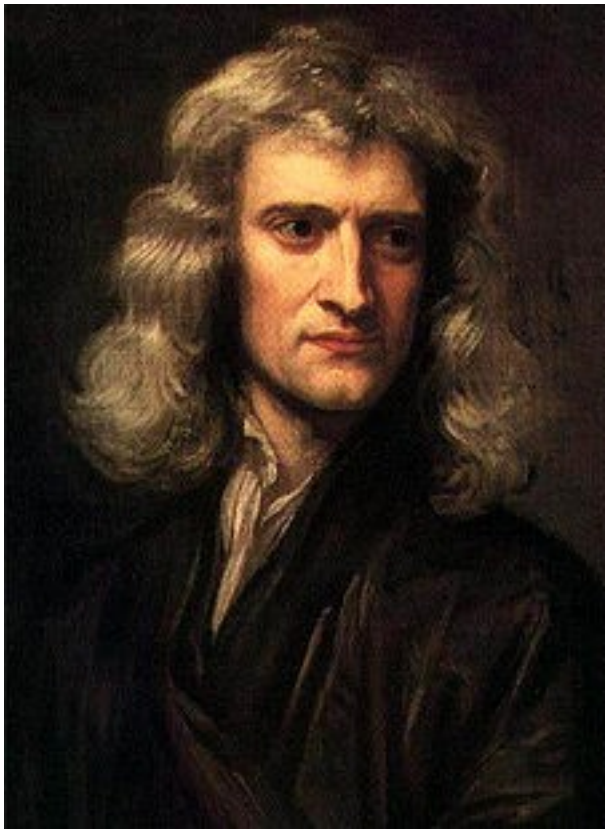
- You have done a very similar analysis to Kepler.
- Mercury's orbit has e = 0.206
  - It has the most eccentric orbit of all planets
  - Mars has e = 0.093, much harder to tell, but still, not a circle

Isaac Newton (1642 - 1727)

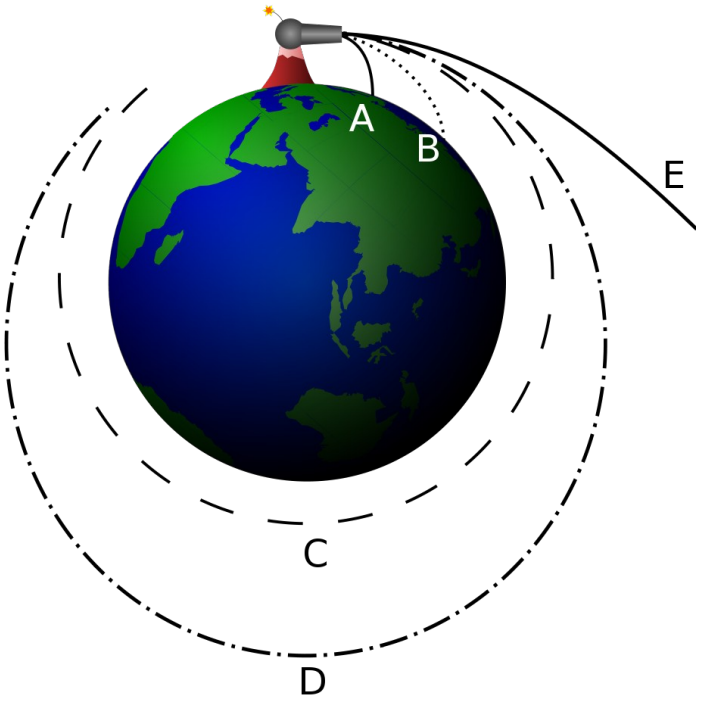


- Calculus
- Three laws of motion: Galileo described how bodies move. Newton explained why.
- Gravity: Kepler described how the planets moved, Newton explained why.
- Unified Earth and Heavens in a single theory. The Moon is "constantly falling".
- Explains immediately why the planets orbit the more massive Sun.

Isaac Newton (1642 - 1727)



The moon is constantly falling,
and constantly missing the ground.



Isaac Newton (1642 - 1727)

Nature and Nature's laws lay hid in night;

God said, "Let Newton be!" and all was light

Newton's epitaph,

by Alexander Pope

"If I could see further, was only because I stood on the shoulders of giants"

Isaac Newton,

referring to Galileo and Kepler.

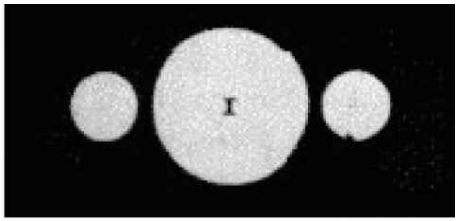
Newton's tomb,
Westminster Abbey, London.

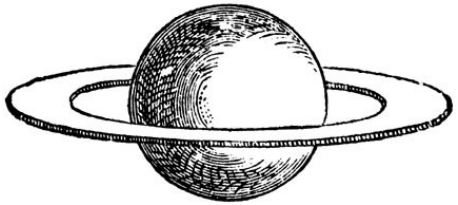
Christiaan Huygens (1629 - 1695)

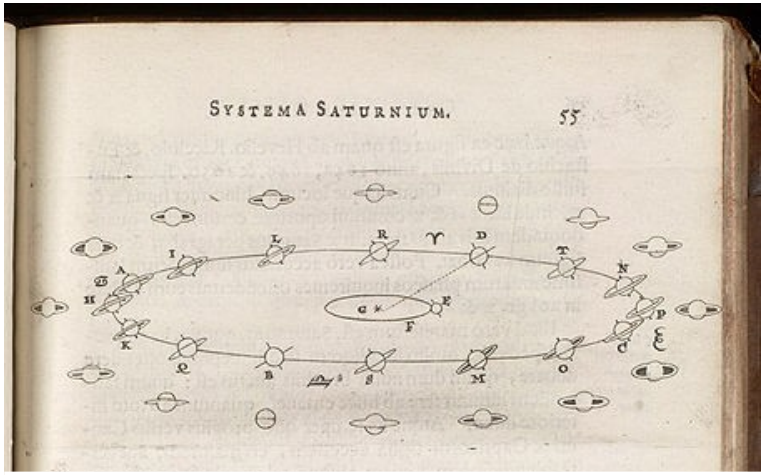
-Discoverer of Titan, Saturn's giant moon

-Understood what confused Galileo...

"**Saturn is surrounded by a thin, flat, ring, nowhere touching the planet.**"





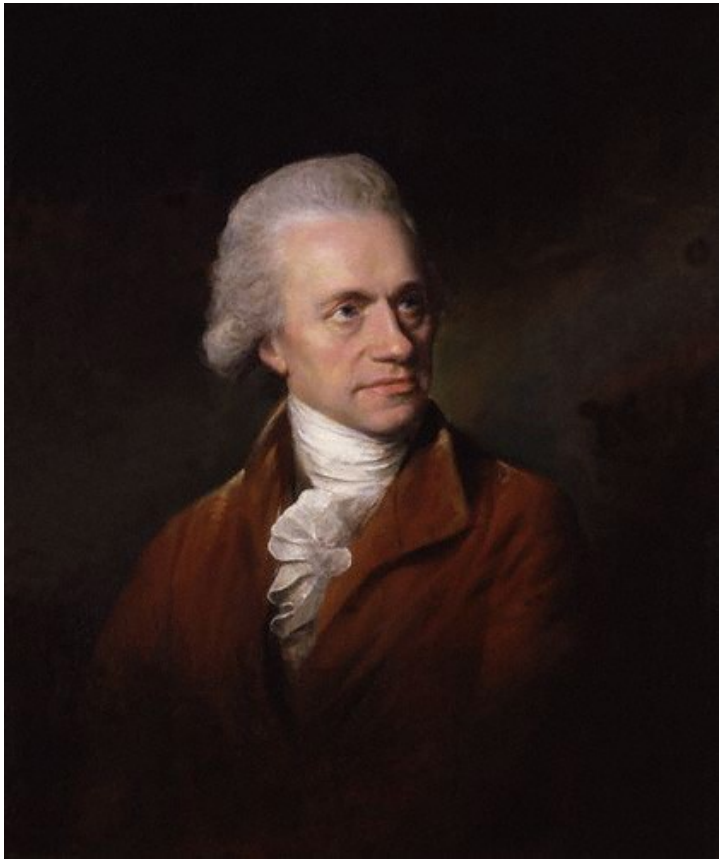


William Herschel (1738-1822)

"I don't know what to call it. It is as likely to be **a regular planet moving in an orbit nearly circular to the sun** as a Comet moving in a very eccentric ellipsis. I have not yet seen any coma or tail to it."

Nevil Maskelyne, Astronomer Royal,

on reply to Herschel, April 23, 1781.



"a moving star that can be deemed **a hitherto unknown planet-like object** circulating beyond the orbit of Saturn"

Johann Bode,

communication to the German Astronomical Society, 1781.

By the observation of the most eminent Astronomers in Europe **it appears that the new star**, which I had the honour of pointing out to them in March 1781, **is a Primary Planet of our Solar System**.

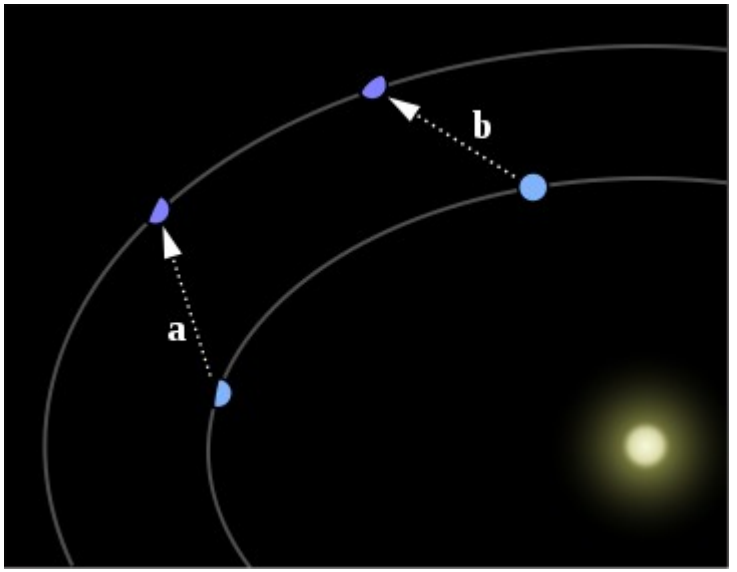
William Herschel,

"accepting" that it was indeed a planet.

"With the point of his pen"

Uranus orbit had anomalies even when the tug of all planets were taken into account.

Le Verrier postulated the existence of **another planet**, whose tug on Uranus should explain the observations...
... and calculated where the planet should be.



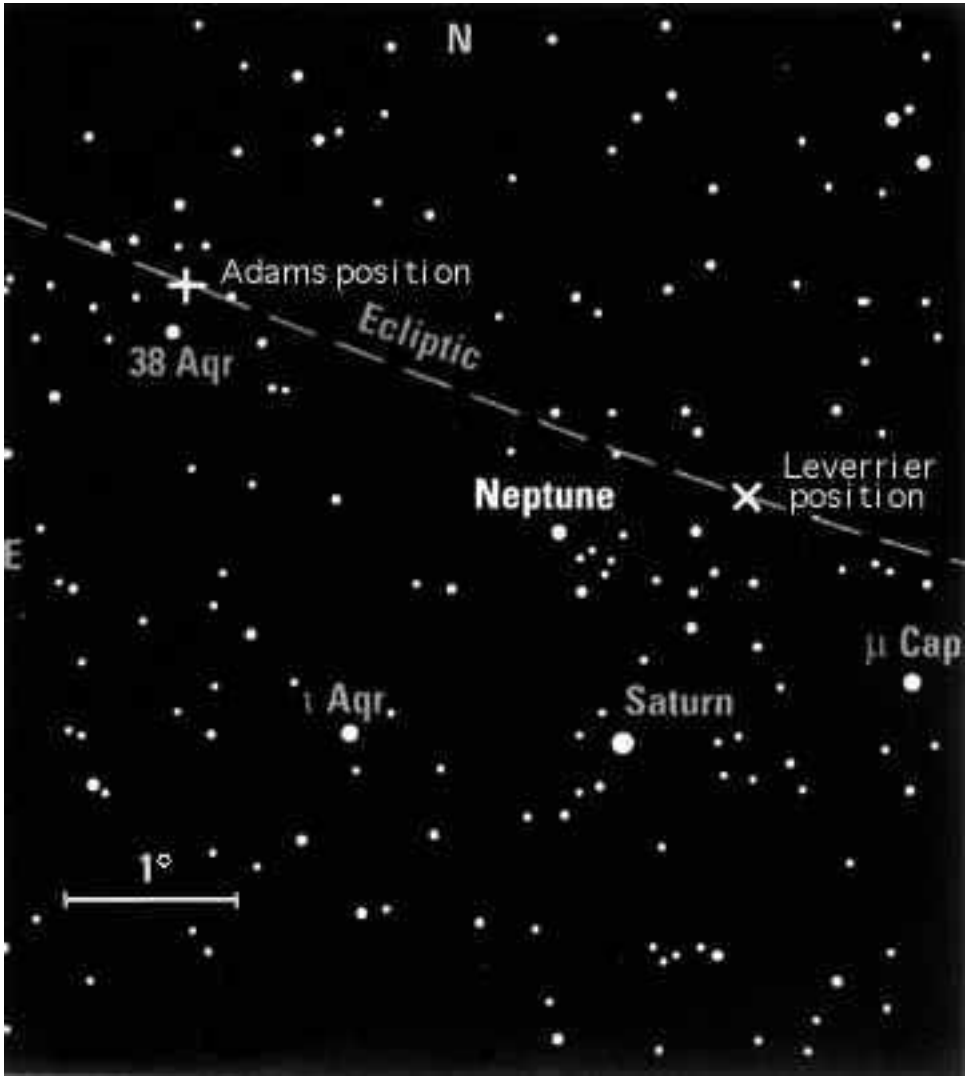
"With the point of his pen"

The planet whose place you have computed *really exists!*

Galle to Le Verrier

"The man [...] discovered a planet with the point of his pen."

Arago on Le Verrier



Early 20th Century

- 1930 – Pluto. The discovery of Neptune in 1846 did not fully explain Uranus' orbit. A 9th planet was postulated, Percival Lowell dedicated his life to find the planet.

1930ASPL...1..121L

LEAFLET 30—August, 1930

THE NEW PLANET PLUTO

By Frederick C. Leonard, S.M., Ph.D.
Of the University of California at Los Angeles

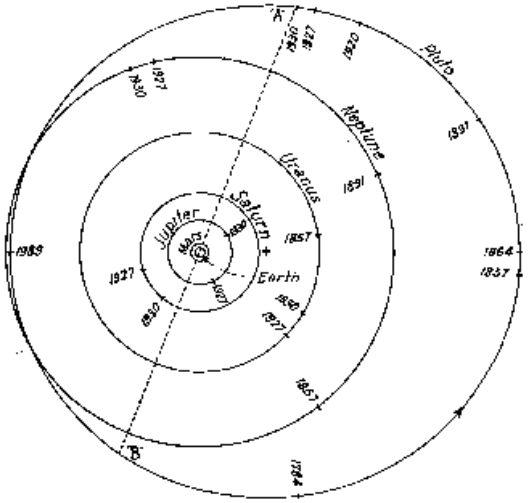
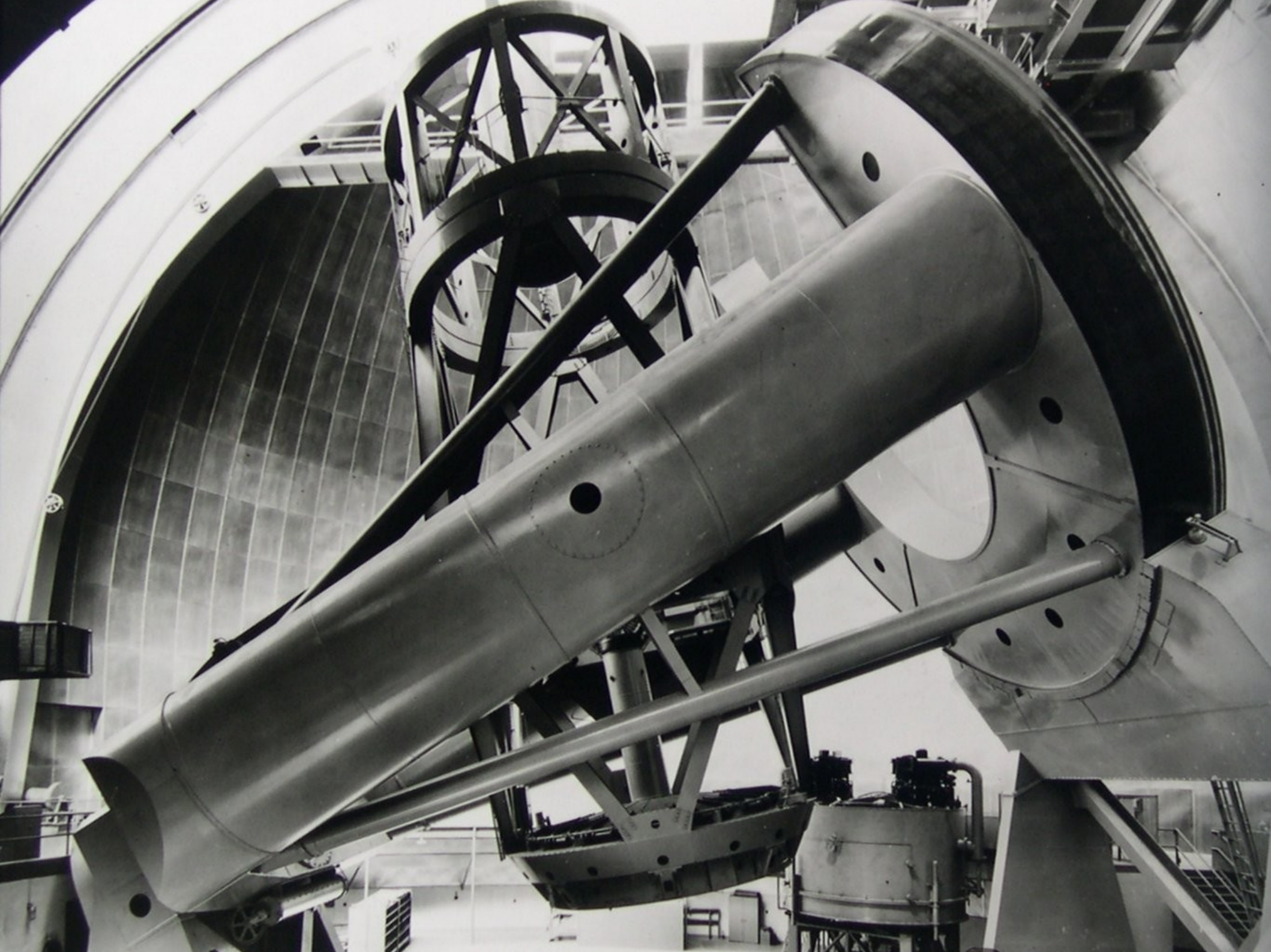
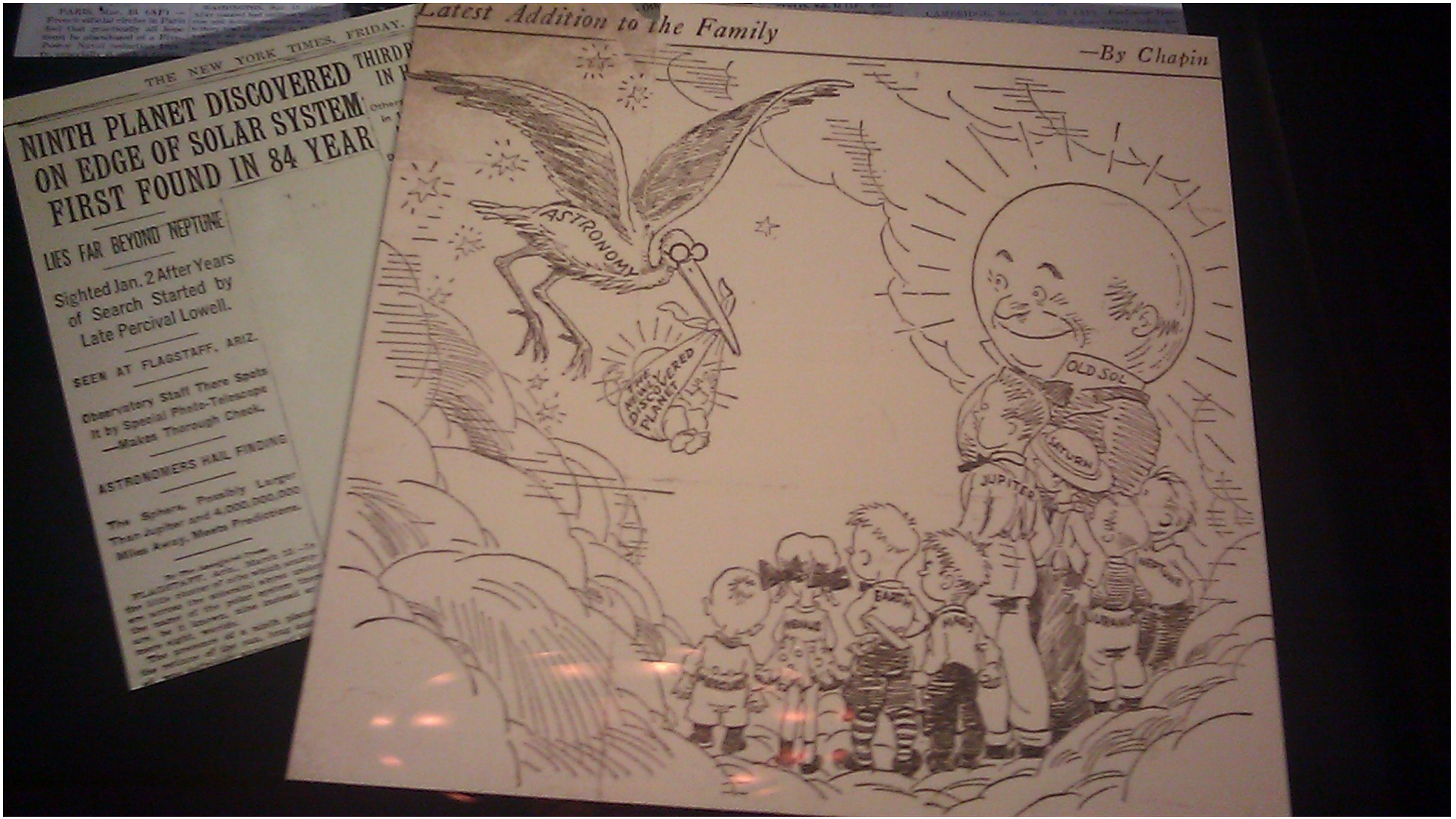


Illustration adapted from a diagram prepared by Mr. F. L. Whipple, showing the orbits of the planets Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. The innermost circle depicts the orbit of the Earth, 1 "astronomical unit," or 93,000,000 miles in radius. The planets all revolve around the Sun from west to east—that is, in a counter-clockwise direction. To make the representation of Pluto's orbit more realistic, the plane in which it is drawn should be rotated from left to right about the dotted line AB, through an angle of 17 degrees to the plane of the printed page. The




THE NEW YORK TIMES, FRIDAY.
NINTH PLANET DISCOVERED ON EDGE OF SOLAR SYSTEM; FIRST FOUND IN 84 YEAR
LIES FAR BEYOND NEPTUNE
Sighted Jan. 2 After Years of Search Started by Late Percival Lowell.
SEEN AT FLAGSTAFF, ARIZ.
Observatory Staff There Spots It by Special Photo-Telescope Makes Thorough Check.
ASTRONOMERS HAIL FINDING
The Sphere, Possibly Larger Than Jupiter and 4,000,000,000 Miles Away, Meets Predictions.
Latest Addition to the Family
—By Chapin
ASTRONOMY
THE NEWLY DISCOVERED PLANET
OLD SOL
SATURN
JUPITER
EARTH