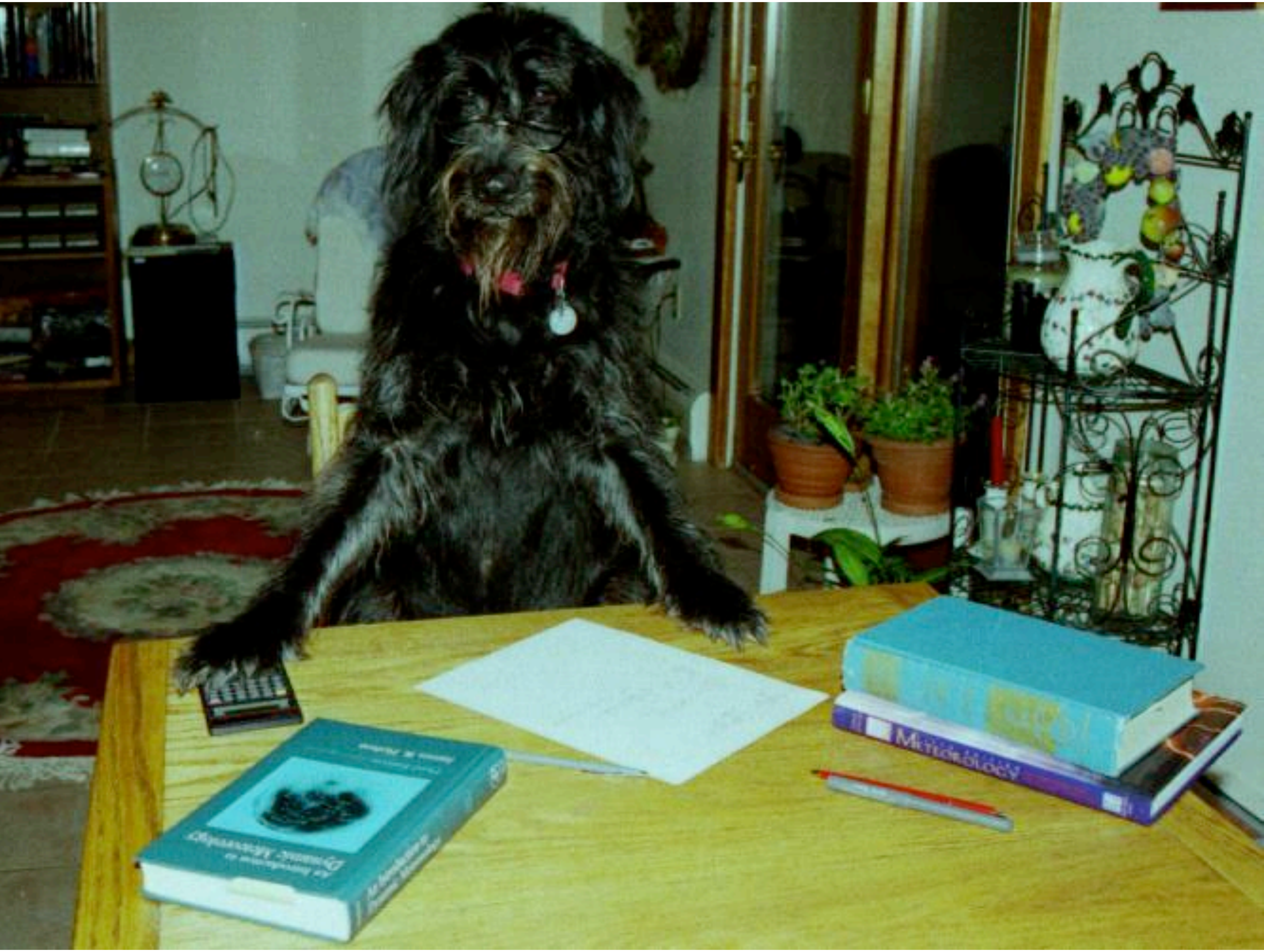

METEOROLOGY

Celestial Mechanics

What is it?

How and why bodies (planets, stars, meteors, etc.) move around the heavens.

Cassini Mission
15 September, 2017

Celestial Mechanics

Evolution of a theory?

Death of one at the sake of another?

Both!

Astronomy

For many early civilizations, Astronomy was developed to help determine the auspicious day and hour for performing sacrifices.

Seasonal planting for agricultural societies

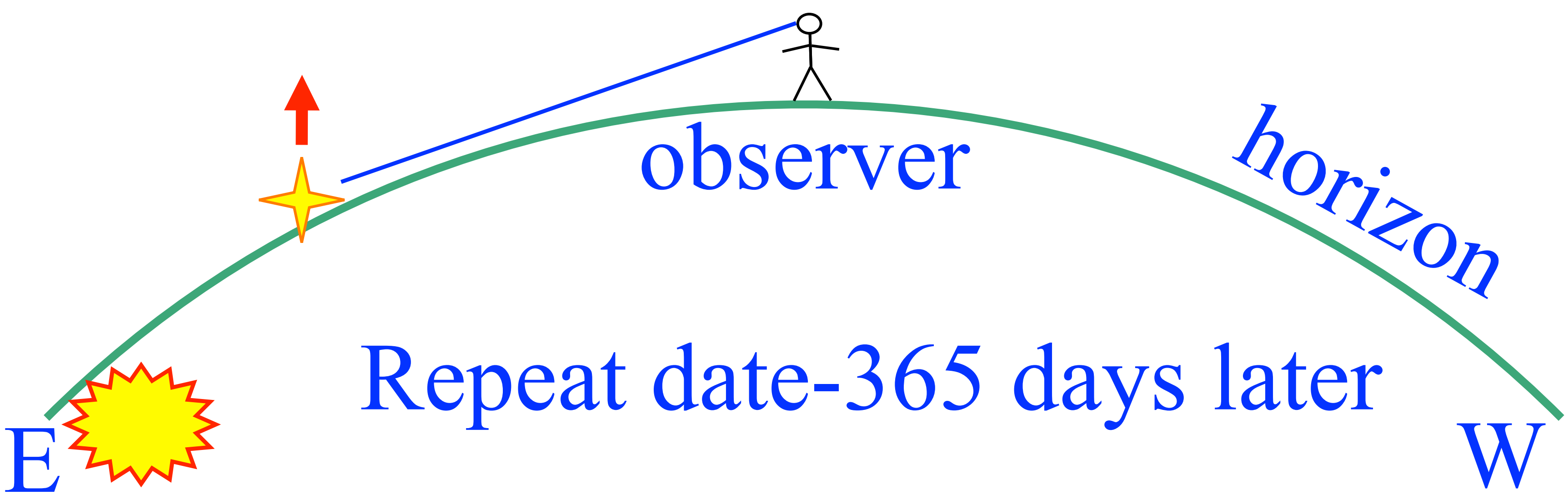
Early observers

Babylonians, Assyrians, Egyptians, Indians, Mayans ... knew the approximate length of the year.

A few centuries Before Christ (BC) the Egyptians adopted a 365 day year.

The Chinese had a working calendar and had determined the length of the year a few centuries BC as well.

The Egyptians looked for the date when the star Sirius could first be seen in the dawn sky rising just before the sun.



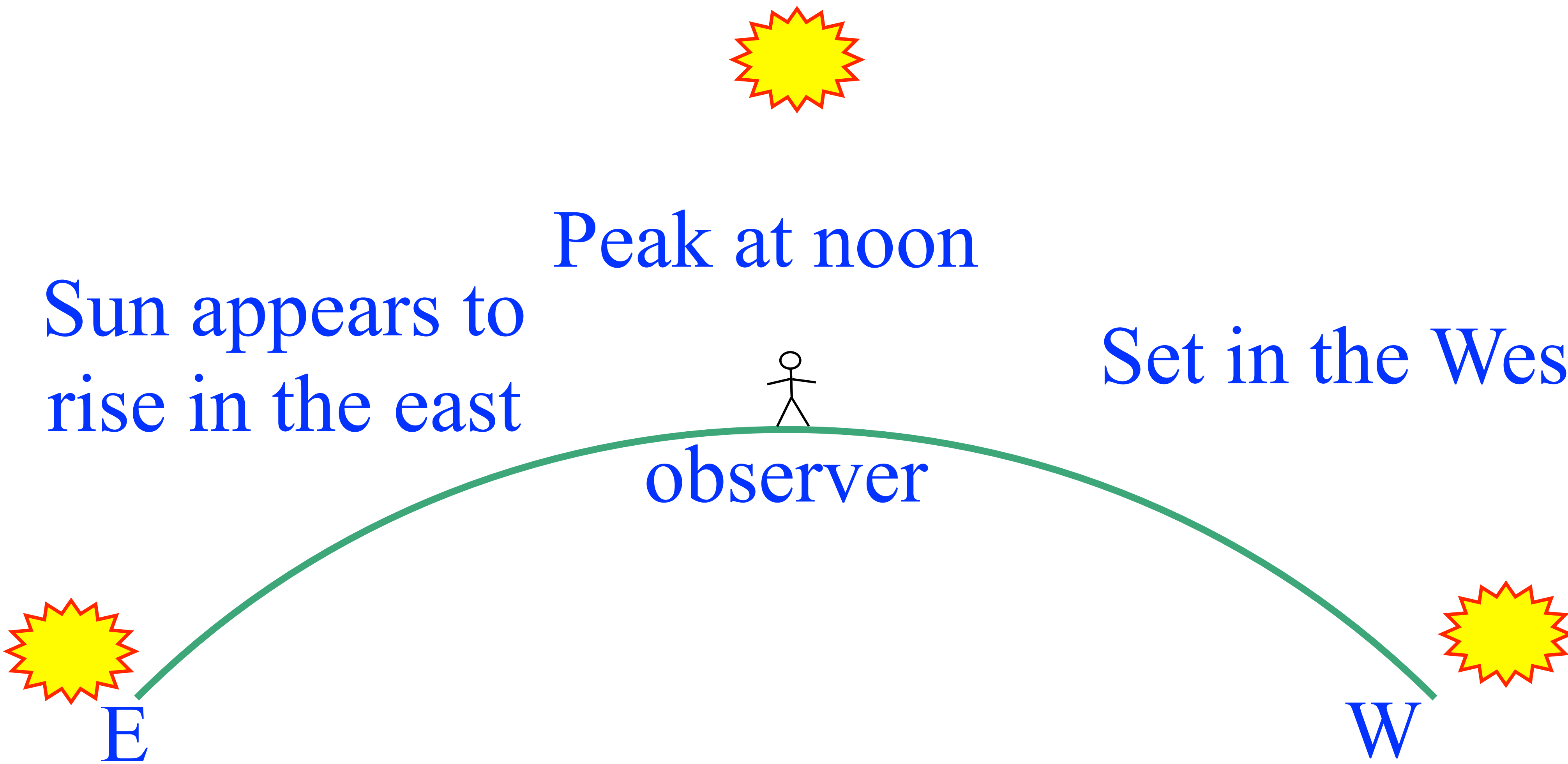
Observations of the ancients

To understand the cosmology of the ancients, we need to think about the signs that they observed. What was their world like.

No space shuttle, no satellites, no imaging instrumentation, no telescopes, no …

They observed by eye in their local environment

What did the Ancients see (and feel)



Class Exercise

Put your hands on you desk and close your eyes until I ask you to open them.

Try to feel your environment with all your senses.

What did they feel?

To the ancients, with no other forms of observing, the Earth was stationary, and the sun, planets, and stars moved around them.

An Earth centered cosmos was a natural choice.

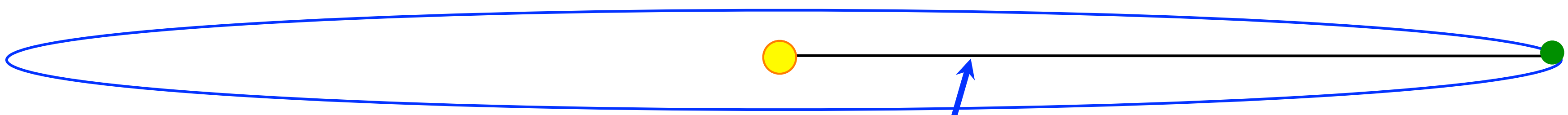
We don’t feel like we are moving?

Do you know how fast you were going?

Yes, officer. A little under 67 thousand miles per hour.

How fast are you are moving?

Earth revolves around
the sun once per year.



Ave distance = 93 million miles

Circumference = $2\pi r$ = $5.84x10^8$ mi

$$\frac{5.84x10^{8}\ mi}{365\ day}\times\frac{1\ day}{24\ hr}=66{,}705\ {}^{mi}\!/\!_{hr}$$

If we can not feel ourselves revolving about the sun is there any other motion we should worry about?

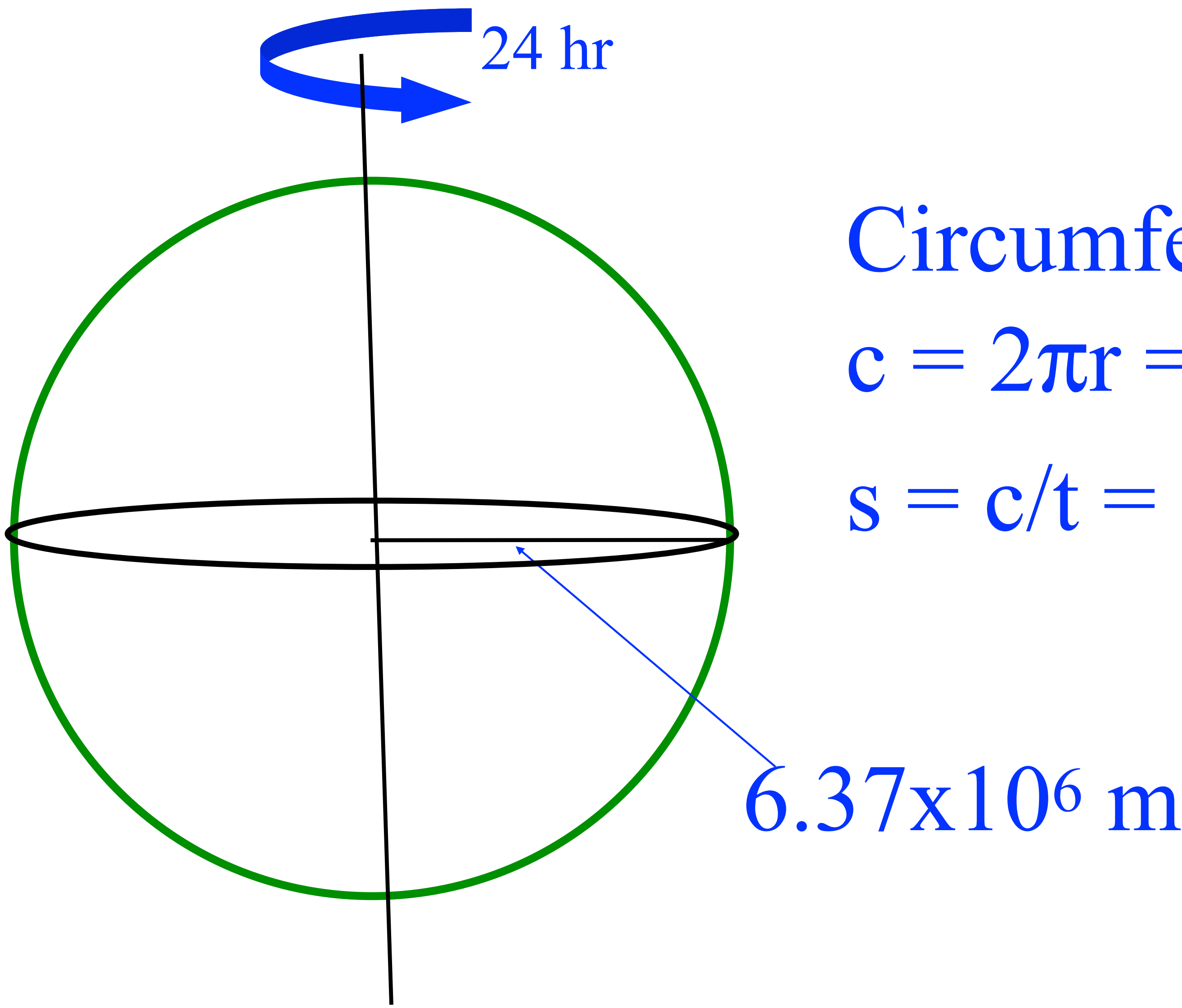
The earth makes 1 revolution per day

Radius = 6.37×10^6 m

~ 3959 mi

Stretch out at the Equator

At equator

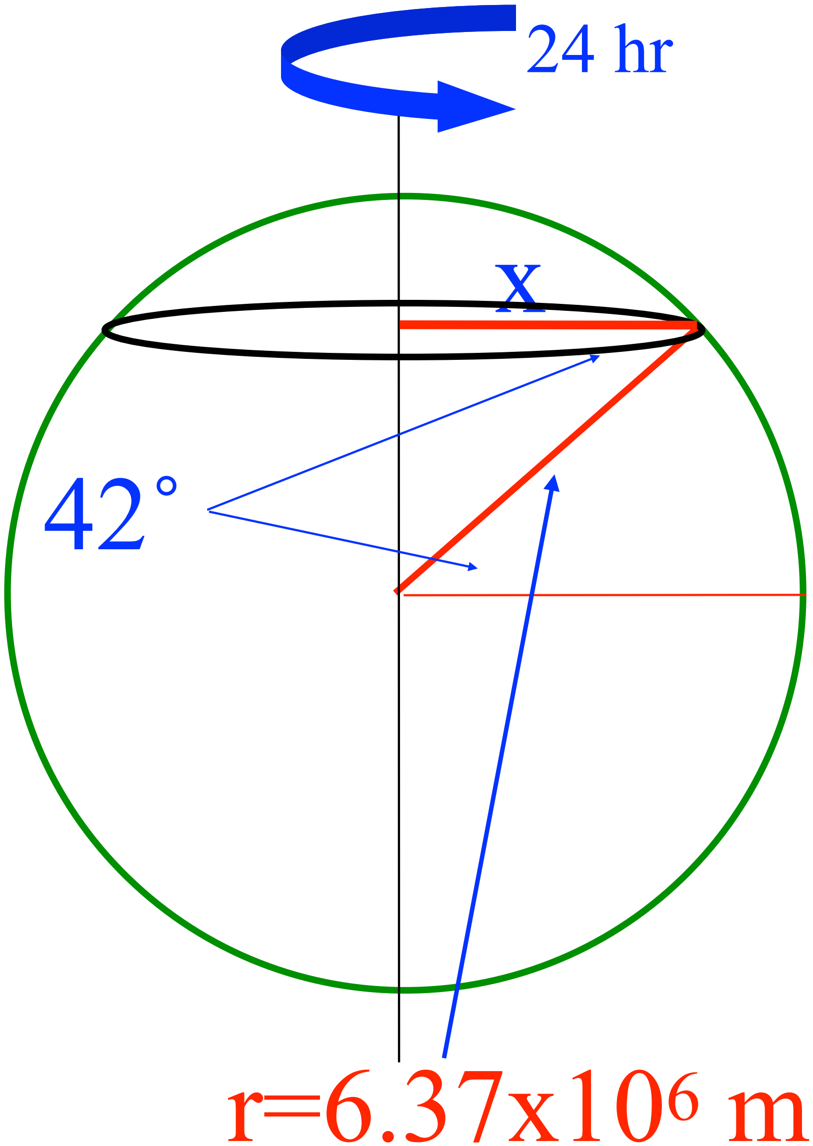


Circumference is

$c = 2\pi r = 24{,}875$ mi

$s = c/t = 1040$ mph

Lowell, MA 42° N

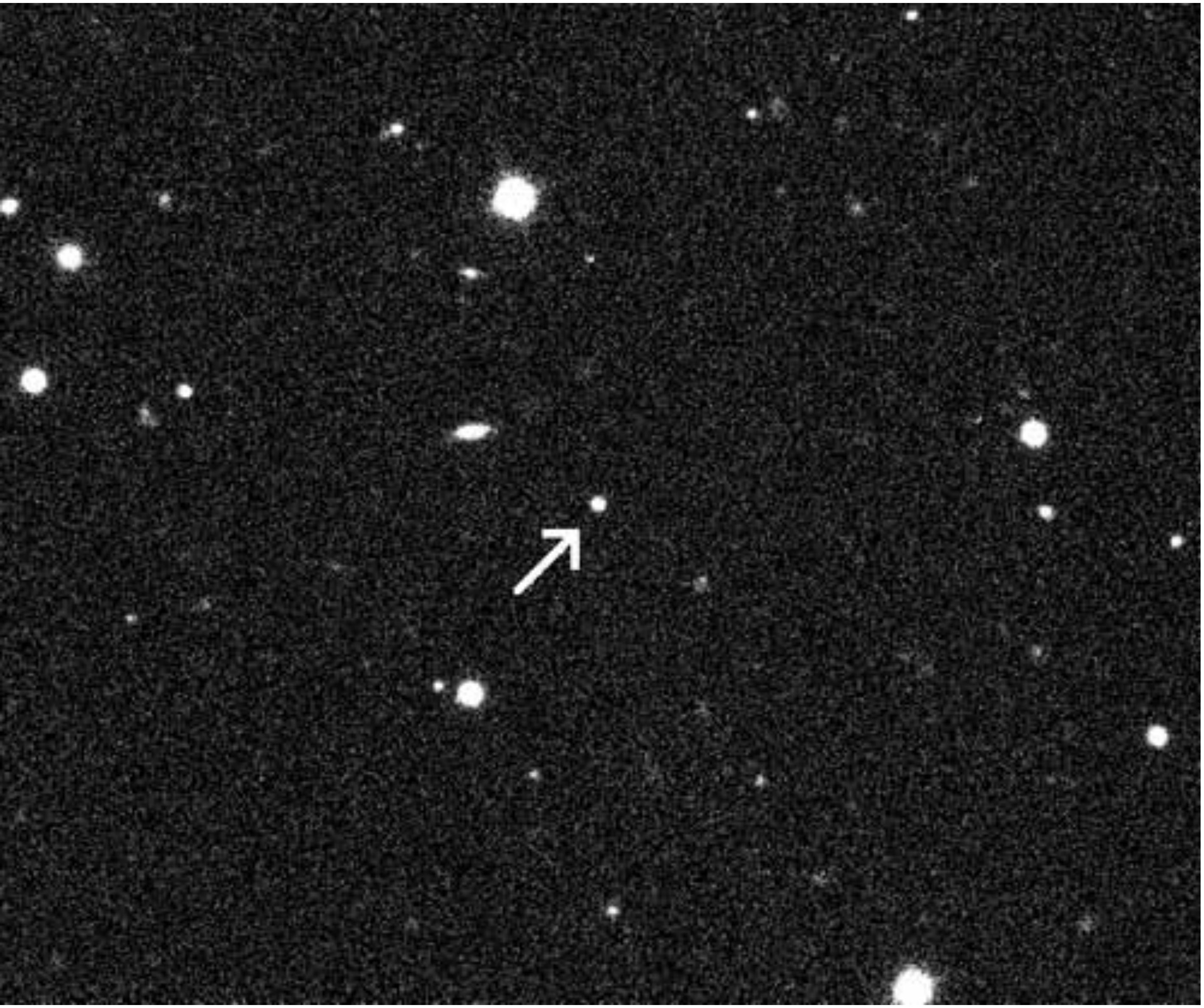


$x = r \cos 42 = 2942$ mi

Circumference

$c = 2\pi r = 18{,}485$ mi

$s = c/t = 770$ mph



Astronomers have discovered a star traveling over 1.5 million mph -- fast enough to escape the gravitational pull of the Milky Way galaxy. This image from the Sloan Digital Sky Survey shows an area of the sky one-fiftieth the size of the full moon (the arrow marks the star). Photo: Courtesy of SDSS Collaboration

http://www.wired.com/news/space/0,2697,66542,00.html?tw=wn_1techhead

Animal goo inspires better glue

5, September 30, 2017

McGill University researchers and colleagues have created a surgical glue that mimics the chemical recipe of slime that slugs exude when they're startled. The adhesive was stuck to a pig heart even when the surface was coated in blood. The glue was used to plug a hole in the pig heart-the heart still held in liquid after being inflated and deflated tens of thousands of times.

https://www.sciencenews.org/article/animal-goo-inspires-better-glue

Observations of Eudoxus and Aristotle -

The Earth is stationary

Sun, moon, planets revolve around the Earth

Rise in the East and set in the West or circle around the sky

The Greeks carefully observed the motions of the sun, moon, and five strange “stars “ that we now know to be planets.

Together these give us the days of the week.

Day	celestial object	
Sunday	the sun	Dimanche
Monday	the moon	Lundi
Tuesday	Mars	Mardi
Wednesday	Mercury	Mecredi
Thursday	Jupiter	Jeudi
Friday	Venus	Vendredi
Saturday	Saturn	Samedi

Eudoxus ~370 BC

Cosmological model

The basis was perfect spheres , all with the same center, the earth, all spinning at unchanged speeds.

With 27 spheres in all, this system imitated the observed motions of the planets.

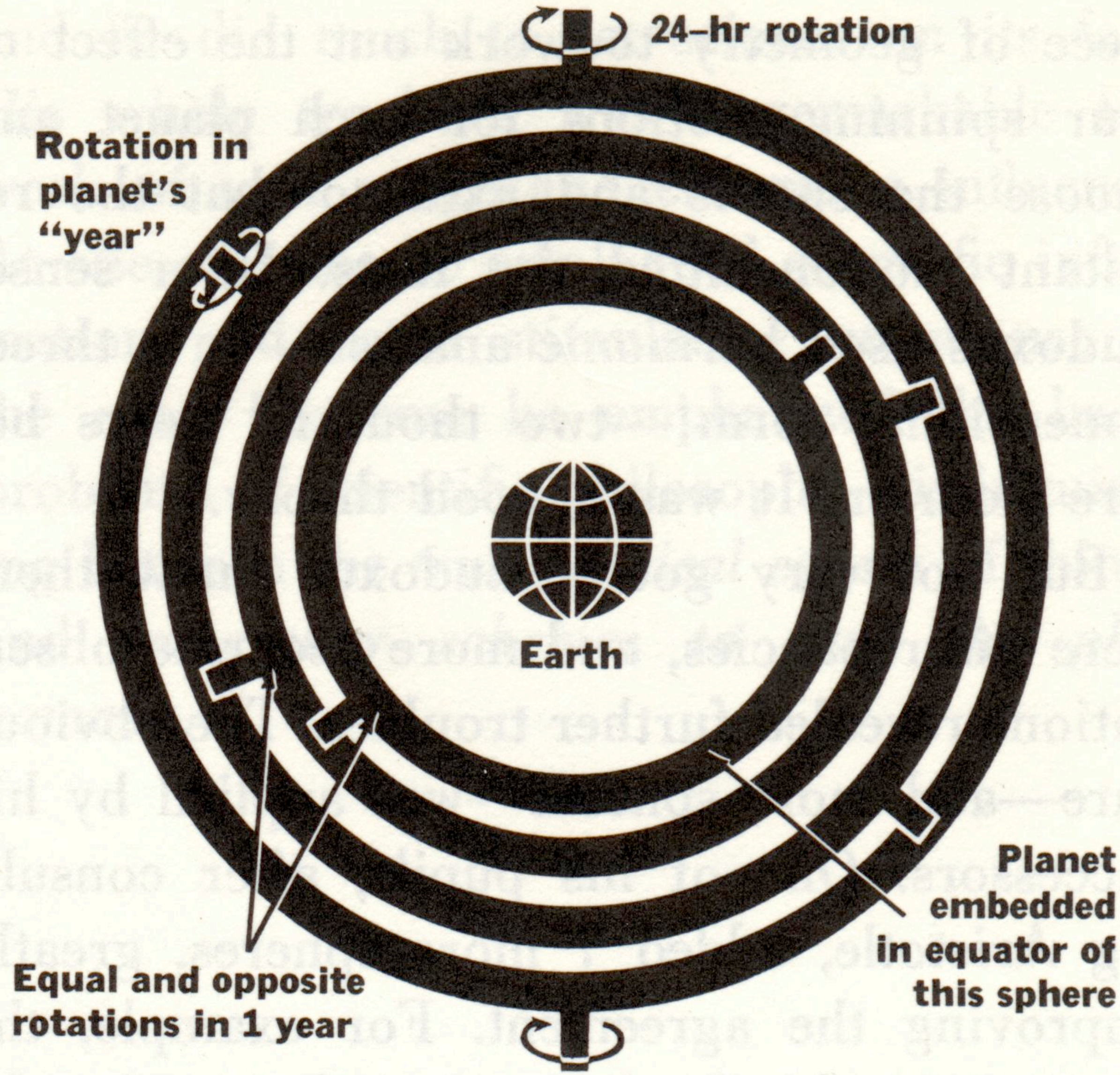


Figure 3-28. Part of Eudoxus' scheme used four spheres to imitate the motion of a planet. The sketch shows the machinery for one planet. The outermost sphere spins once in twenty-four hours. The next inner sphere rotates once in the planet's "year." The two innermost spheres spin with equal and opposite motions, once in our year, to produce the planet's epicycloid loops.

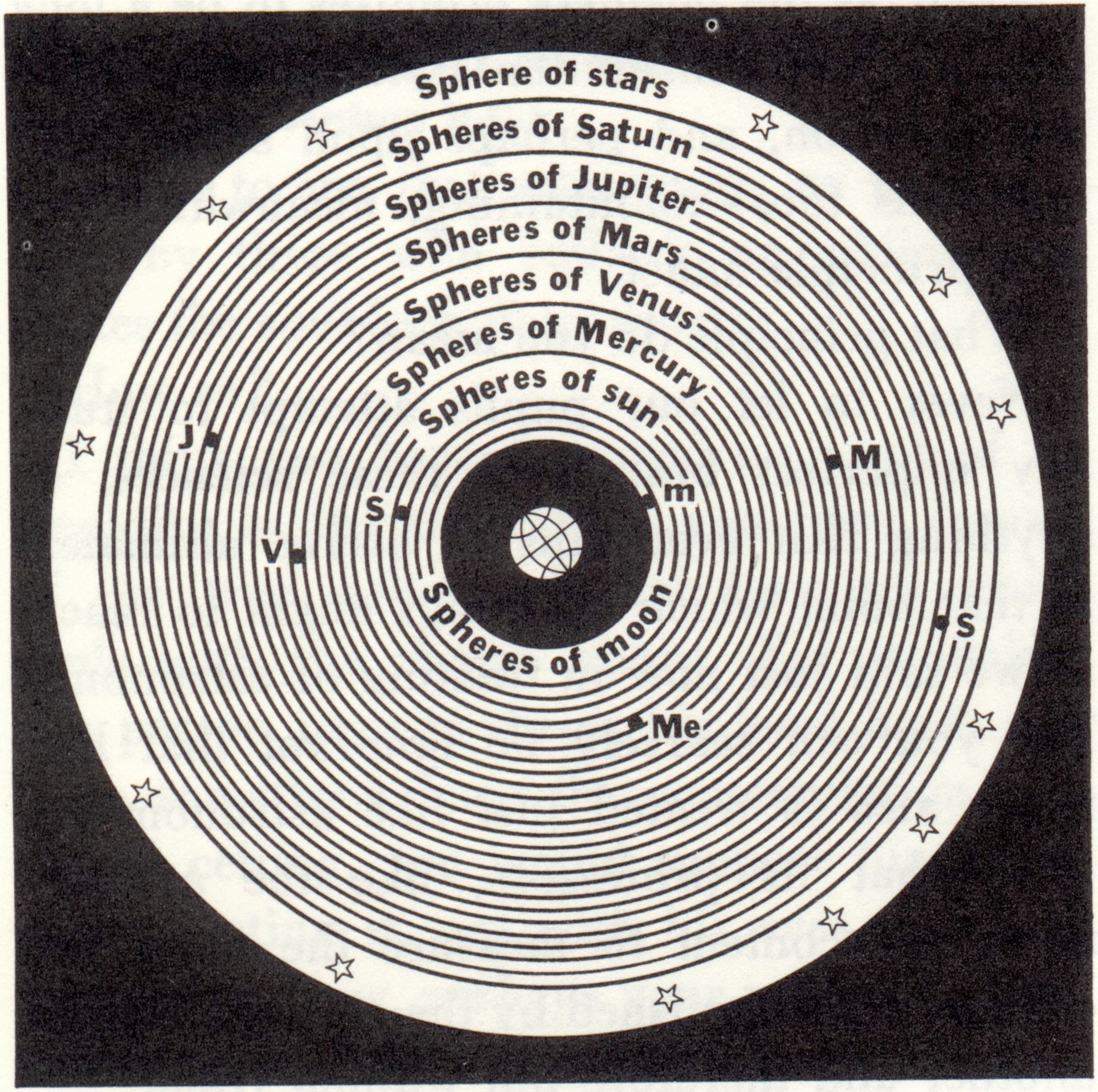
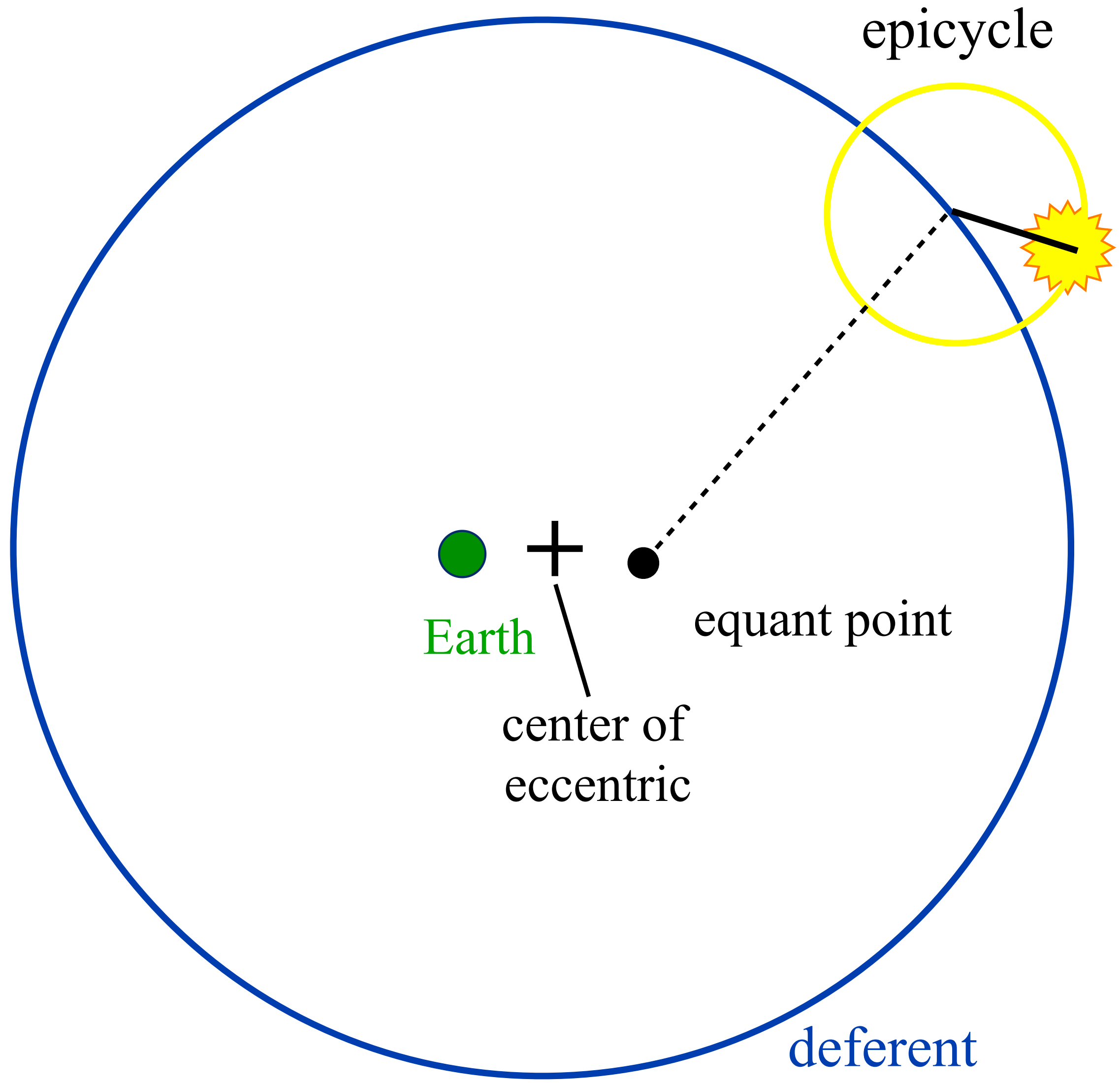
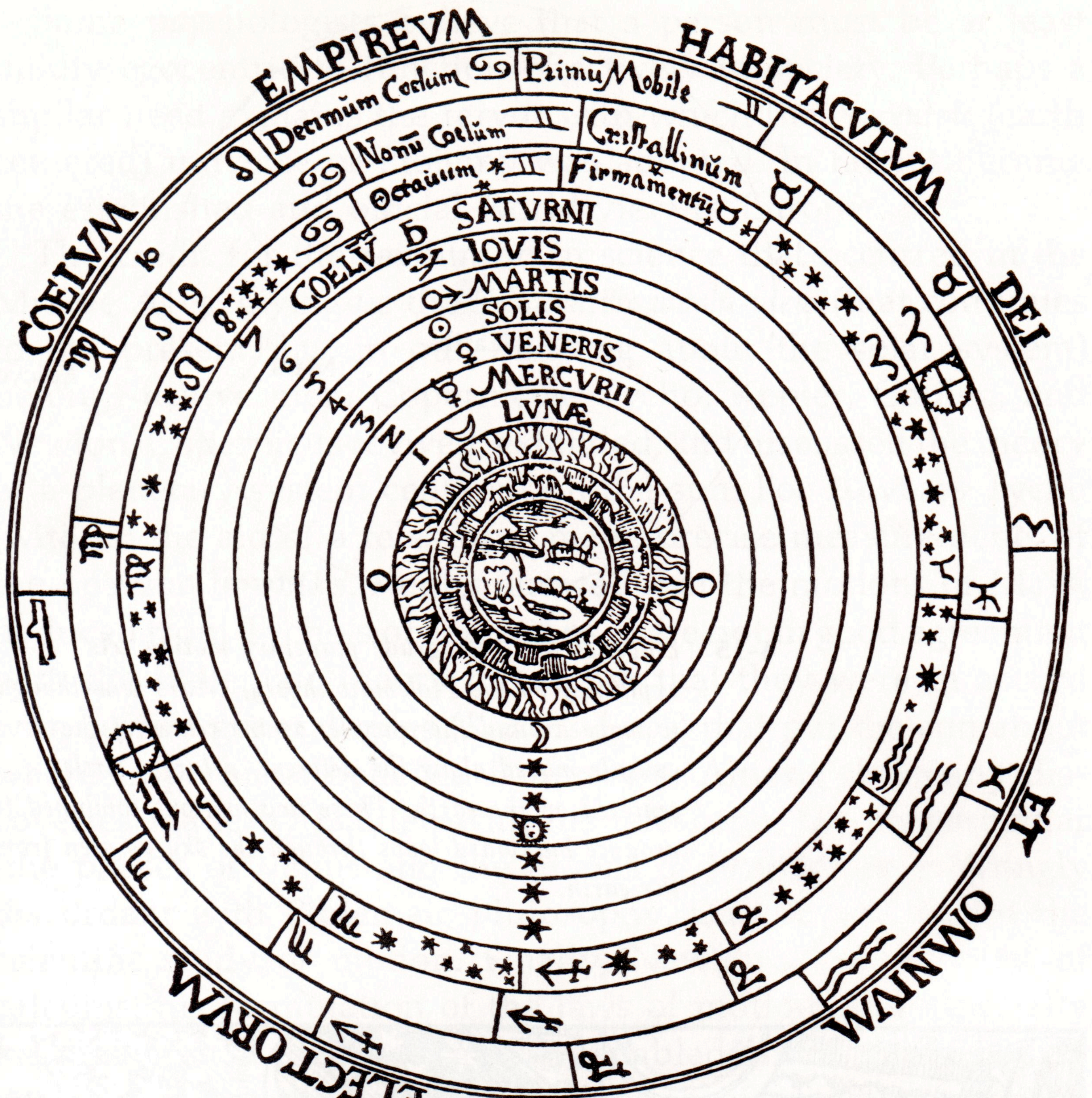


Figure 3-27. Eudoxus' scheme of many concentric spheres. Each body, sun, moon, or planet, had several spheres spinning steadily around different axes. The combination of these motions succeeded in imitating the actual motions of sun, moon, and even planets across the star pattern.

Last great Greek astronomer
Ptolemy – 140 AD

Ptolemy's cosmological system was based on geocentric motion. It accounted for the motions of the planets.





Ptolemy’s Universe

140 AD – 1543 AD

After the barbarian invasions, the Catholic Church, through Thomas Aquinas, discovered the writings of Aristotle.

The earth centered universe became doctrine.

Ptolemy’s Universe lasted 1400 years

Geocentric universe ~ 2000 years (probably longer)

Sun centered universe only ~ 500 years

Why did it change?

Nicolas Copernicus
1473-1543

- Well educated
- Argued that the heavens must be more simple than Ptolemy's design
- There was evidence that the system was not working.

By the time of Copernicus the traditional mark of the beginning of Spring in the Northern Hemisphere moved back from March 21 to March 11   10 days!!!!

Hint → Ptolemy's model does not work

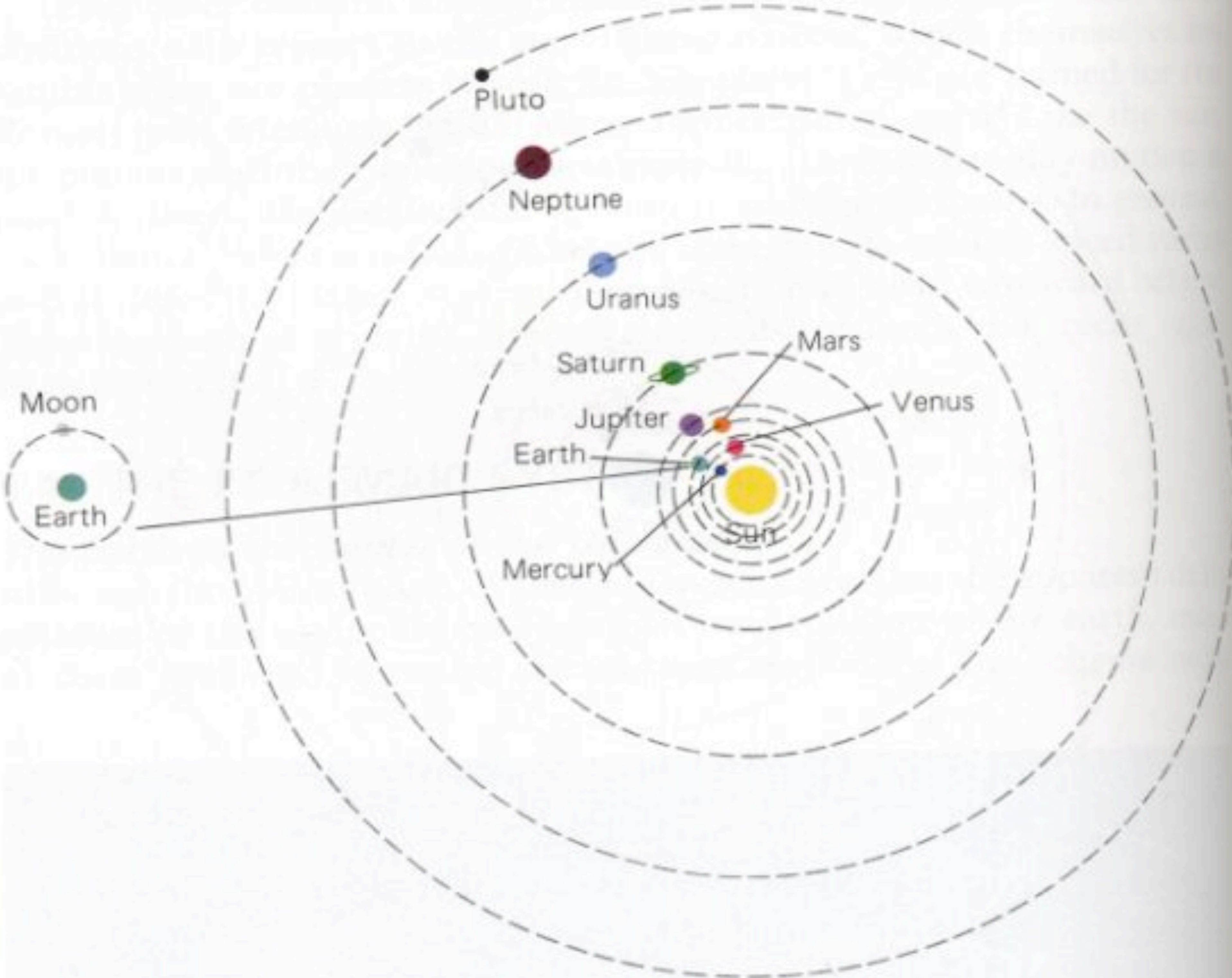
"On the Revolution of the Celestial Spheres" was published just before his death. In it Copernicus proposed a new arrangement for the universe.

1543

NICOLAI COPERNICI

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

pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoq; minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac


Pluto
Neptune
Uranus
Mars
Saturn
Venus
Moon
Jupiter
Earth
Earth
Sun
Mercury

The hypothesis was accepted by some but not by others.

Martin Luther – "This fool wishes to reverse the entire science of astronomy: but sacred scripture tells us that Joshua commanded the sun to stand still, and not the earth."

Distance of Planets from the Sun in AU determined by Copernicus

planet	Copernicus	Modern
Mercury	0.38	0.39
Venus	0.72	0.72
Earth	1.00	1.00
Mars	1.52	1.52
Jupiter	5.22	5.20
Saturn	9.18	9.54

The next step

Tycho Brahe (1546-1601)

Danish, follower of Aristotle's physics

believed in a motionless Earth

Tycho Brahe

“if the Earth actually rotated a cannonball fired in the direction of the Earth’s rotation should go farther than if it were fired in the opposite direction.”

Tests were done and there was no measurable difference. So Brahe concluded he was right.

Cannons in Lowell

We saw the rotation of the earth yields a ground speed of ~770 mph

Lets say the cannon ball is in the air for 5 seconds

$$770\frac{mi}{hr}\times\frac{1hr}{60\min}\times\frac{1\min}{60s}=0.21\frac{mi}{s}$$

$$in\ \ 5\ \ \text{seconds}$$

$$0.21\frac{mi}{s}\times\ 5\,s\approx 1\,mile$$

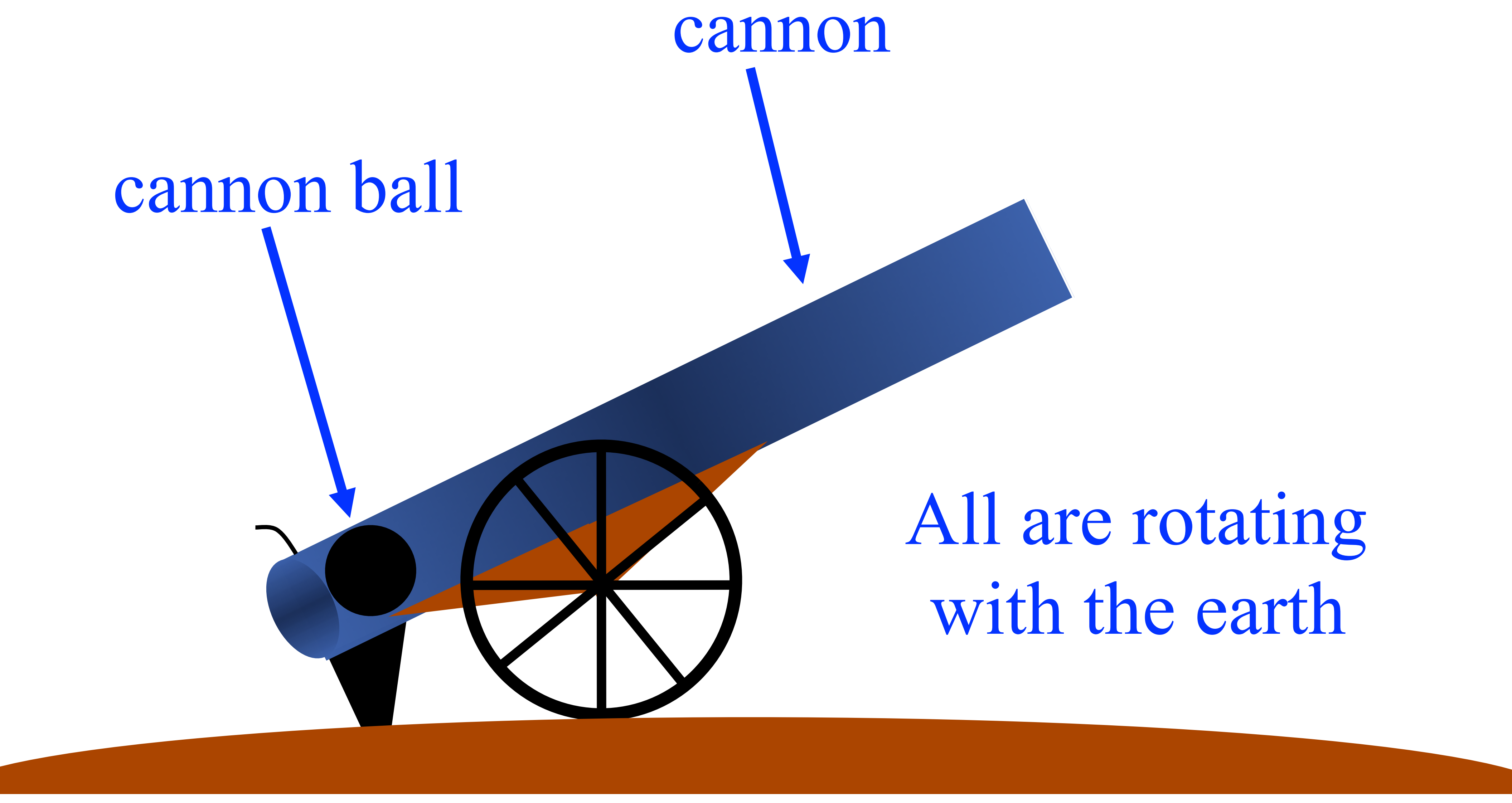
Why can’t the difference be detected?

Going with and against the rotation of the earth the difference should be 2 miles according to Brahe.

Why was it not detected?

Are we really not moving!!!

INERTIAL frame of reference



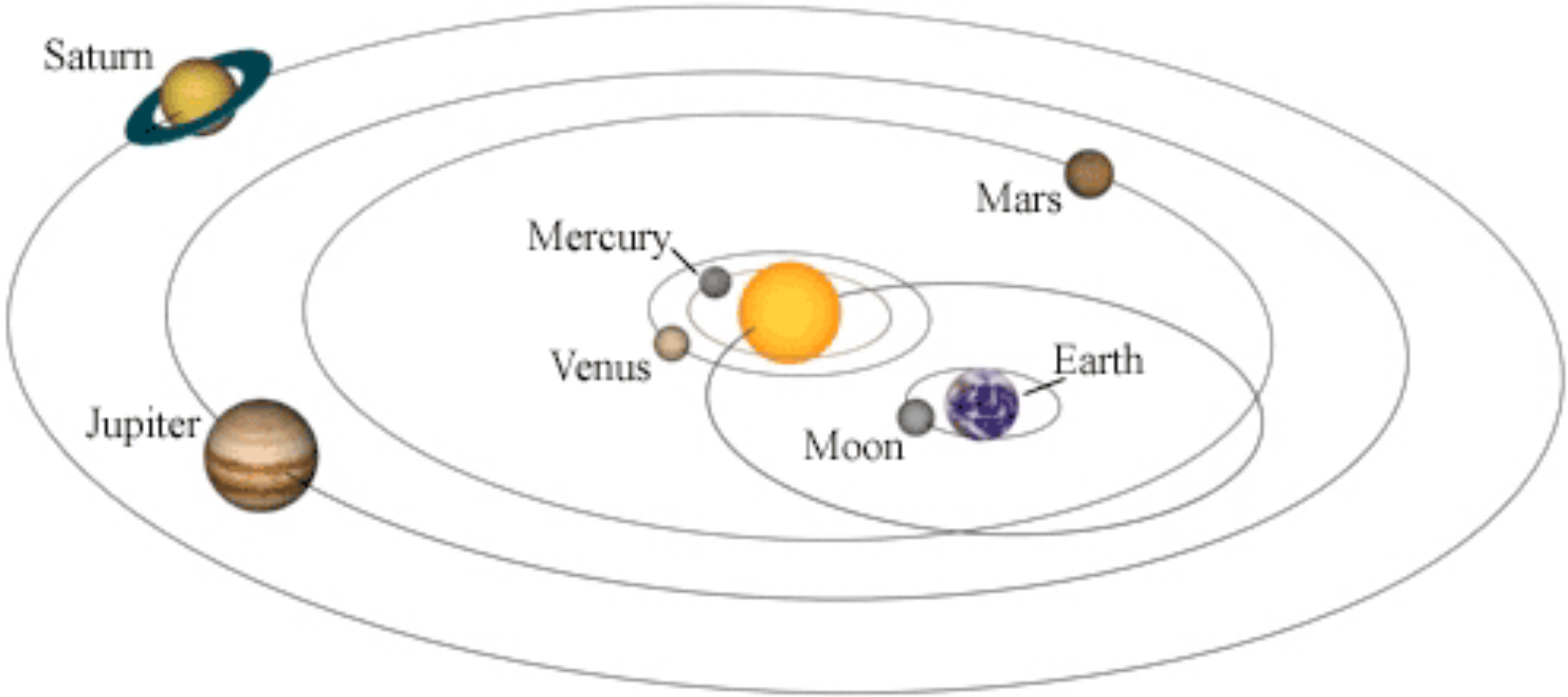
All are rotating with the earth

These facts were unknown until Galileo and not appreciated until Newton.

Brahe was given an observatory on an island (Hven) between Denmark and southern Sweden, and lots of $$$$$

He had bigger instruments built for his observatory

Bigger instruments → more accurate measurements



Tycho’s Universe

image: http://www.polaris.iastate.edu/EveningStar/Unit2/unit2_sub3.htm

Brahe and the staff at his observatory catalogued the positions of over 1000 stars. This was the largest and most accurate data set ever on celestial motion.

On his deathbed, Brahe bequeathed the records of his observatory and the instruments to Johannes Kepler.

http://faculty.uml.edu/Robert_Gamache

Johannes Kepler (1571-1630)

Kepler was the eldest child of a poor family from southwest Germany.

He studied theology, astronomy, mathematics

Johannes Kepler (1571-1630)

He was a numerologist, and believed in mathematical mysticism.

He tried various more accurate theories to explain the motions of the planets, including numerology and music.

Johannes Kepler (1571-1630)

"God is celebrated in astronomy"

What he really was good at was mathematics and he studied the records from Brahe's observatory.

From his work came Kepler's three laws of planetary motion

Johannes Kepler (1571-1630)

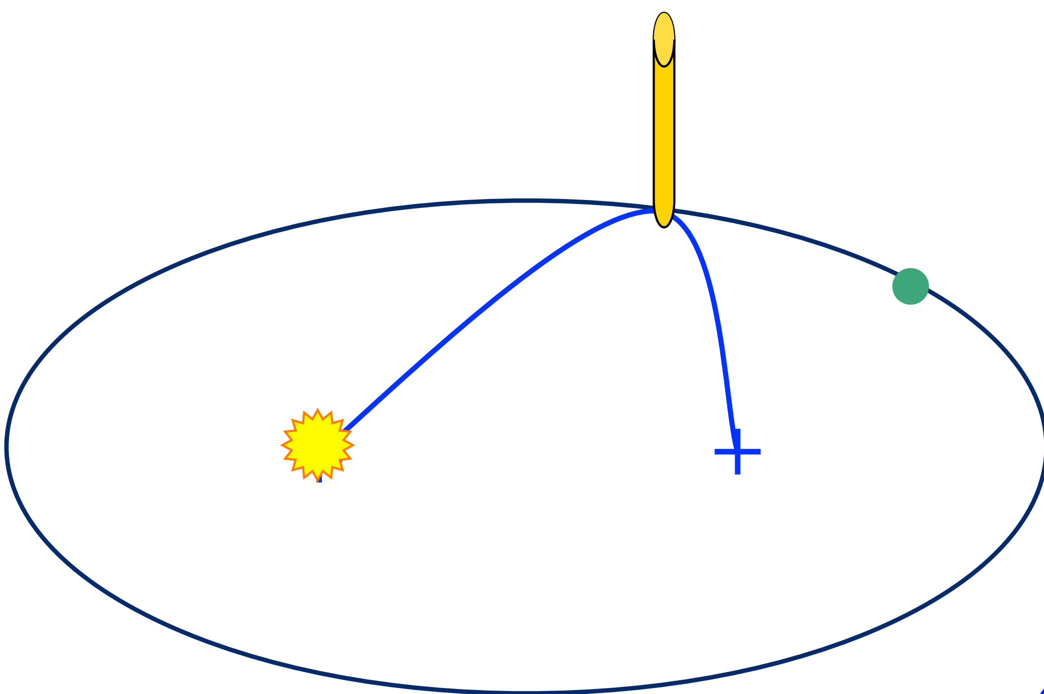
He was a firm believer in the cosmology of Copernicus.

He noted that the more distant from the sun the longer the period of revolution.

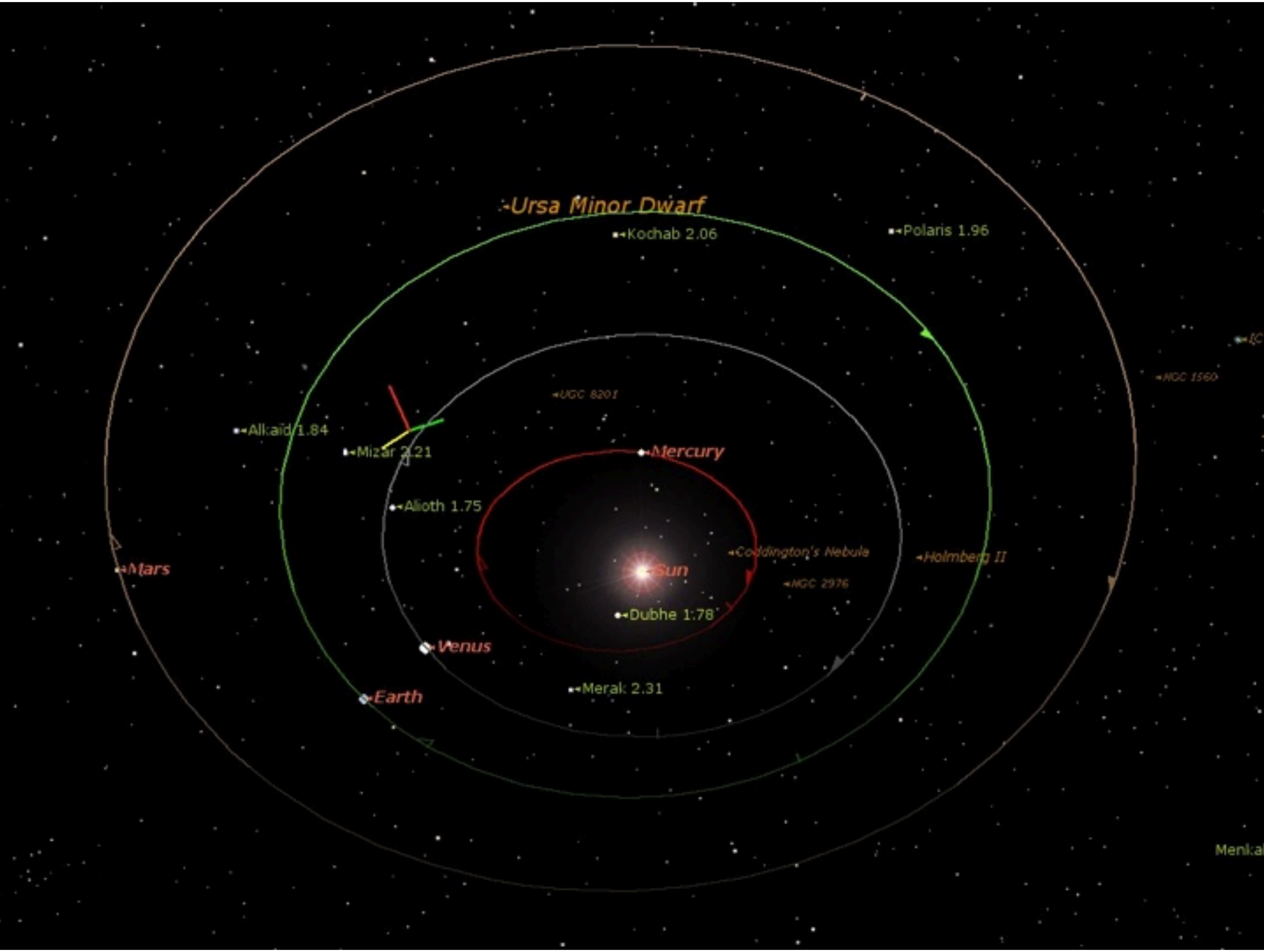
From his work the "spirits" and celestial "intelligence" were replaced by the notion of forces.

Kepler's First Law

The path of each planet is an ellipse with the sun at one focus.



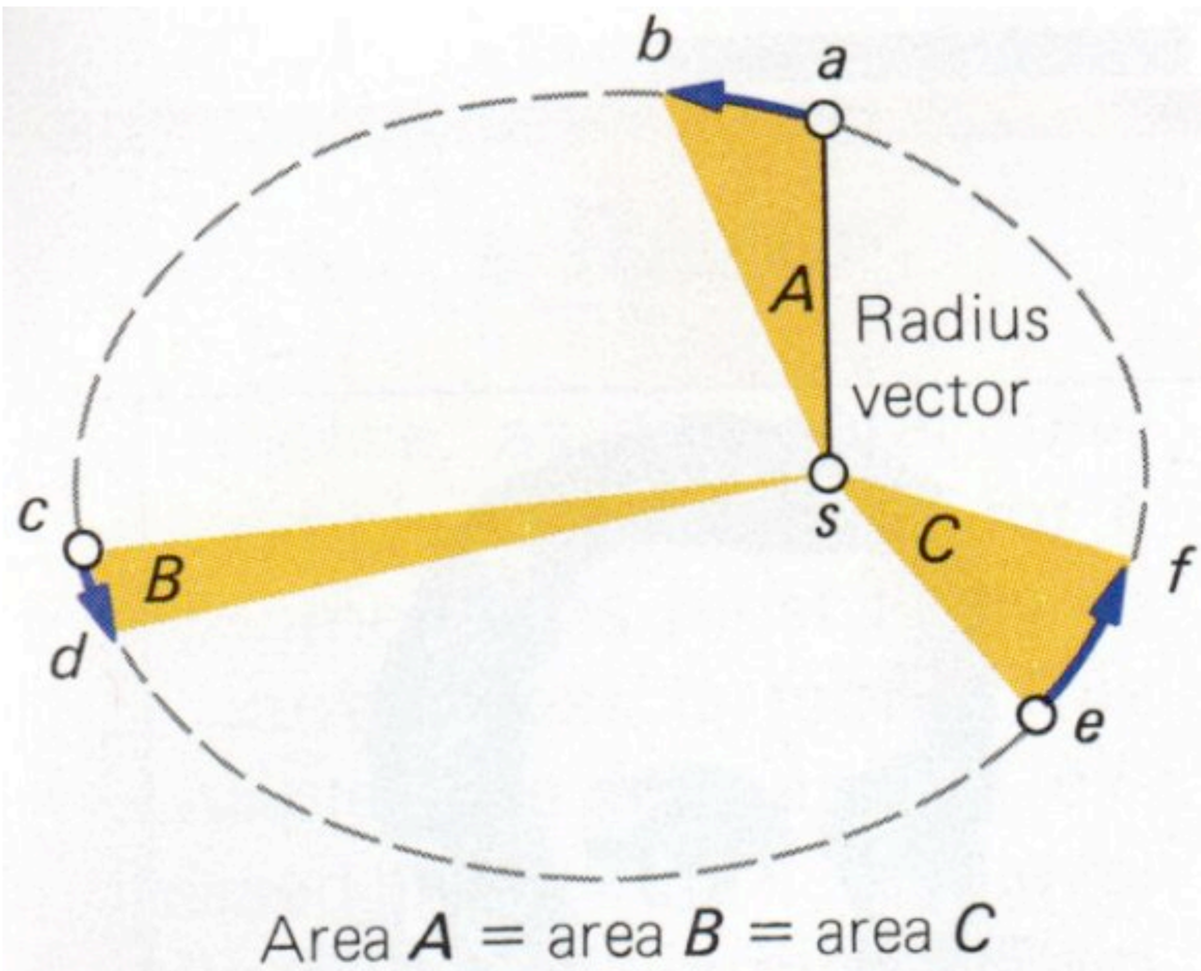
ellipse



Ursa Minor Dwarf
Kochab 2.06
Polaris 1.96
UGC 8201
Alkaid 1.84
Mizar 2.21
Mercury
Alioth 1.75
Coddington's Nebula
Holmberg II
Mars
Sun
NGC 2976
Dubhe 1.78
Venus
Merak 2.31
Earth
NGC 1560

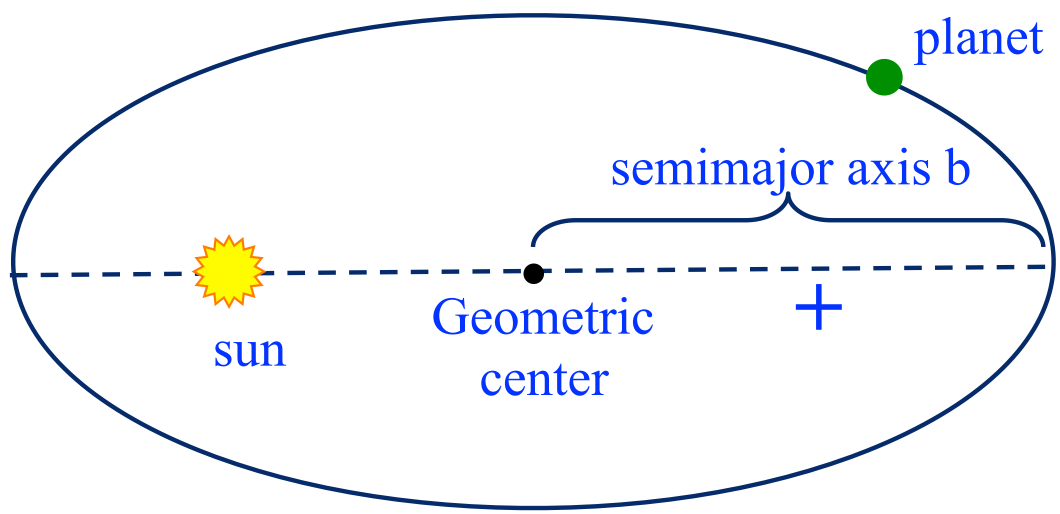
Kepler's Second Law

The line from the sun to the planet sweeps out equal areas in equal times.



Kepler's Third Law

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



Kepler's Third Law

This can be written symbolically as

$$T^2 = K_{sun}\, b^3$$

T is the period of the orbit, the time it takes for the planet to complete one orbit around the sun.

K_{sun} is the constant of proportionality, 1 yr^2/AU^3

b is the length of the semimajor axis

Ellipses not Circles!!!

Kepler worked for months to try to find the circular orbits that would fit Copernicus' model.

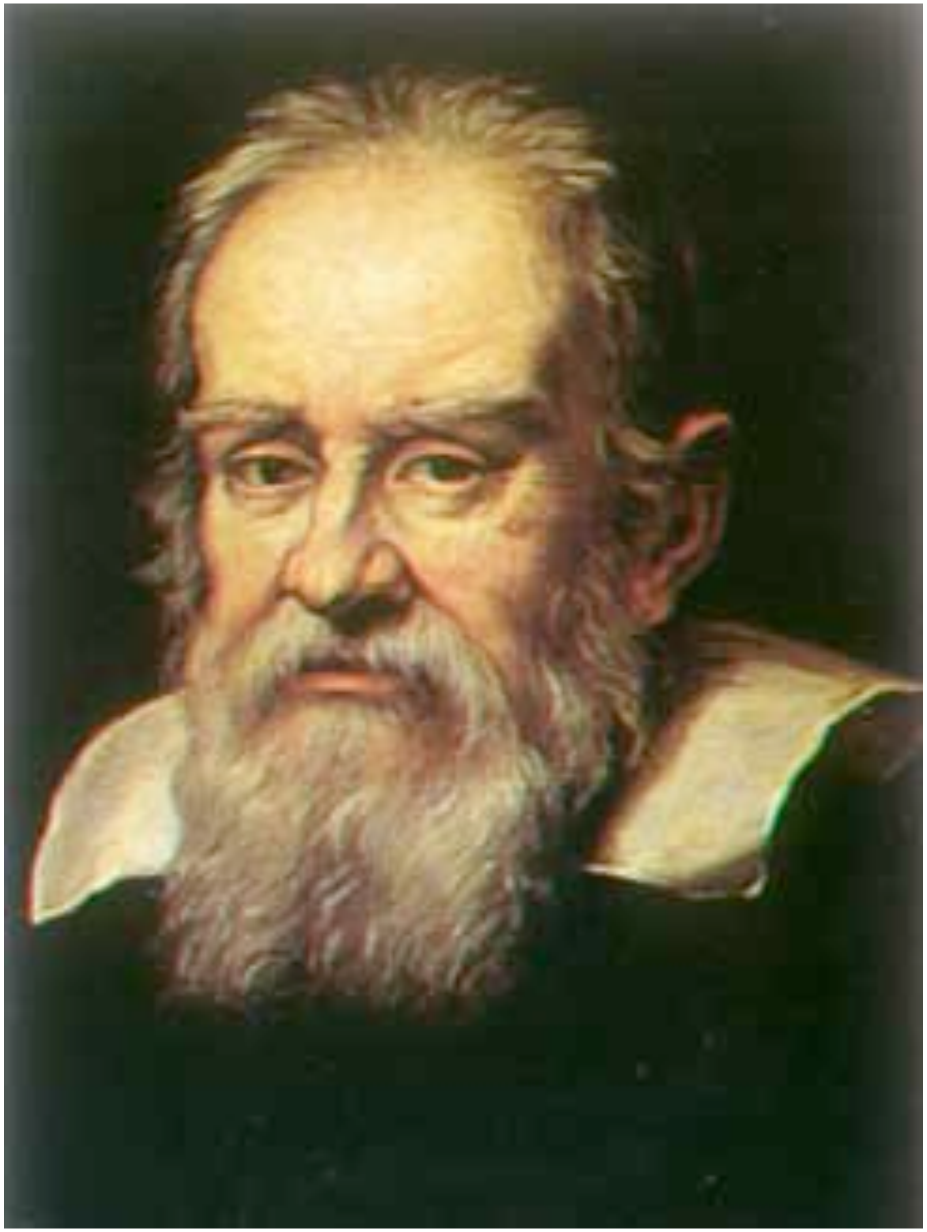
However, Brahe's data were too good. The data were extensive and precise.

The result was elliptical orbits in the model.

Orbital Data for the Planets

planet	semi-major axis (AU)	period (year)
Mercury	0.39	0.24
Venus	0.72	0.62
Earth	1.00	1.00
Mars	1.52	1.88
Jupiter	5.20	11.86
Saturn	9.54	29.46
Uranus	19.19	84.01
Neptune	30.06	164.79

Galileo Galilei (1564-1642)



Contemporary of Kepler

well educated

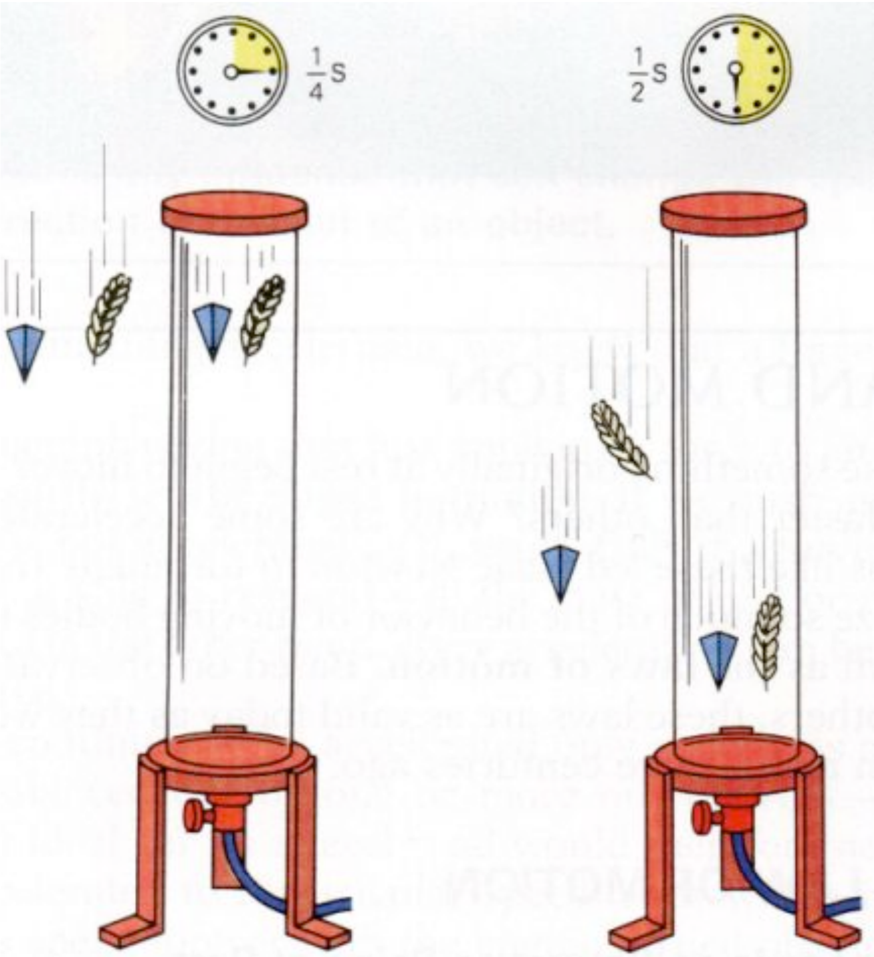
professor of mathematics and astronomy at the University of Pisa

Later moved to University of Padua

Galileo Galilei (1564-1642)

Experiments on mechanics

Cannonballs from the tower of Pisa



All objects fall at the same speed in a vacuum

Galileo Galilei (1564-1642)

Concept of inertia

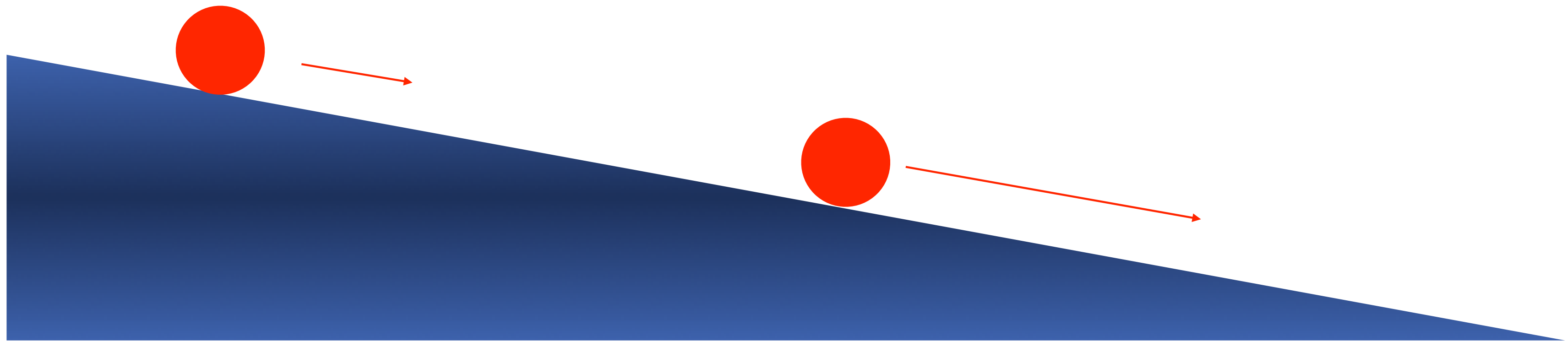
Inertia - The reluctance of an object to change its state of rest or of uniform motion in a straight line.

Galileo Galilei (1564-1642)

Concept of acceleration

Acceleration is how velocity changes with time.

$$a = \frac{dv}{dt}$$



Galileo Galilei (1564-1642)

Sometime in the 1590s Galileo adopted the heliocentric cosmology.

The telescope – he built many and made many years of astronomical observation.

He was able to prove the heliocentric cosmology to be correct.

Galileo Galilei (1564-1642)

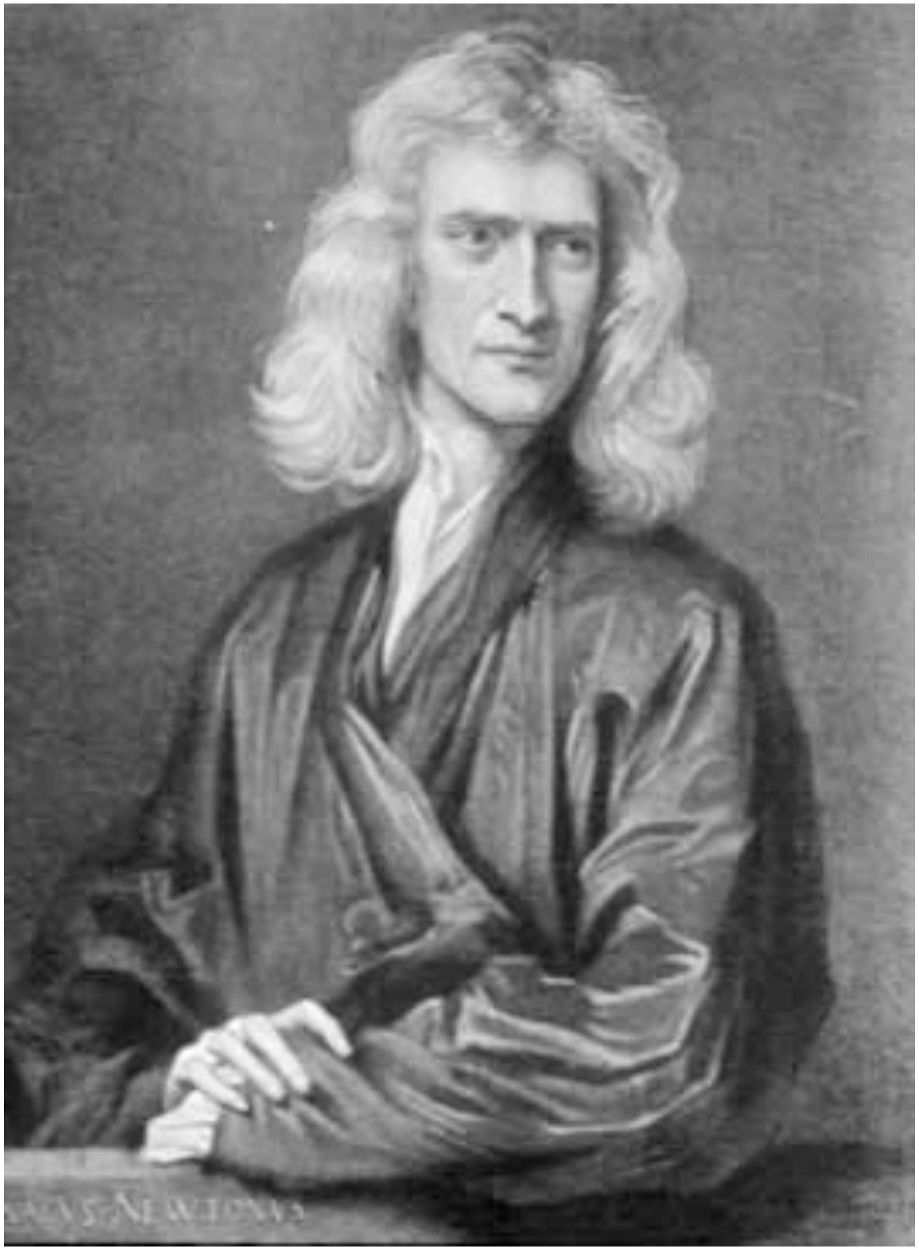
Decree of 1616 forbad one to “hold or defend” the heliocentric hypothesis.

Galileo Galilei (1564-1642)

Decree of 1616 forbad one to “hold or defend” the heliocentric hypothesis.

Because I said so!!!

Sir Isaac Newton (1642-1727)



– mechanics, i.e. the motion of bodies such as the planets, comets, moons around planets, shooting a puck, a soccer ball, a cannonball, or an apple falling on your head.

Optics, calculus

According to the well-known story, it was on seeing an apple fall in his orchard at some time during 1665 or 1666 that Newton conceived that the same force governed the motion of the Moon and the apple.

He calculated the force needed to hold the Moon in its orbit, as compared with the force pulling an object to the ground.

Isaac Newton

To give you a sense of the time (late 1600s to early 1700s:

Isaac Newton was a practitioner of Alchemy

He also wrote a treatise *(Observations Upon the Prophecies of Daniel and the Apocalypse of St. John)* on interpreting the secrets of certain books of the bible.

Newton's Laws of Motion

1. Every body continues in a state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed on it.

Newton’s Laws of Motion

2. Any change of motion is proportional to the force that acts, and it is made in the direction of the straight line in which the force is acting.

Newton's Laws of Motion

3. To every action there is always an equal and opposite reaction;

or,

the mutual actions of two bodies upon each other are always equal and act in opposite directions.