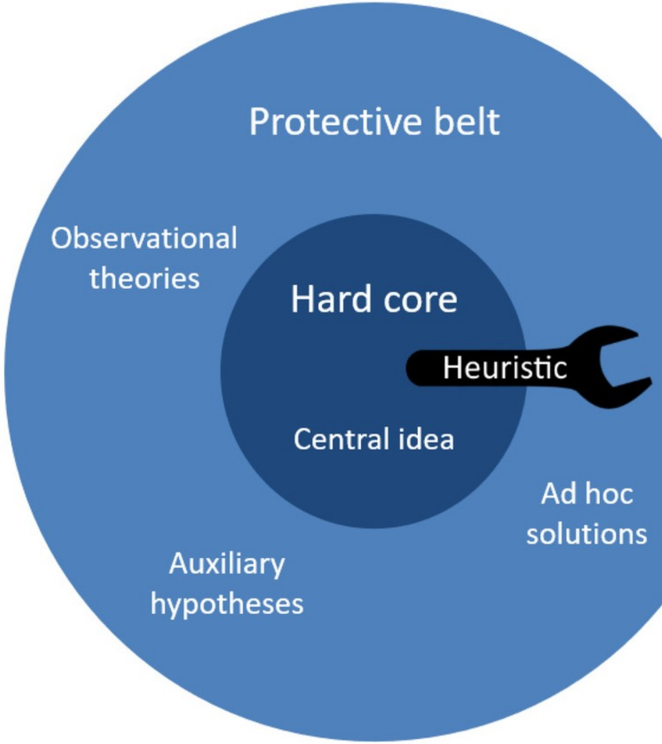
Planets, Stars, and Galaxies

Chapters 2 & 3

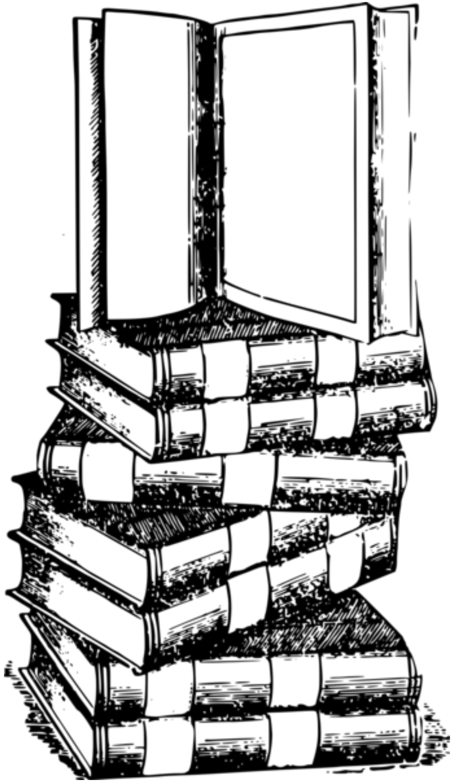
Based on slides from Dr. Lauren Woolsey

Review from last class

Lakatosh's Research Programme



From Jorritma, 2021. Published in *viruses*

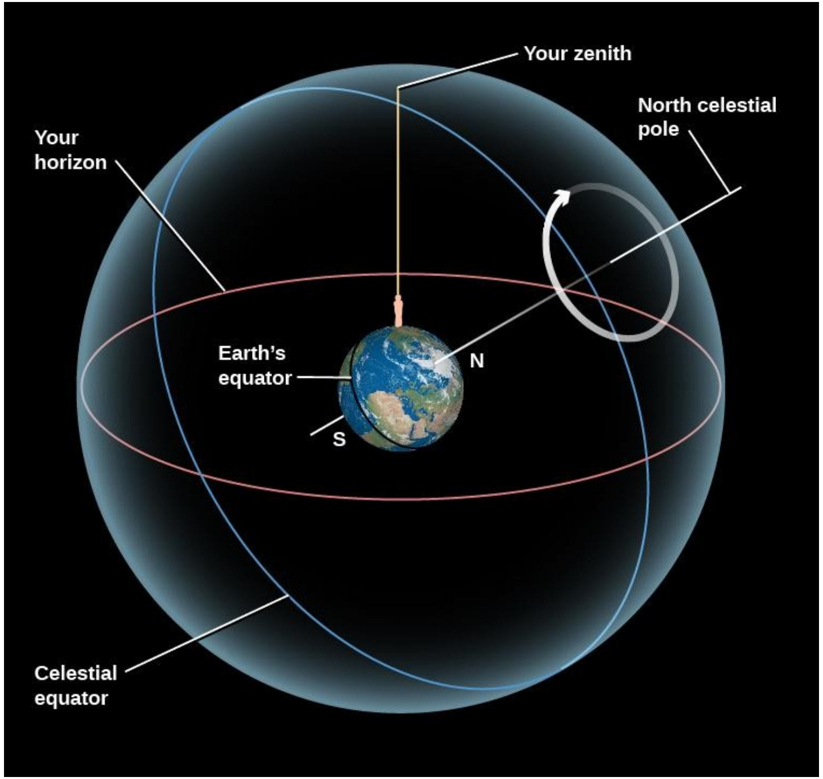


2.1 The Sky Above

Learning Objectives

By the end of this section, you will be able to:

- Understand the modern meaning of the term *constellation*
- Define the main features of the celestial sphere
- Explain the system astronomers use to describe the sky
- Describe how motions of the stars appear to us on Earth
- Describe how motions of the Sun, Moon, and planets appear to us on Earth



Constellations and Asterisms

In the modern definition of a **constellation**, it is the patch of sky (or sector) that gets the name, rather than the set of stars themselves.

Of the 88 official constellations defined by the IAU in 1928, 48 are ancient in origin.

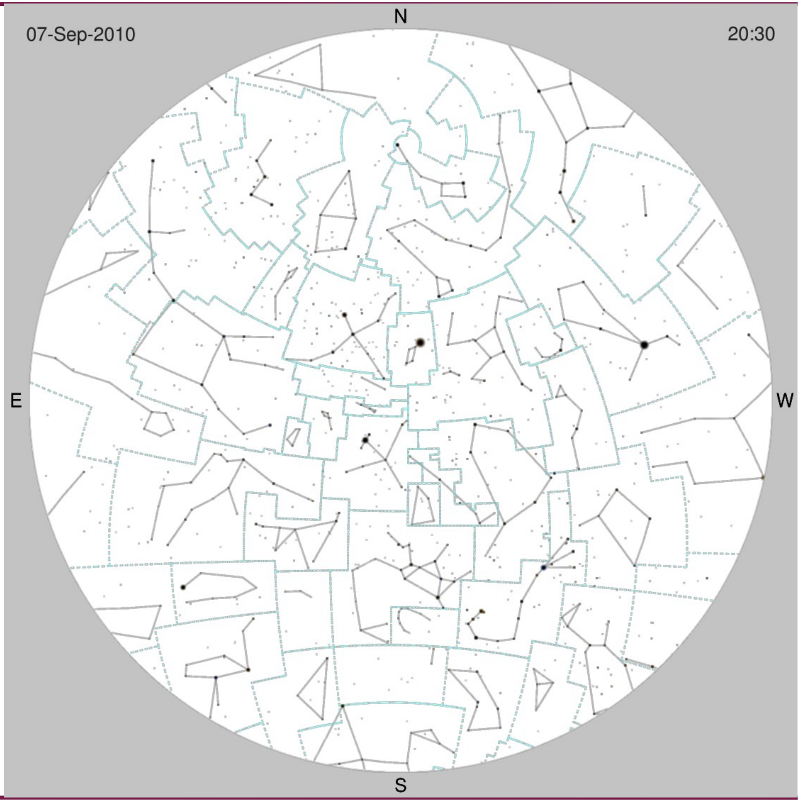
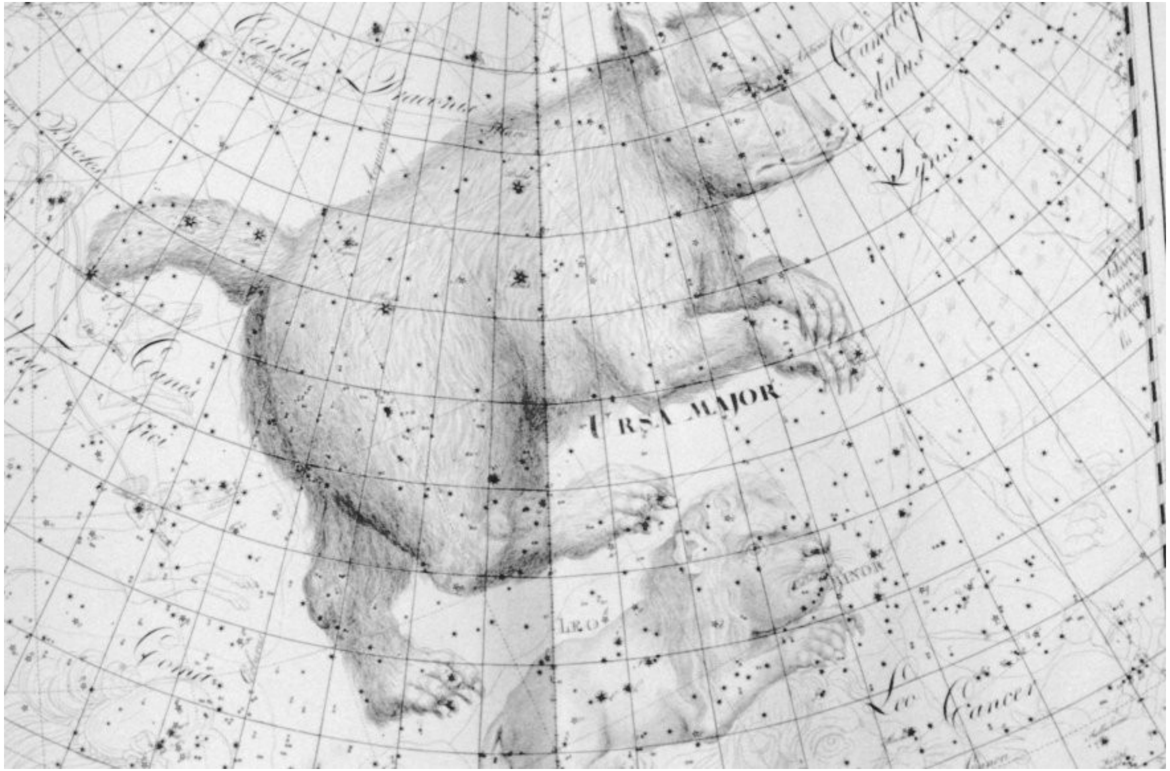


Image Credit Link: https://www.ifa.hawaii.edu/~barnes/ast110l_f10/constellations.html

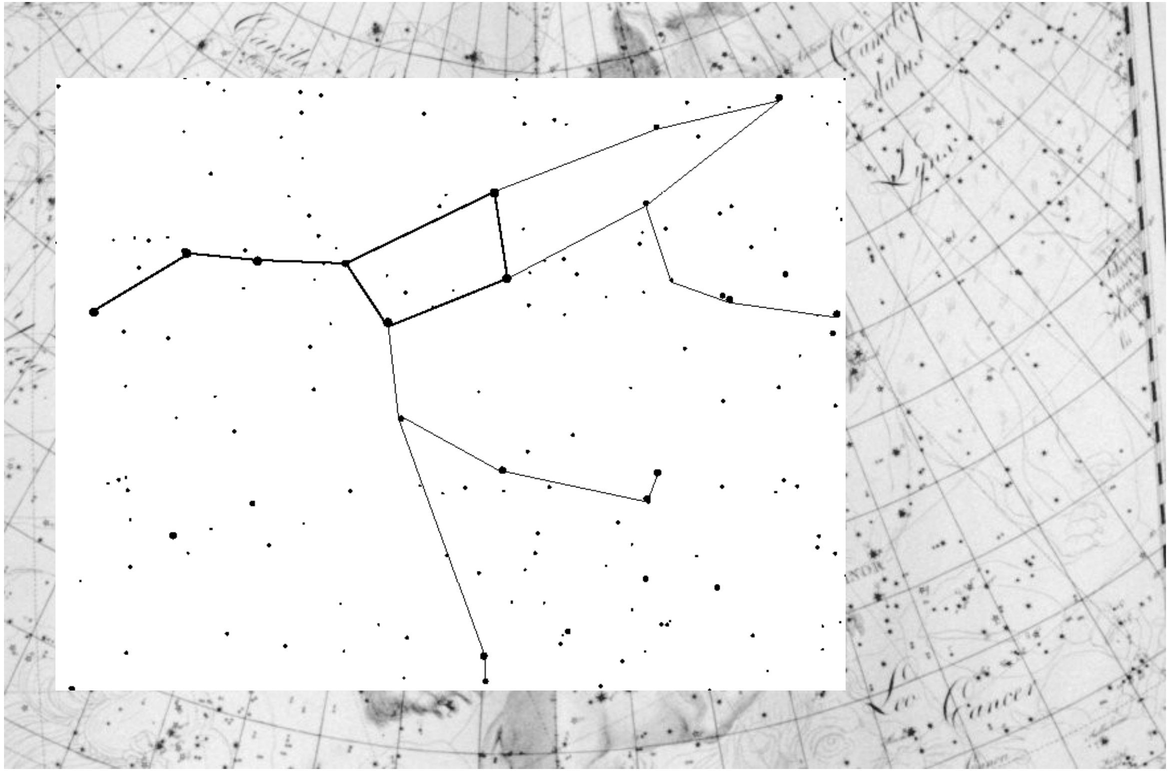
Constellations and Asterisms



Can you identify a common set of stars in the **<u>constellation</u>** shown here called ***Ursa Major*** (the great bear)?

Image Credit Link: http://stars.astro.illinois.edu/sow/uma-bo.html

Constellations and Asterisms

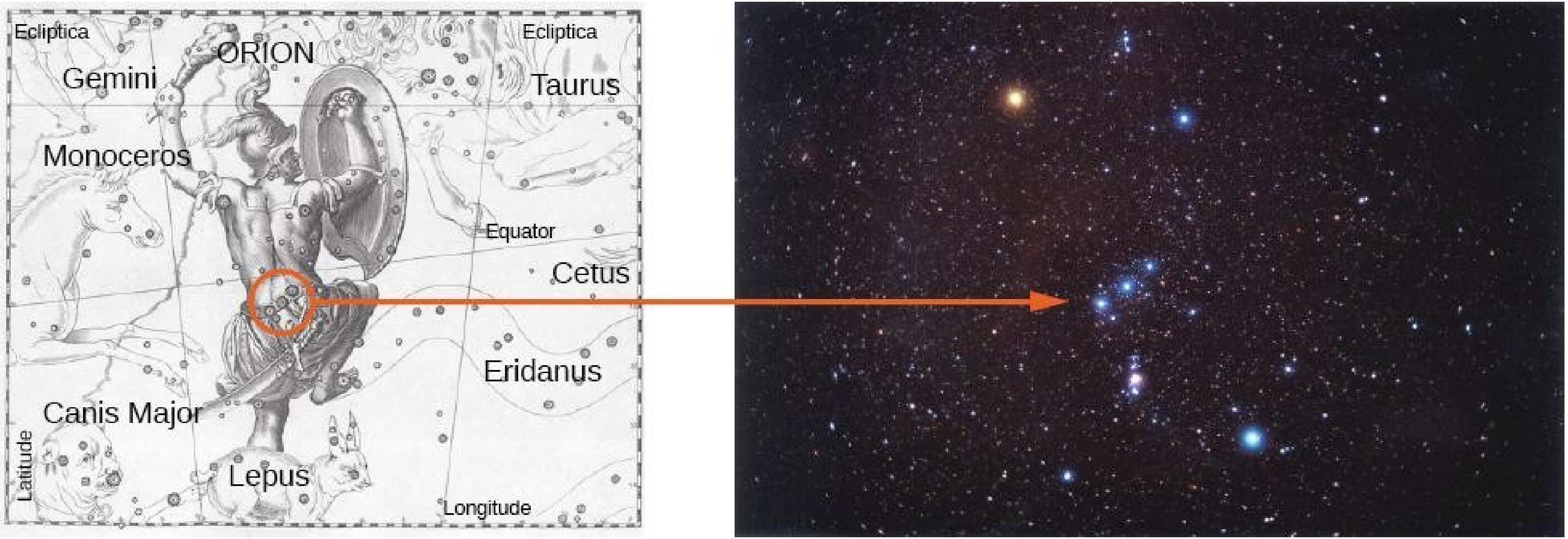


This simplified star chart might help.

An **asterism** is a *subset* of stars that form a widely recognized shape. The ***Big Dipper*** is a great example.

Image Credit Link: http://www.physics.csbsju.edu/astro/constellations/ursa_major_nl.html

Constellations and Asterisms

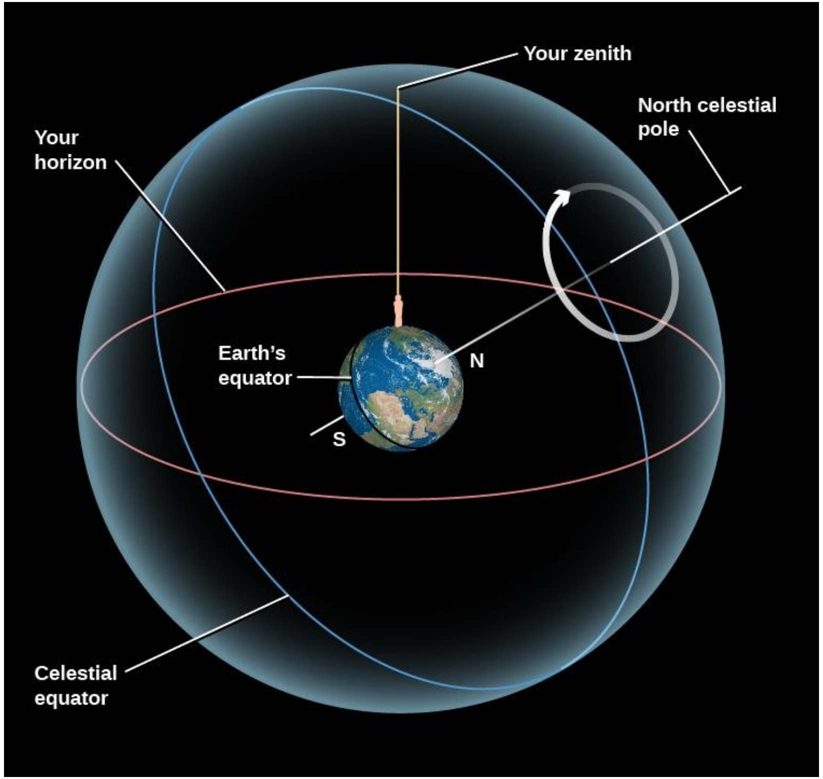


(a) (b)

Orion's Belt is an **asterism** within the **constellation** of *Orion*.

The Celestial Sphere

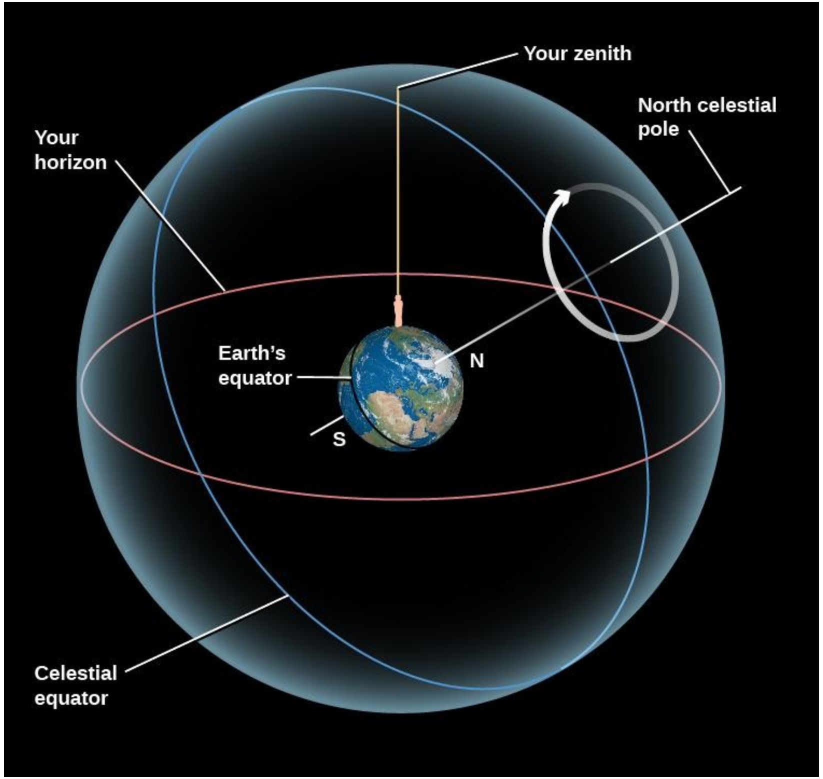
To help us understand how stars move through our skies, we make a simplified scientific model of the sky. We'll call this the **Celestial Sphere**. This assumes all stars, no matter how far they are, are projected onto a sphere around the Earth.



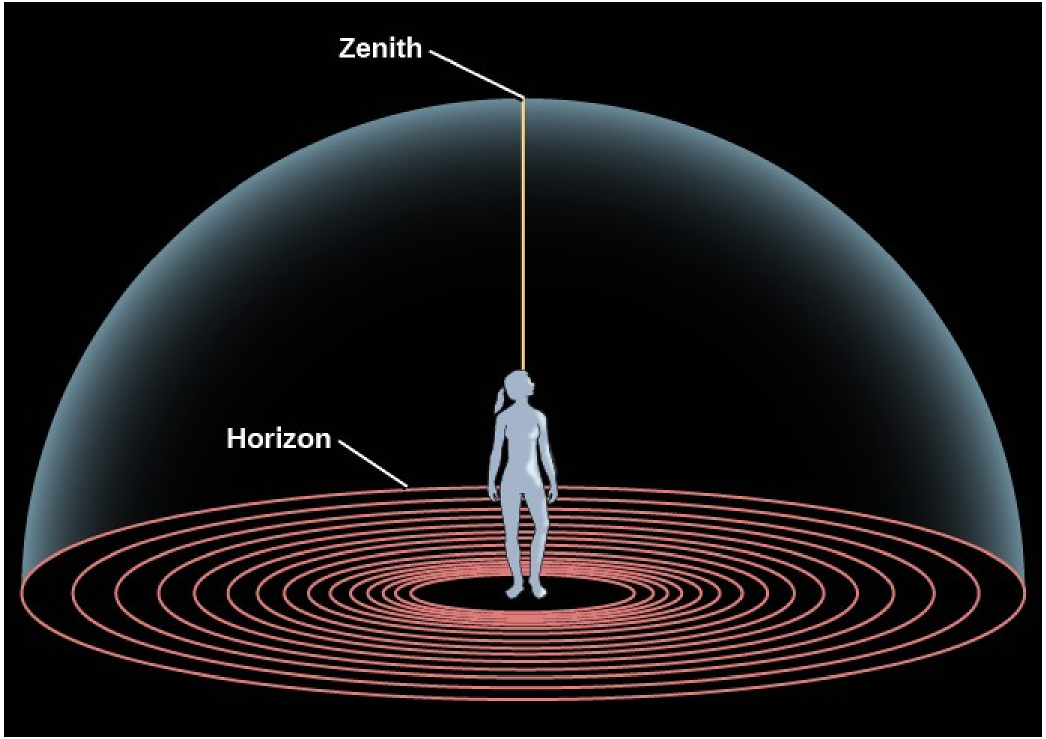
The Celestial Sphere

New terms we'll learn:

- Horizon
- Zenith
- Nadir
- Celestial Equator
- North celestial pole
- South celestial pole
- Ecliptic*



The Celestial Sphere: Observer-Centered Terms

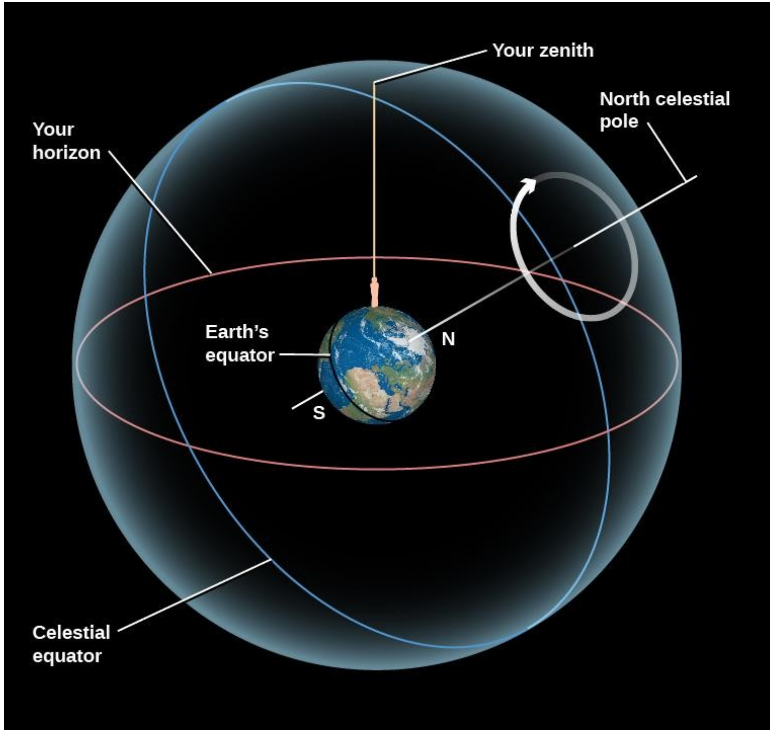


Horizon: where the dome of the sky you can see meets the ground from your point of view.

Zenith: the point directly over your head.

Nadir: the point directly below your feet.

The Celestial Sphere: Fixed Points in Space



Celestial Equator: the projection of the Earth's equator into space.

North celestial pole: the projection of the Earth's geographic north pole into space.

South celestial pole: the projection of the Earth's geographic south pole into space.

The Celestial Sphere: Star Motions

In the celestial sphere model, we pretend that the Earth is fixed and that the stars move across the sky.

If we had a camera take a long exposure picture of the night sky, we would see **star trails**, showing how stars appear to move because the **Earth is rotating on its axis**.

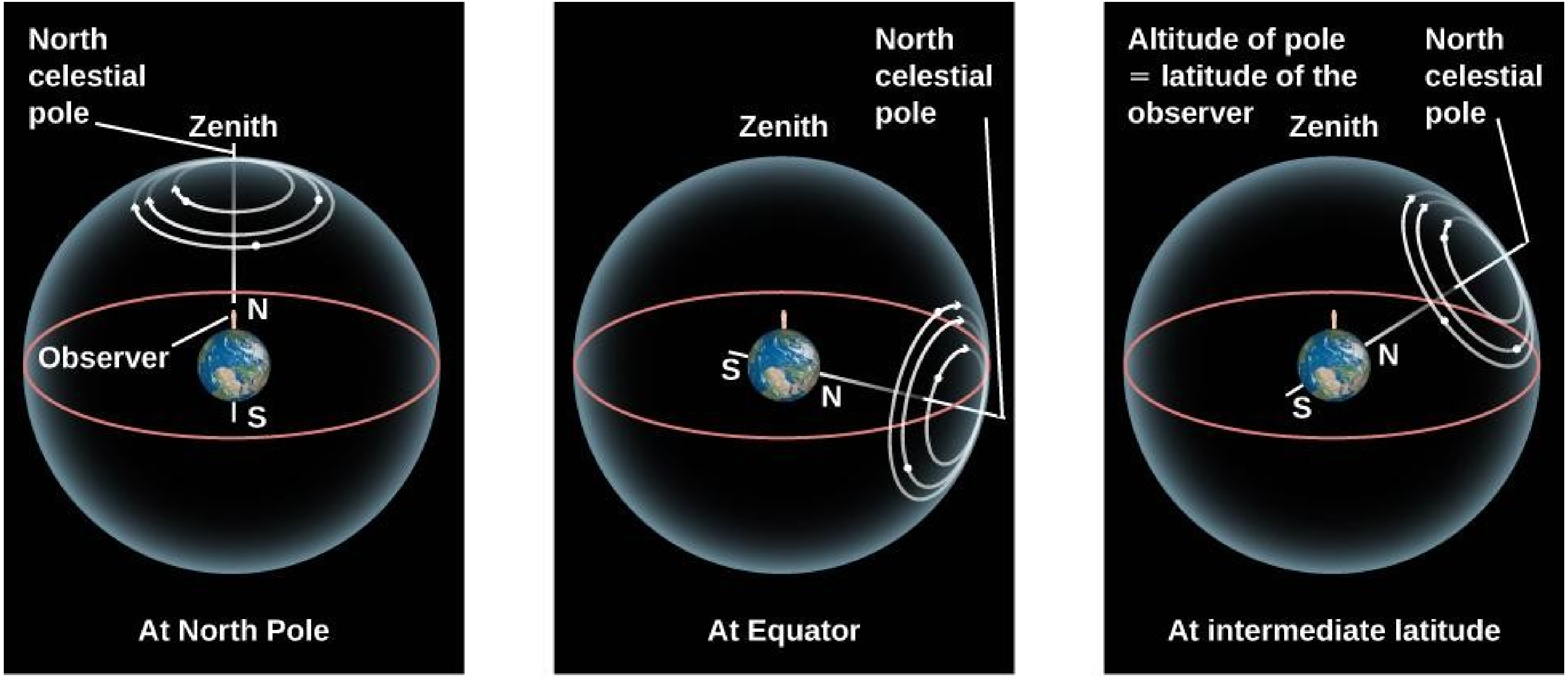
The Celestial Sphere: Star Motions

This is an example of star trails, taken in Hawaii. Look at how the stars appear to make big circles.

What object is at the "center" of those circle motions?

Image Credit Link: http://apod.nasa.gov/apod/ap051220.html

The Celestial Sphere: Star Motions



(a) (b) (c)

The Celestial Sphere: Star Motions

Pause-and-Think MC Question:

You see a star rising due East. When this star reaches its highest position above the horizon, where will it be?

A) high in the Northern sky

B) high in the Southern sky

C) high in the Western sky

D) directly overhead

The Celestial Sphere: Star Motions

Pause-and-Think MC Question:

Imagine you are camping in a field outside Volcan. Looking directly north, you see a star just barely above the horizon. About fifteen minutes later, you notice that it has shifted position slightly. Which way did it move?

A) to the right, (east)

B) to the left, (west)

C) up, (rising)

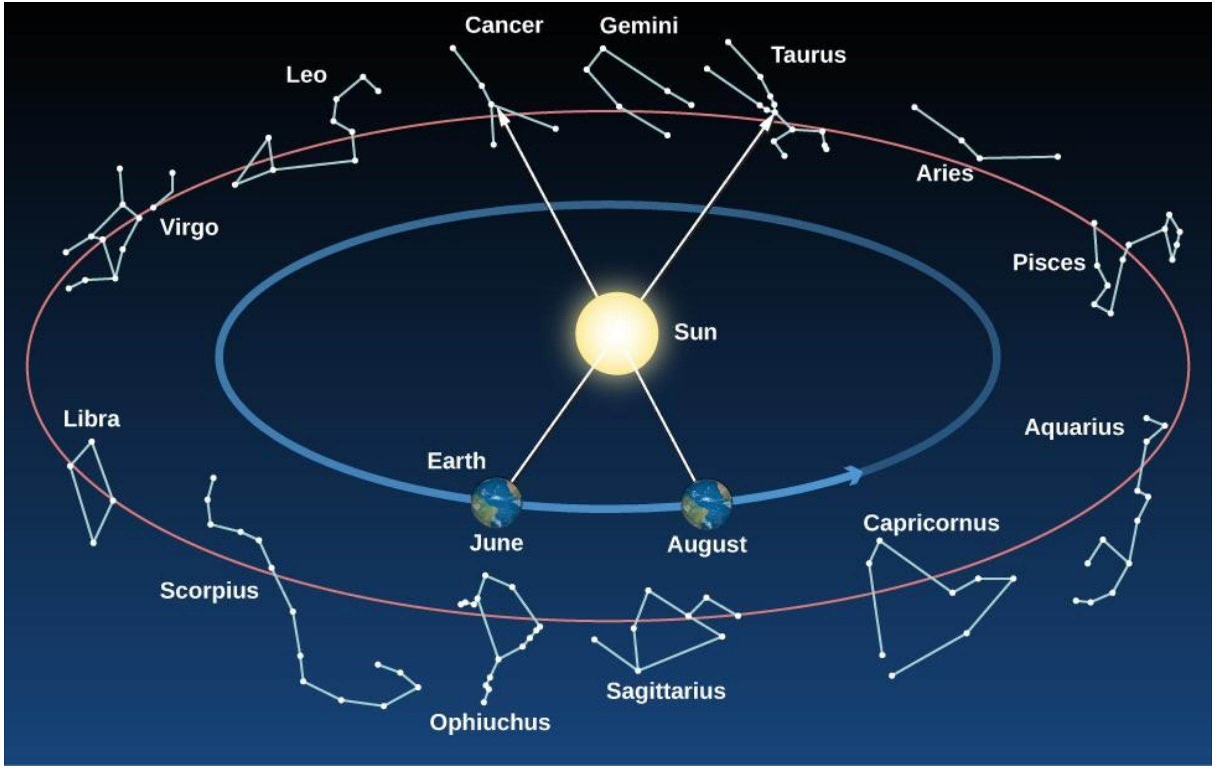
D) down, (setting)

The Ecliptic

Do you know your astrological sign? (a.k.a. sign of the zodiac)

While the book calls **Astrology** is a ***pseudoscience*** (see Section 2.3), it is more in the camp of spiritual belief. Nevertehless, it has roots in astronomical observation.

The Ecliptic



The astrological signs represent the constellations that the Sun “appears” in throughout the year.

But that also means that our night time constellations change during year.

The Ecliptic

Pause-and-Think MC Question:

You go out tonight and see the star Rigel barely rising above your eastern horizon at 10 PM. One week later at 10 PM this same star will be:

A) slightly higher in the sky.

B) at the exact same height as before.

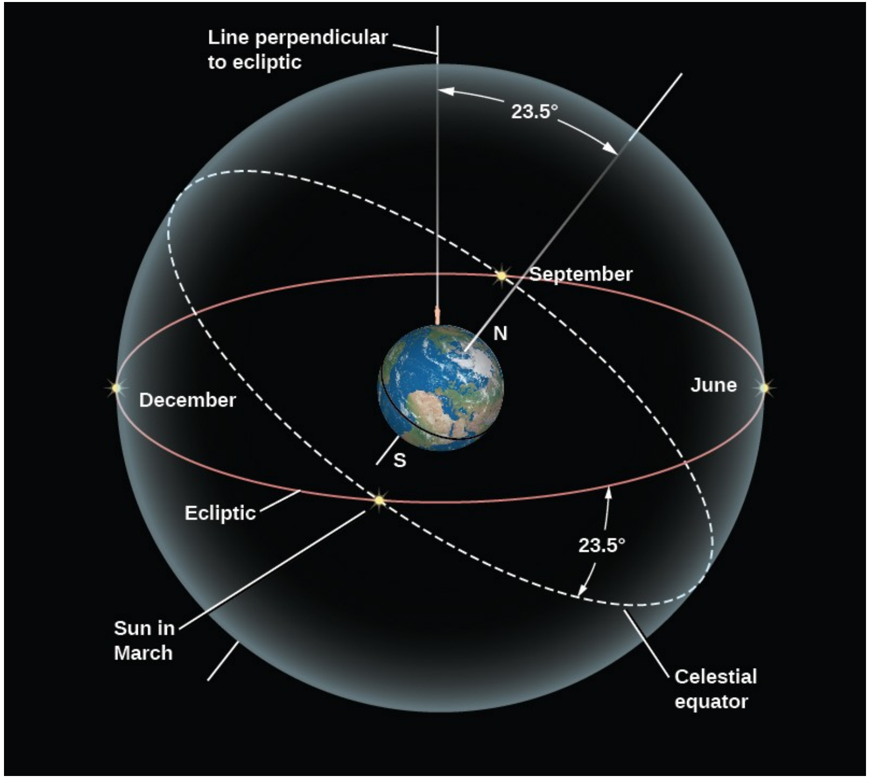
C) just below your horizon.

D) setting on your western horizon.

Let’s open Stellarium and find out

- https://stellarium-web.org

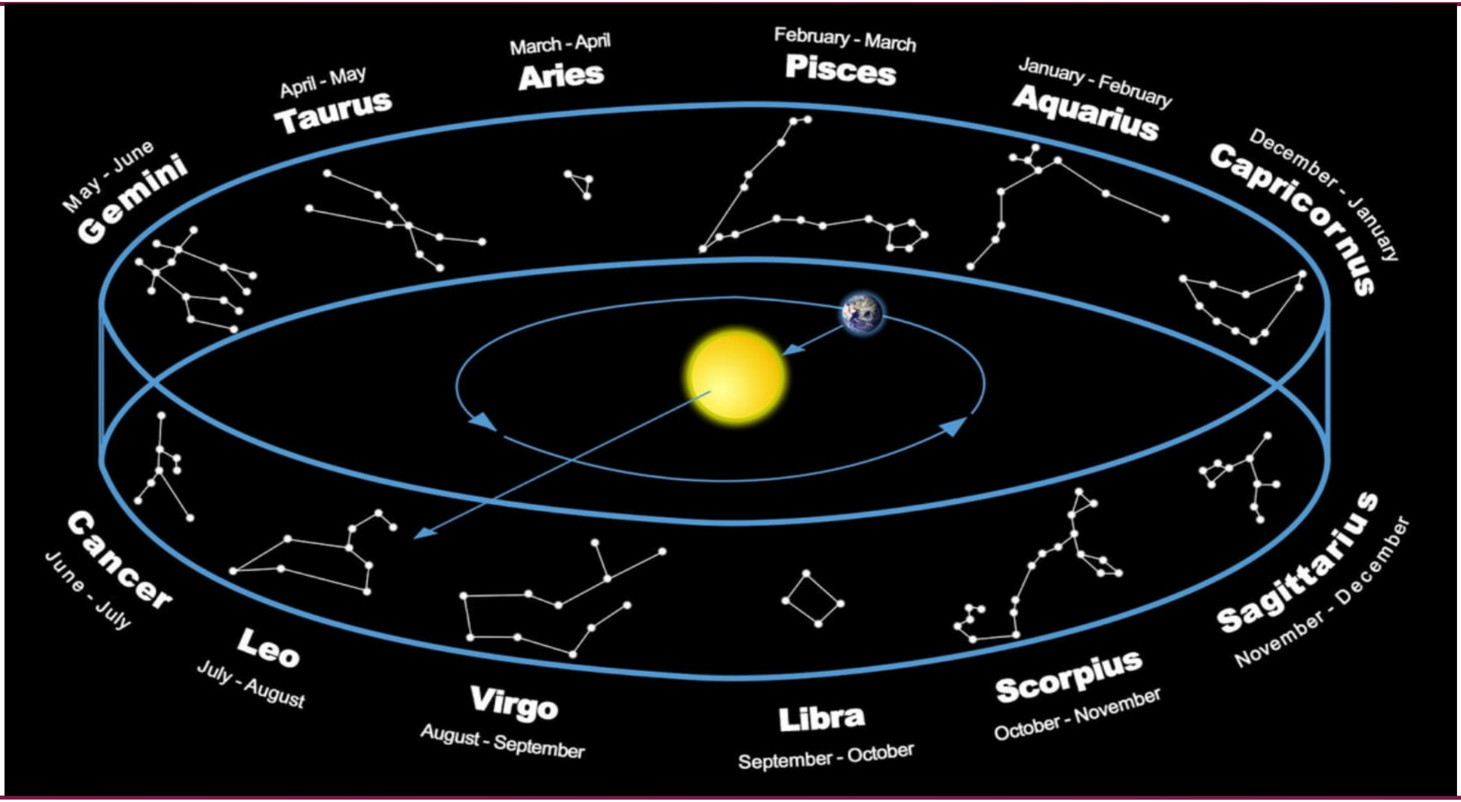
The Ecliptic



The **ecliptic** is tilted 23.5° with respect to the **celestial equator**, because the Earth itself is tilted 23.5° relative to its path around the Sun.

They cross at two points, special dates in our calendar. More on this in Chapter 4!

Review from last time…



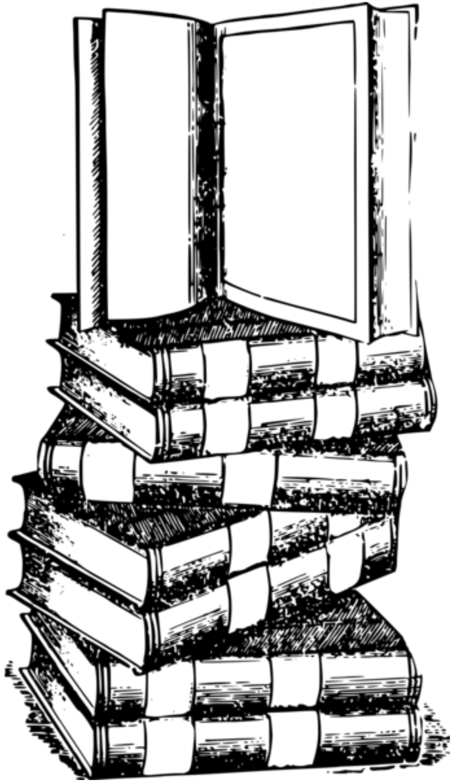
The Celestial Sphere: Star Motions

Picturing what the motions of the sky look like can be difficult for many students.

We will have further activities beyond this introductory lecture (worksheets, animations, etc) to practice these ideas.

Supplemental Workbooks

- Lecture Tutorials for Introductory Astronomy, by Prather, Slater, et al:
  "Position," "Motion," and "Seasonal Stars"
- Learning Astronomy by Doing Astronomy, by Palen and Larson:
  "Activity 1: The Celestial Sphere and Sky Maps"



Nicolaus Copernicus was born in Poland and trained as a cleric. He developed his **heliocentric universe** idea in *De Revolutionibus Orbium Coelestium*, which was printed months before he died in 1543.

He printed it posthumously on purpose, because he was afraid of the backlash from the Church

“others before me…”

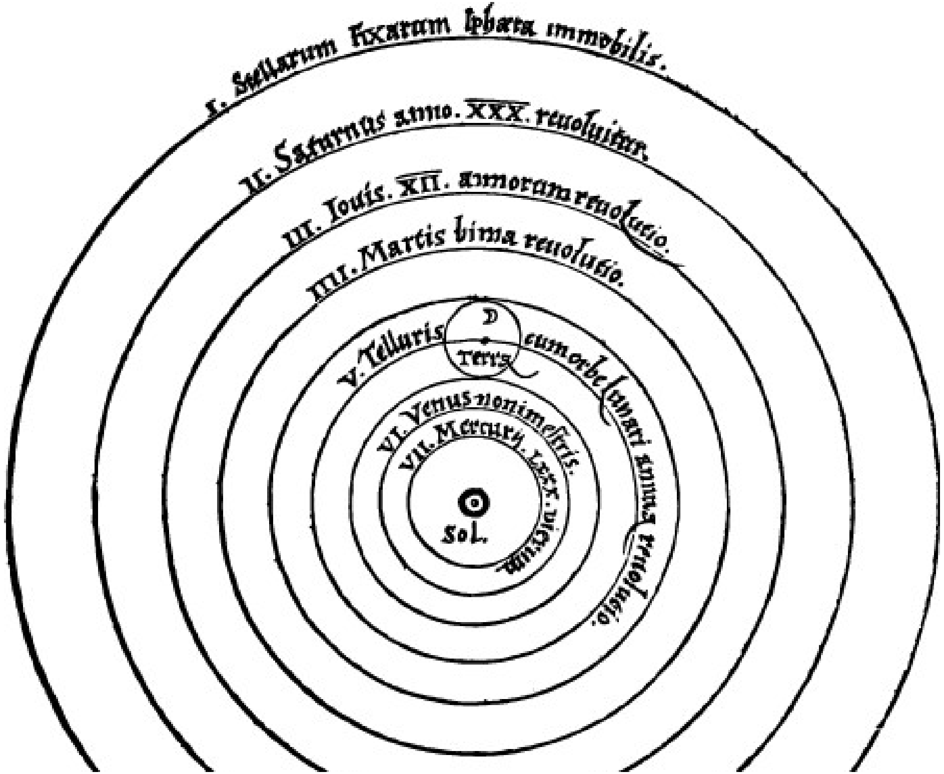
There where at least a couple of documented Greeks that held a heliocentric view.

Some think that the earth remains at rest. But Philolaus the Pythagorean believes that, like the sun and moon, it revolves around the fire in an oblique circle. Heraclides of Pontus and Ecphantus the Pythagorean make the earth move, not in a progressive motion, but like a wheel in a rotation from west to east about its own center.

Therefore, having obtained the opportunity from these sources, I too began to consider the mobility of the earth. And even though the idea seemed absurd, nevertheless I knew that others before me had been granted the freedom to imagine any circles whatever for the purpose of explaining the heavenly phenomena.

From the Revolutions of the Heavenly Bodies

The Renaissance and the Copernican Revolution



The six known planets were in the correct order. Retrograde motion was a natural consequence of their orbits.

Yet the model was not instantly accepted.

Galileo Galilei, Father of Modern Science

Galileo is responsible for the modern view of science and the transition from authority-based “science” to an observation-based science.

Galileo developed experiments to study:

- How objects would move without friction (the basis of the law of inertia)
- How objects accelerate (the basis of the law of gravity)

Galileo Galilei, Father of Modern Science

The telescope was invented in Holland around 1608, and Galileo improved the design in his workshop. His first few observations at amazed him:

1. **Craters, peaks on the moon**
2. Stars too faint to see by eye
3. Moons around Jupiter
4. Rings around Saturn
5. Spots on the Sun

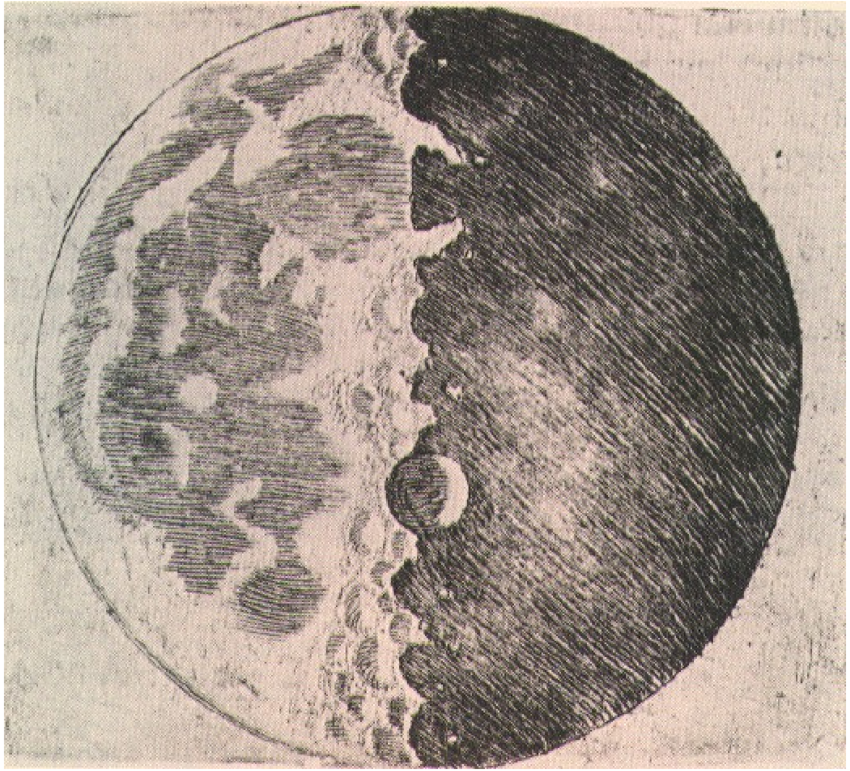


Image Credit Link: https://www2.hao.ucar.edu/Education/FamousSolarPhysicists/galileo-drawings-writings

Galileo Galilei, Father of Modern Science

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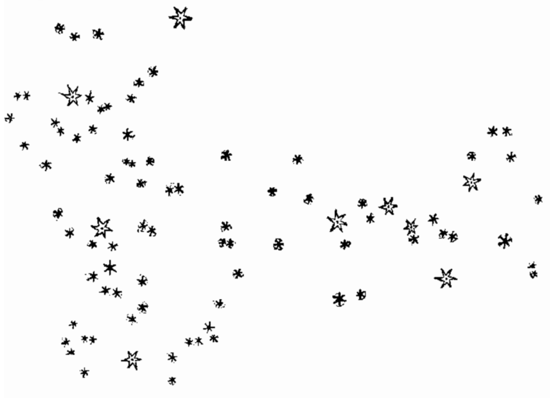

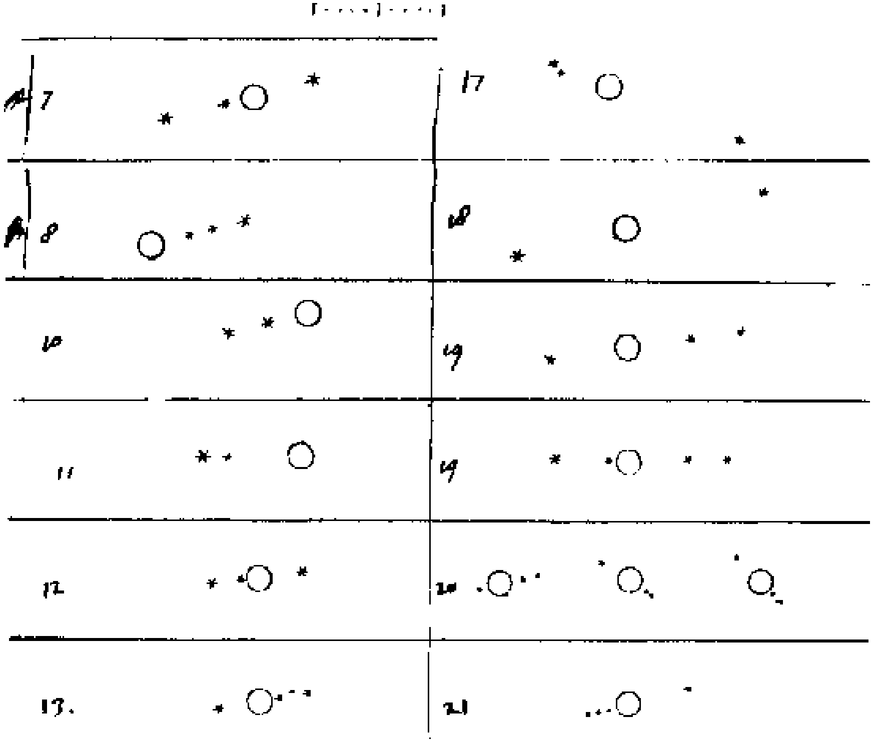

Image Credit Link: https://www2.hao.ucar.edu/Education/FamousSolarPhysicists/galileo-drawings-writings

Galileo Galilei, Father of Modern Science

Beyond this initial list, the definitive proof that the Earth **could not** be at the center of the solar system was Galileo's observation of the **phases of Venus**.

http://astro.unl.edu/classaction/animations/renaissance/venusphases.html

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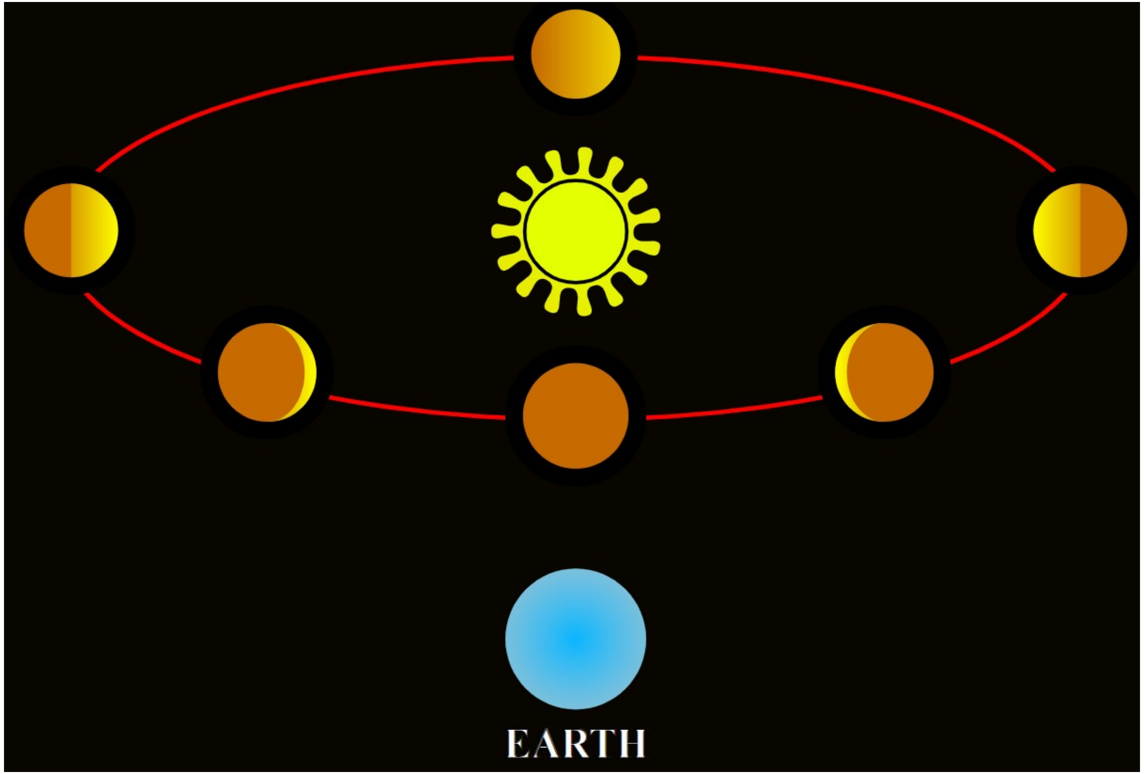
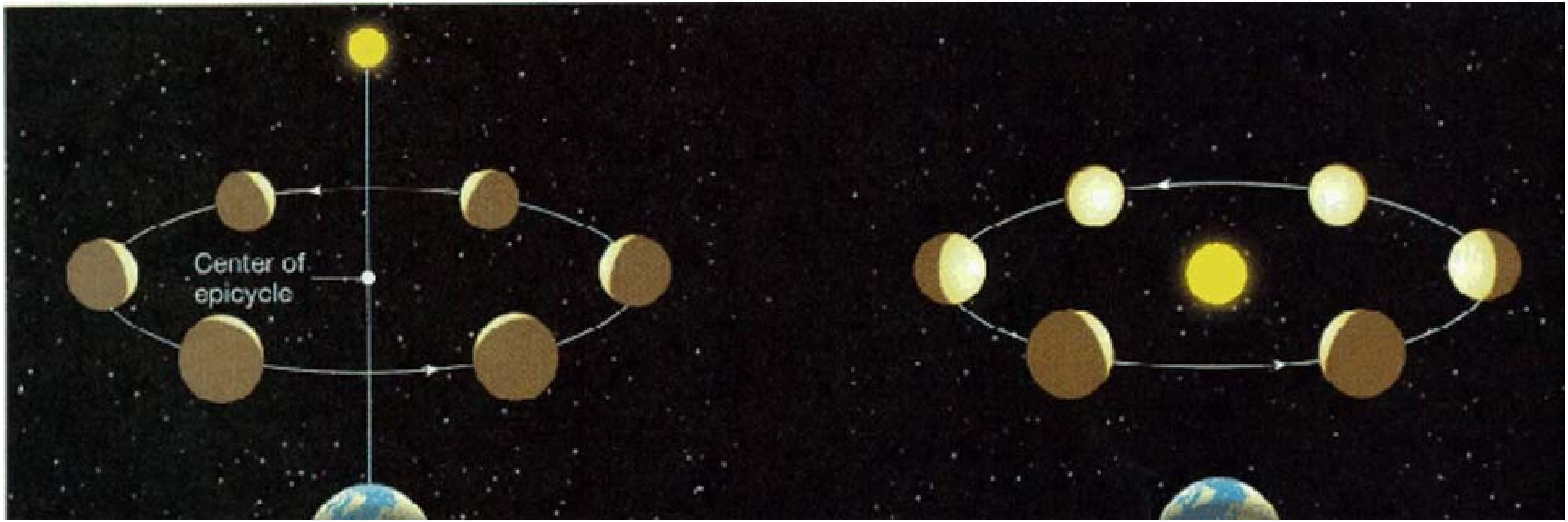


By Nichalp, Public Domain, https://commons.wikimedia.org/w/index.php?curid=857453

Galileo Galilei, Father of Modern Science



The observations of Venus's phases was the final nail in the coffin of all of the geocentric "universe" models.

By Parvis Ansari, accessed at this link: http://ircamera.as.arizona.edu/NatSci102/NatSci/lectures/galileo.htm

Galileo Galilei, Father of Modern Science

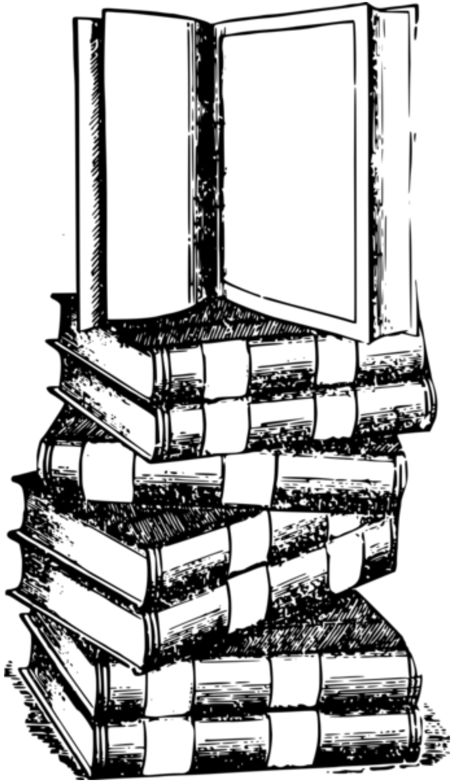
Within 40 years of the observations, only the heliocentric “universe” was taught. This was not without pushback from the Roman Catholic Church.

Galileo published *Dialog Concerning the Two Chief World Systems* with permission from local censor in Florence and the head censor at the Vatican in 1630. However, he was charged with disobeying the papal decree from 1616 (not heresy) and convicted in 1632.

He was sentenced to spend the rest of his life under house arrest. His work became a foundation of the Newtonian revolution in science.

His books were on the Church’s forbidden list until 1836. He was “found innocent” in 1992 by a special commission (i.e. they admitted they were wrong).

A Review of Newton's Laws



A bit about myself: I like both Astronomy and Philosophy

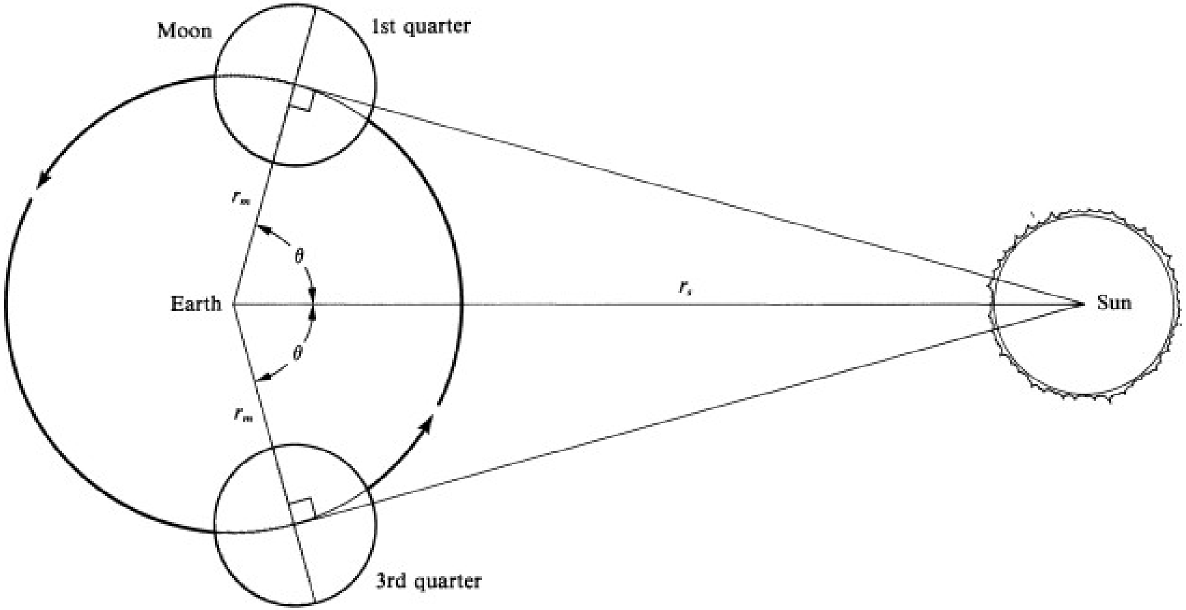
- Physics undergraduate studies mostly at Universidad de los Andes, Mérida
- Astronomy and **Philosophy** undergraduate studies in University of Central Florida
- Masters in **Philosophy** of Physics at University of Oxford
- Masters and Phd in Astrophysics at the University of Colorado, Boulder

At the end, one does not always need to choose

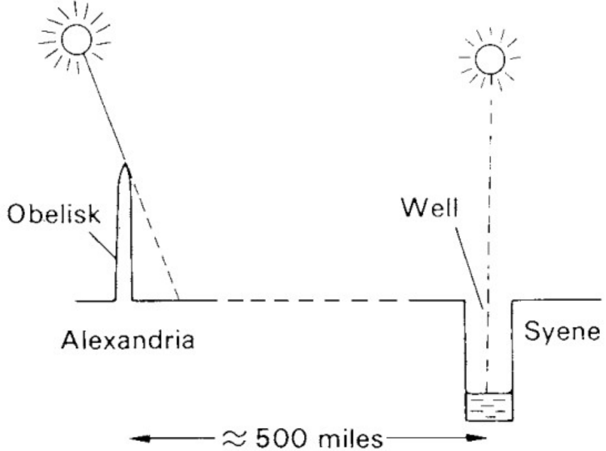
Period of the moon ≈ 29.5 days

Curvature of the Earth

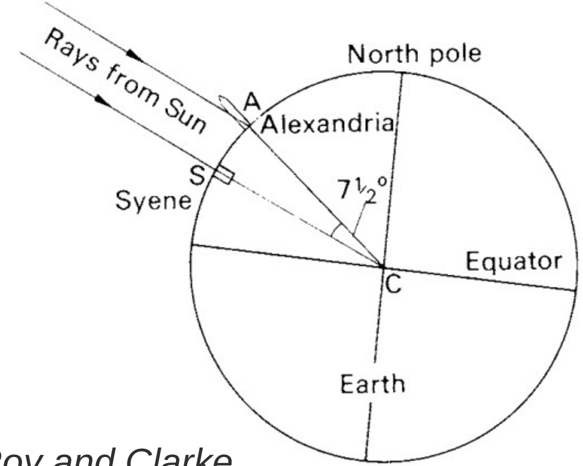
Aristarchus discovered the sun is very far away, and potentially huge compared to Earth, Erastothenes used this to compute the radius of the Earth



Aristarchus' argument, *From Shu, Intro. to Astronomy*



The observations of Eratosthenes.



From Roy and Clarke

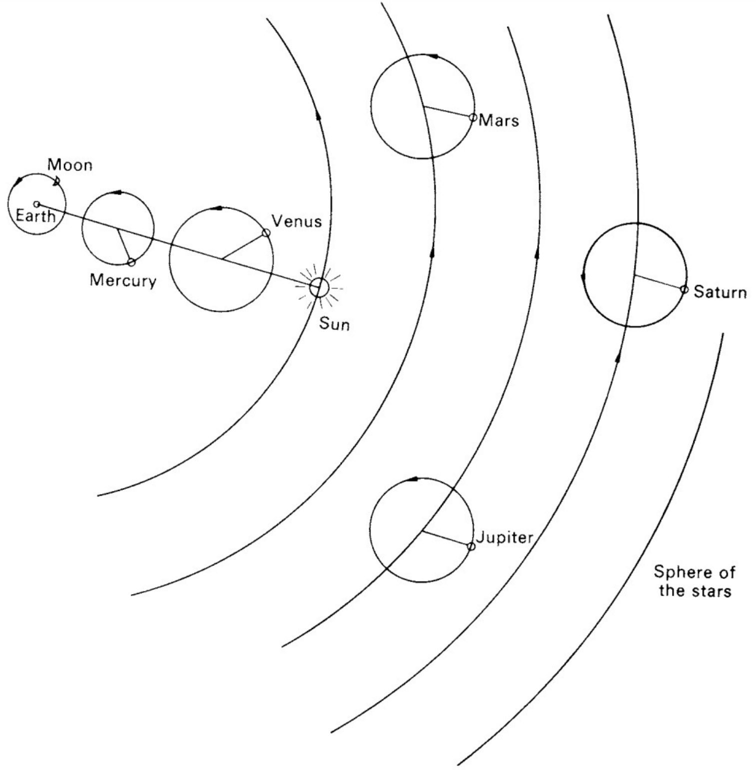
Ptolomy (~100 ac)

The Earth was the fixed at the center of the Universe.

The stars were fixed to the surface of a transparent sphere which rotated westwards in a period of one sidereal day.

The Sun and the Moon revolved about the Earth.

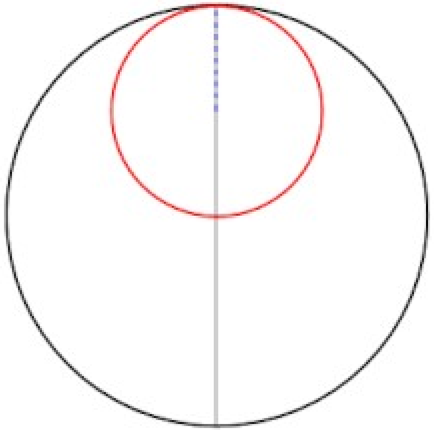
When the Arabian astronomer of the Middle Ages accumulated more accurate observations of the planets, they found that the Ptolemaic theory had to be modified still further (al-Tusi).



From Roy and Clarke, under CC0

Nasir al-Din al-Tusi (1200)

He exposed problems present in Ptolemy's work. In 1261, he published his*Tadkhira*, which contained 16 fundamental problems he found with Ptolemaic astronomy.

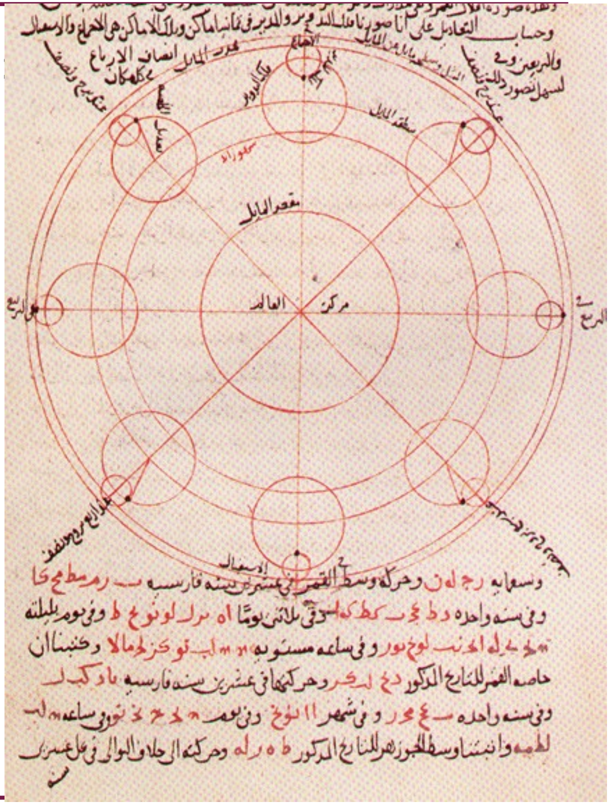


He changed how the epicycles work.

An animated example of a Tusi-couple. Made using Wolfram Mathematica. CC3.

Ibn al-Shatir (1300)

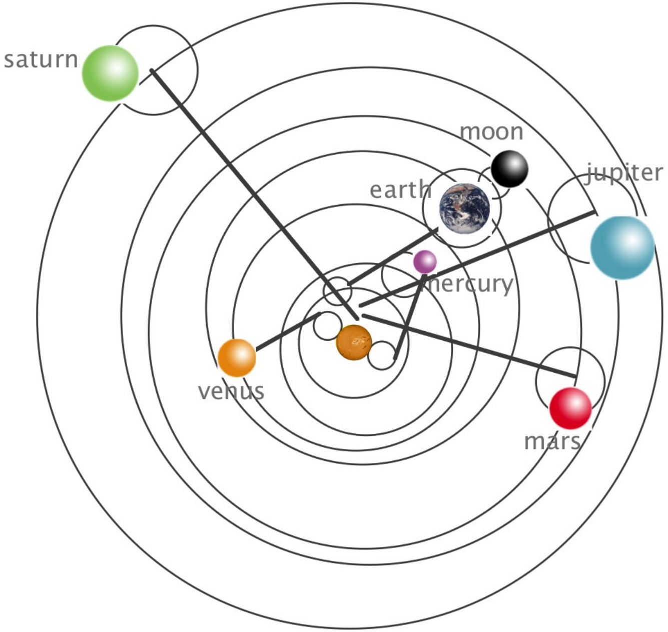
Completes Ptolomy’s model by adding extra epicycles



From his work: The New Planetary Handbook

A common misconception

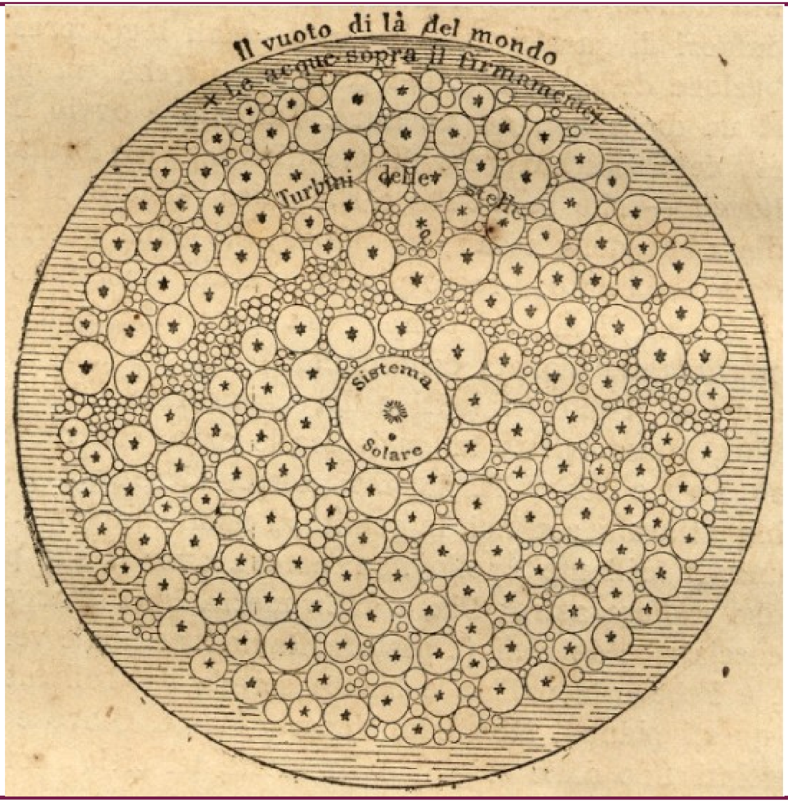
Contrary to popular belief, the Copernican Heliocentric model was actually
quite complicated as it used about the same number of epicycles as Ptolomy.



Descartes Vortex theory

- There was no action at a distance, rather, gravity acted through contact with a vortex, which made all planets orbit the sun.

From Descartes, *A System of the World*



Descartes creates the 1st law of Newton

The claim that Descartes was the first to formulate the principle of inertia is based on the first two of his laws of nature, which read as follows: [2]

> *The First Law of Nature*: Each thing, insofar as in it lies, always perseveres in the same state, and when once moved, always continues to move.
>
> *The Second Law of Nature*: Every motion in itself is rectilinear, and therefore things which are moved circularly always tend to recede from the center of the circle which they describe.

Now compare this with Newton's first law of motion, which is the classic statement of the principle of inertia:

> Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.[3]

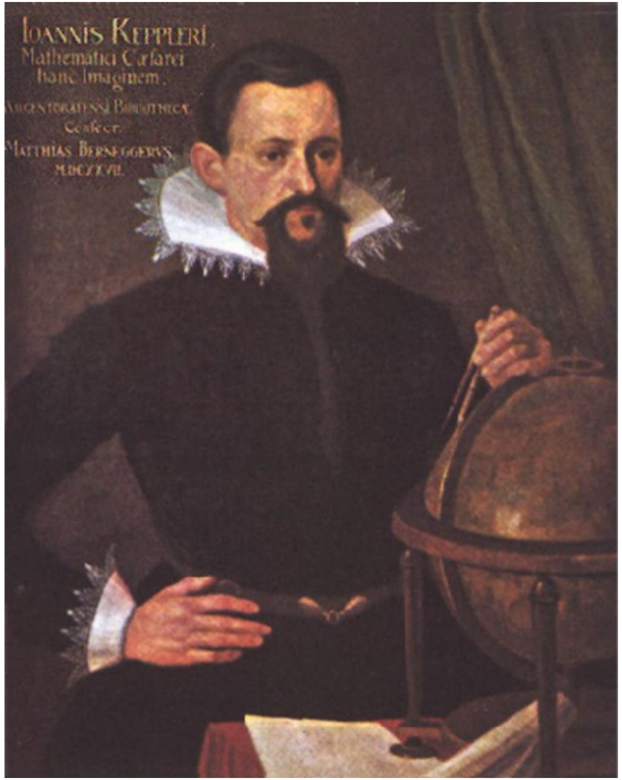
From Descartes' Laws of Motion, Richard J. Blackwell

Tycho Brahe and Johannes Kepler

At the time, the debate between Heliocentric and Geocentric cosmologies was the biggest discussion between astronomers.

The offset between the real and predicted position of objects was measurable

Tycho Brahe recorded the position of planets for decades. His first recorded observation was done when he was 17 years old, and the last the year of his death, when we was 57.



Heliocentric and Ptolomeic model where at a draw

Tycho Brahe compared predictions from both, and while the Ptolomeic model did significantly better for predicting the motions of Venus, Mercury, and the Sun, the Heliocentric model did better predictions for Mars, Jupiter, and Saturn.

These are the name of ephemerides tables

Planet	Observed	Stadius	Carello
Venus	25°	22° 54′ (-3° 6′)	24° 3′ (-57′)
Mars	14°	12° 52′ (-1° 8′)	11° 20′ (-2° 40′)
Saturn	30°	27° 36′ (-2° 24′)	29° 53′ (-0° 7′)
Jupiter	3°	1° 30′ (-1° 30′)	0° 50′ (-2° 10′)

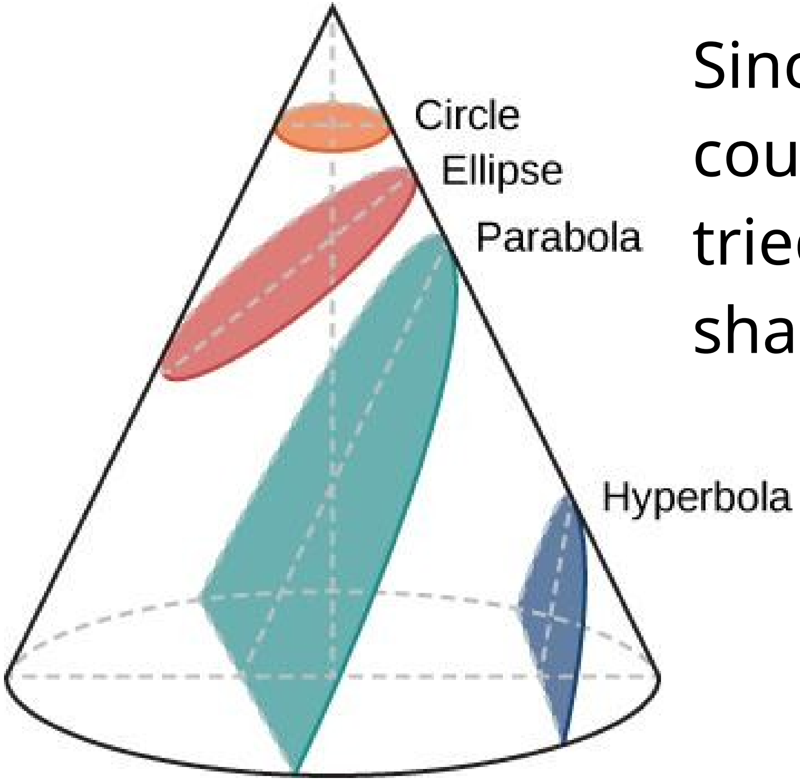
Ptolomeic astronomers, like John Dreyer, attributed the failing of the Ptolomeic model for certain objects to problems with the Carello tables. Clearly, the evidence was far from being strong to pierce through Geocentrism “protective belt.”

Johannes Kepler

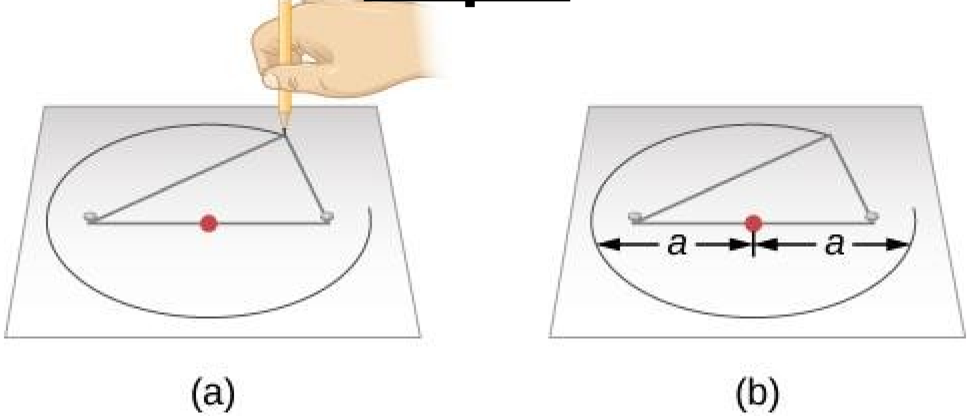
- Worked as a Clerk for Tycho. Wait until Tycho died and took his notebooks

- Finally resolved the discrepancy between both models

Kepler’s Laws of Planetary Motion



Since Kepler determined circles could not fit the orbital data, he tried a different “conic section” shape, called an **ellipse**.

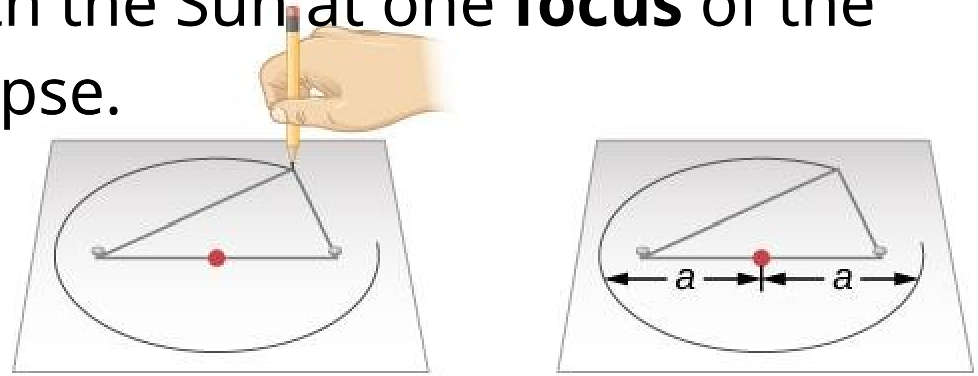


Kepler's First Law

Unlike a circle, an ellipse is not defined by a single central point, but rather two **foci** (singular: focus).

A circle has one radius that describes its size. An ellipse has a "long radius" called the **semi-major axis** (a) and a "short radius" called the semi-minor axis (b).

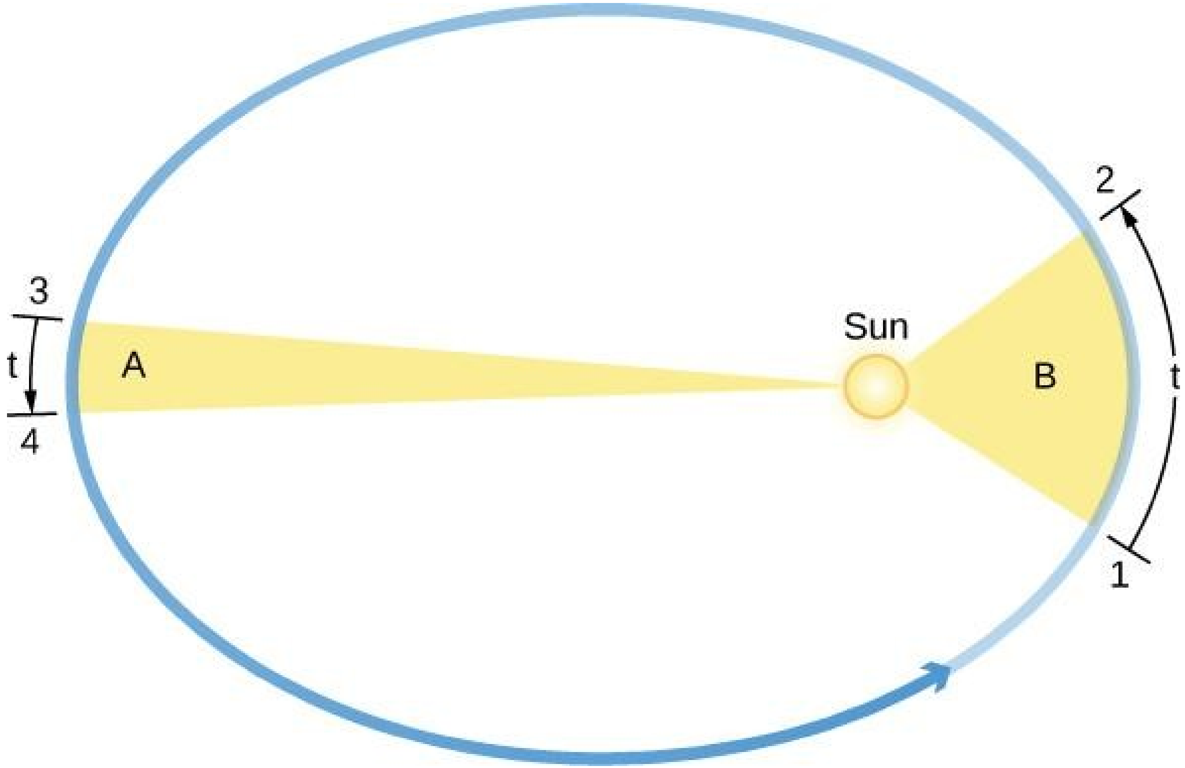
Kepler's First Law states that each planet moves around the Sun in an orbit that is an ellipse, with the Sun at one **focus** of the ellipse.



(a) (b)

Kepler's Second Law

Kepler's Second Law states that the straight line joining a planet and the Sun sweeps out equal areas in space in equal intervals of time.



Kepler’s Second Law

- It states that equal areas are swiped in equal times

$$\frac{area\ SP_1P_2}{t_2 - t_1} = \frac{area\ SP_3P_4}{t_4 - t_3}$$

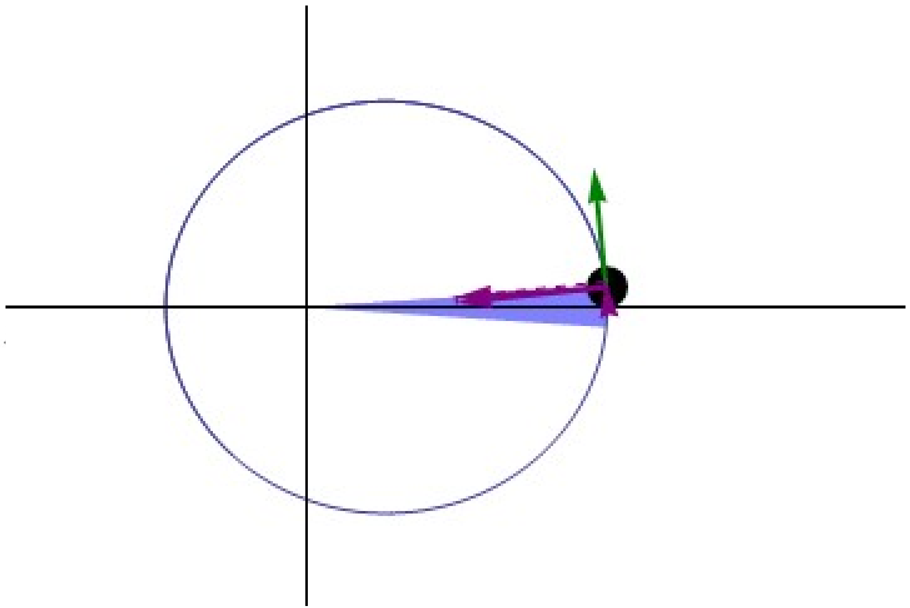
For $t_3 - t_2$ very small these Areas are triangles and:

$$area\ SP_3P_4 = \frac{1}{2}SP_3 * SP_4 * \sin(P_3SP_4) \approx \frac{1}{2}SP_3 * SP_4 * \theta$$

$$SP_4 = SP_4 \approx r$$

$$\frac{1}{2}r_1 * \frac{\theta_1}{\Delta t} = \frac{1}{2}r_2 * \frac{\theta_2}{\Delta t} = \text{constant}$$

$$\frac{\theta_2}{\Delta t} = \omega_2$$



Kepler’s Third Law

- **Kepler’s Third Law** states that: $\frac{P^2}{a^3} = constant$

The square of a planet’s orbital period is directly proportional to the cube of the semimajor axis of its orbit.

Kepler’s Laws of Planetary Motion have stood up to all scientific evidence of the past 500 years.

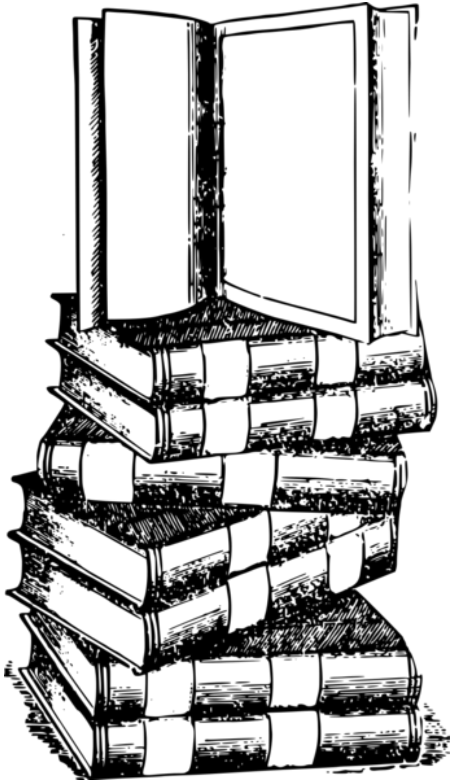
Even though he didn’t understand ***why*** the planets acted this way, he showed that they did.

Kepler’s Laws of Planetary Motion

The ideas within Kepler’s Laws are important but also quite difficult to understand without a mathematics background.

We will have further activities beyond this introductory lecture (worksheets, animations, etc) to practice these ideas.

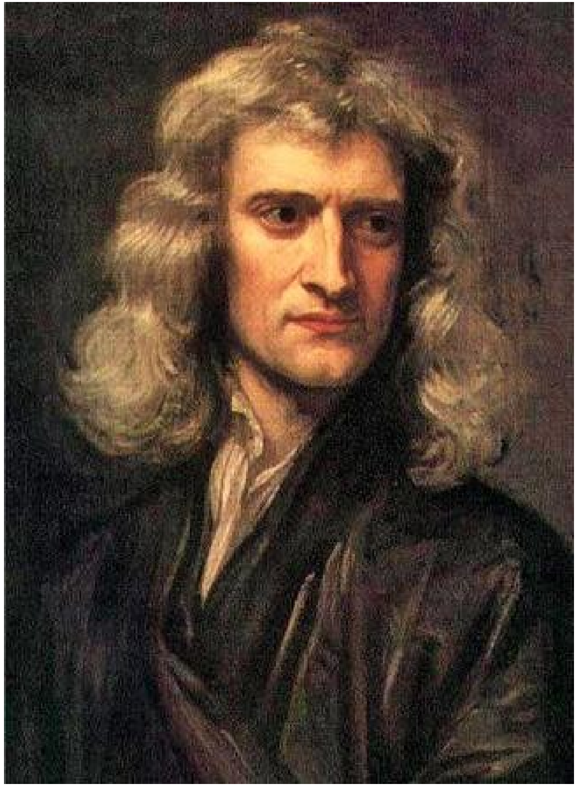
Chapter 3: Orbits and Gravity



Isaac Newton and Orbital Motion

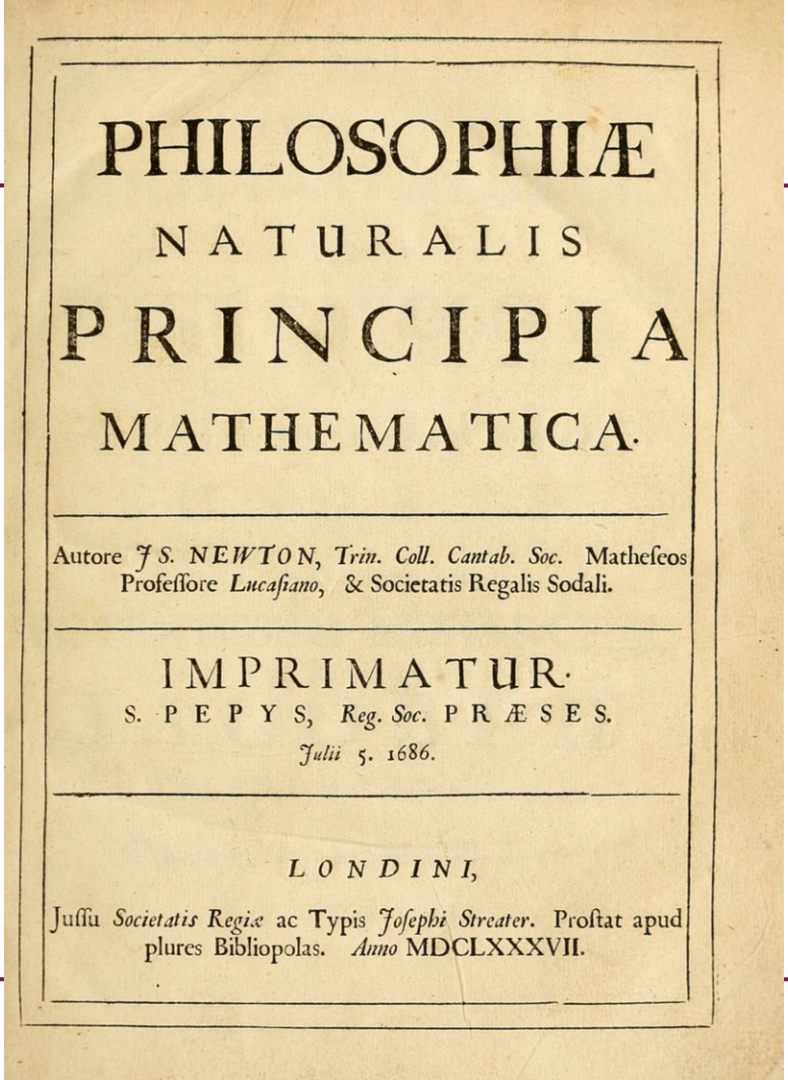
By the time Isaac Newton was born, modern astronomy had been 100 years in development, laying the foundations that we still use today.

Isaac Newton created new ***physical*** interpretations to the ***mathematical*** descriptions of astronomy made by Copernicus, Kepler, and Galileo.



Newton and “The Principia”

- Contains all 3 laws of motion,
the law of gravity,
and multiple concepts that
will define physics for centuries
to come, including today.


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Mathefeos Profeffore *Lucafiano*, & Societatis Regalis Sodali.

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

LONDINI,

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

Newton in Inspired (triggered) by Descartes Philosophy

- A relatively recently translated to English work

De Gravitatione et aequipondio fluidorum (“On the gravity and equilibrium of fluids”) was written two years before the Principia was written as a reply to Descartes.

Since Descartes formulated the law of inertia, the concept of Force as we know it is also due to him.

Rene Descartes, by Frans Hals

Isaac Newton and Orbital Motion

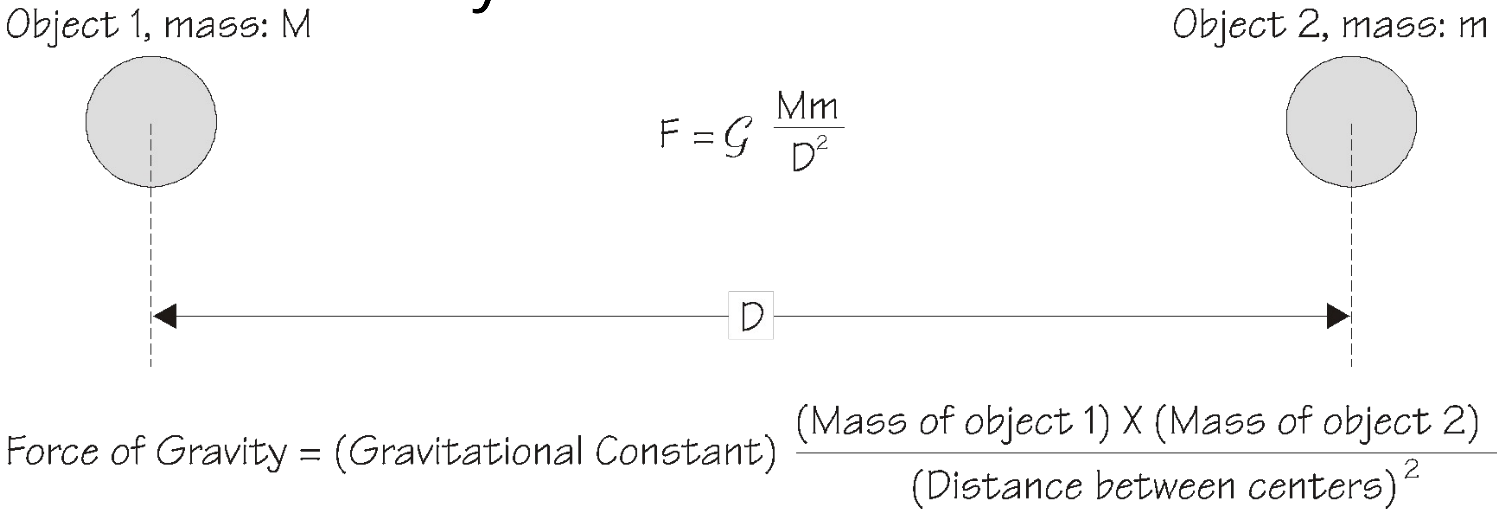
Newton developed the **universal law of gravitation**, a short equation (see right) which says that there is a force between any two masses.

$$F = G\frac{Mm}{r^2}$$

The **acceleration of gravity** of the Earth, Moon, or other astronomical body does not depend on the mass of the dropped object. Galileo had already determined that, and Apollo 15 showed it on the moon with a hammer and a feather!

Isaac Newton and Orbital Motion

The only requirement for gravity to act on an object is that it has mass (i.e. it physically exists) and there is another object with mass anywhere in the universe.



Pause-and-Think MC Question:

Which of the following would cause the force on the Moon by Earth to increase by the largest amount?

A) double the mass of the Moon.

B) double the mass of Earth.

C) move the moon two times closer to Earth.

D) None of the above would change the force.

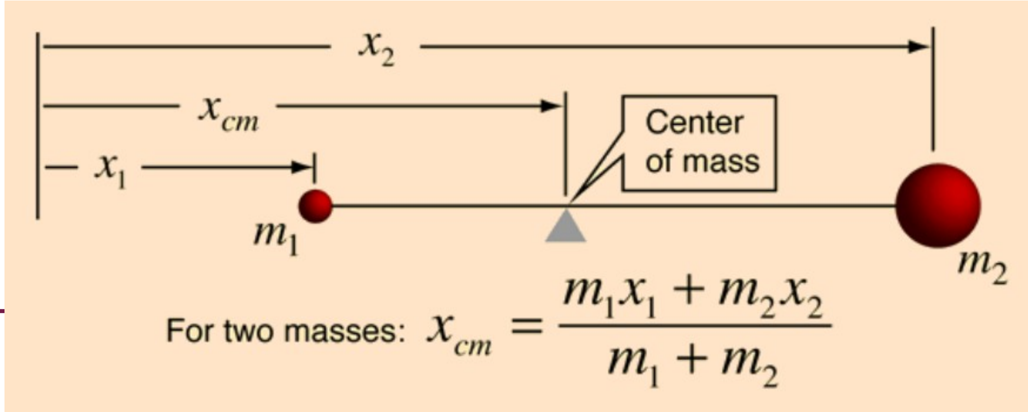
Center of Mass

- Gravitational Force

$$\vec{F} = -\frac{Gm_1 m_2}{r^2}\hat{r}$$

- Center of Mass

$$\overrightarrow{R_{CM}} = \frac{m_1\overrightarrow{r_1} + \overrightarrow{m_2 r_2}}{m_1 + m_2}$$



Newton's formulation of Kepler's 3rd law

- We start by equating the gravitational specific force to the acceleration of the object (Newton invents the term "centripetal acceleration"):

$$\omega = \frac{v_t^2}{r} = \frac{\theta}{\Delta t}$$

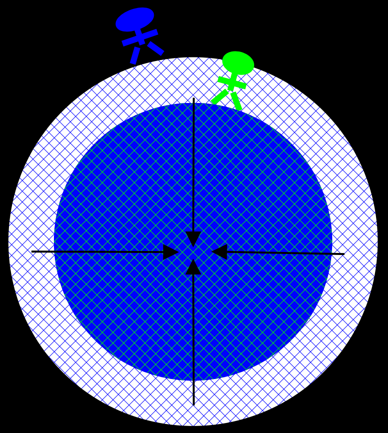
$$\frac{Gm_1}{a^2} = a\omega^2$$

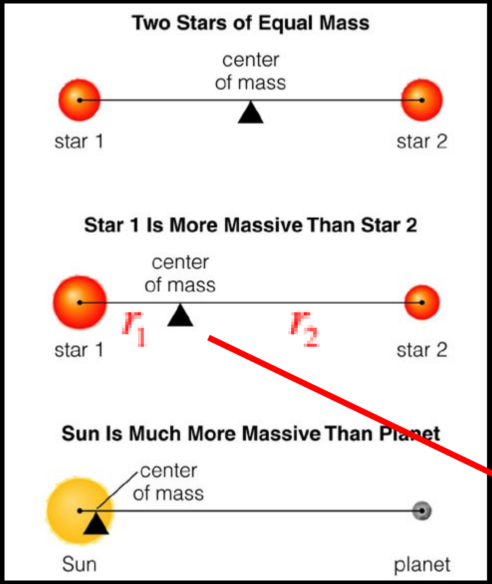
$$\frac{Gm_1}{a^3} = \omega^2$$

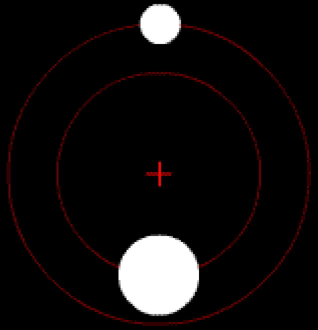
$$\frac{T^2}{(2\pi)^2} = \frac{a^3}{Gm_1}$$

2. Center of mass

- Gravitational attraction is towards the center of mass
- Net force on a particle within an object equals the force produced by the mass within its radius



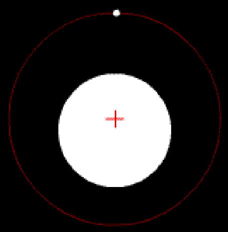


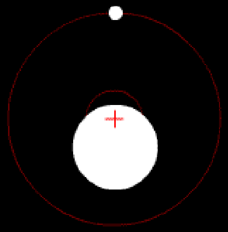


- Two objects rotate about their common center of mass

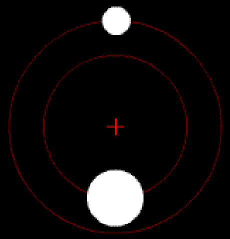
$$m_1 r_1 = m_2 r_2$$

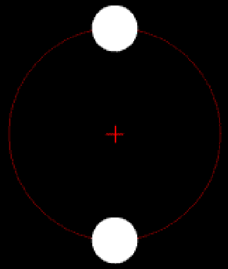
Center-of-mass within more massive partner:





Center-of-mass outside of either object (mass of objects more nearly equal):





Clicker Question:

Which of the following statements is *false*?

a) When I push my car out of a ditch, my car is pushing back on me by the same amount, even if I am successful.

b) When dropped, hammer and a feather fall at the same rate on the moon.

c) The orbit of the Earth will be unaffected by the Sun changing in size as it ages.

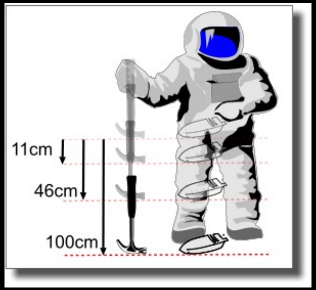
d) A satellite in a circular orbit around the Earth is in uniform motion (no acceleration).

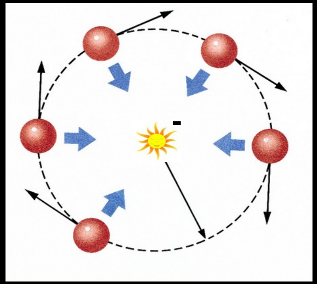
Clicker Question:

Imagine we've discovered a planet orbiting another star at 1 AU every 6 months. The planet has a moon that orbits the planet at the same distance as our Moon, but it takes 2 months. What can we infer about this planet?

a) It is more massive than Earth.
b) It is less massive than Earth.
c) It has the same mass as Earth.
d) We cannot answer the question without knowing the mass of the star.

$$m\frac{v^2}{r} = \frac{GMm}{r^2} \Rightarrow v = \sqrt{\frac{GM}{r}}$$





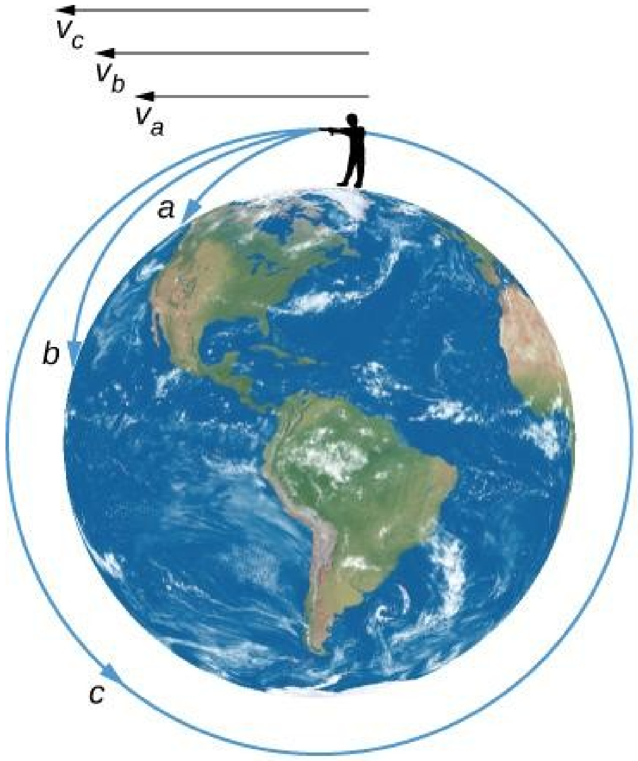
Newton’s Law and Gravity

To be able to orbit something, we need the speed to be fast enough.

Too slow: object falls back to Earth

Too fast: object escapes Earth’s gravity.

Just right: object is on a closed orbit. This “just right” speed for Earth is 17,500 miles per hour (8 km/s)!



Escape Velocity and Conservation of Energy

- In orbital mechanics, objects also have an energy related to it's orbit. This is due to the fact that Energy is **conserved**.

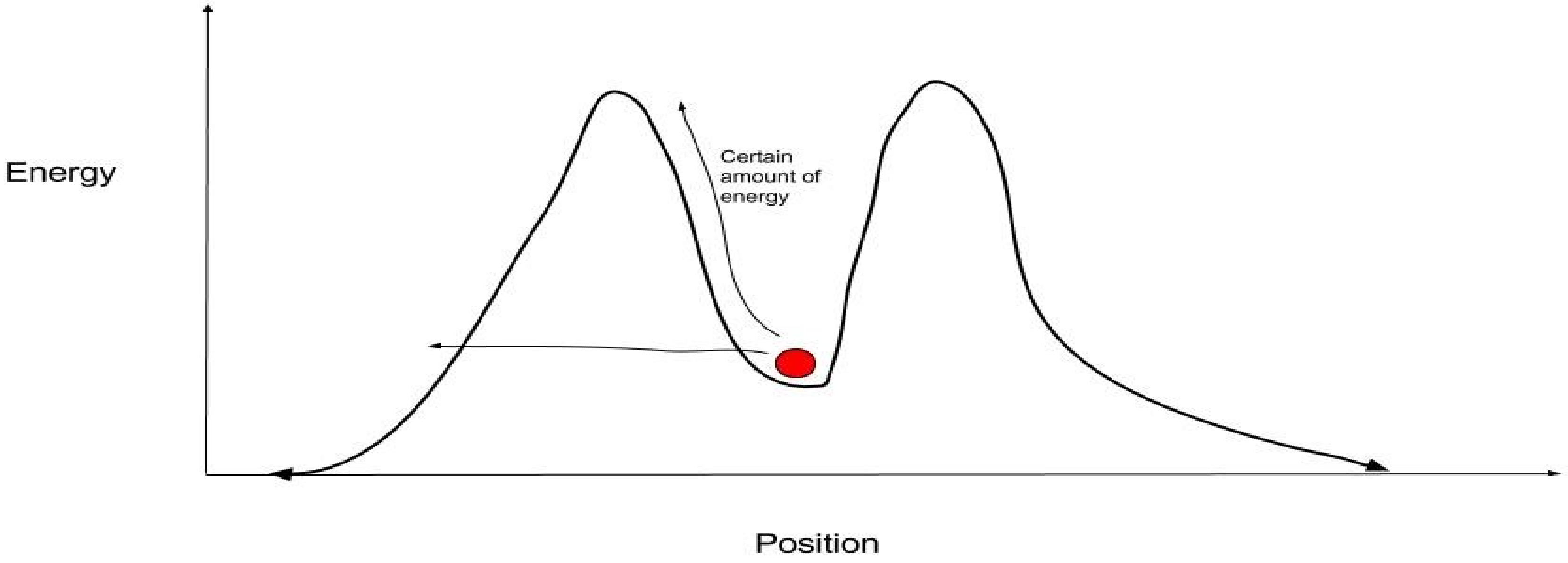
There are two types of energy:

kinetic (relate to speed) $\mathrm{K} = \frac{1}{2}mv^2$

gravitational energy (related to position) $\mathrm{U} = -\frac{\mathrm{Gm}}{r}$

The energy is negative because it acts as a potential well

Potential Well



Escape Velocity

- "Escaping the potential well" means having the speed necessary to escape the gravitational influence of the central body. When this happens, the total energy in Zero.

$$E = K + U$$

$$E = \frac{Gm}{r} - \frac{1}{2}mv_{esc}^2 = 0$$

$$\frac{Gm}{r} = \frac{1}{2}mv_{esc}^2$$

$$\boxed{v_{esc}^2 = \frac{2Gm}{r} \;\text{->}\; v_{esc} = \sqrt{\frac{2Gm}{r}}}$$

2 In Fig. 8-22, a small, initially stationary block is released on a frictionless ramp at a height of 3.0 m. Hill heights along the ramp are as shown. The hills have identical circular tops, and the block does not fly off any hill. (a) Which hill is the first the block cannot cross? [redacted]

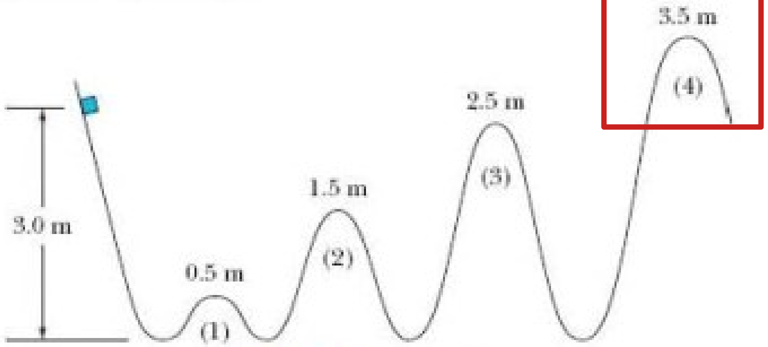


FIG. 8-22 Question 2.

Newton’s Law and Gravity

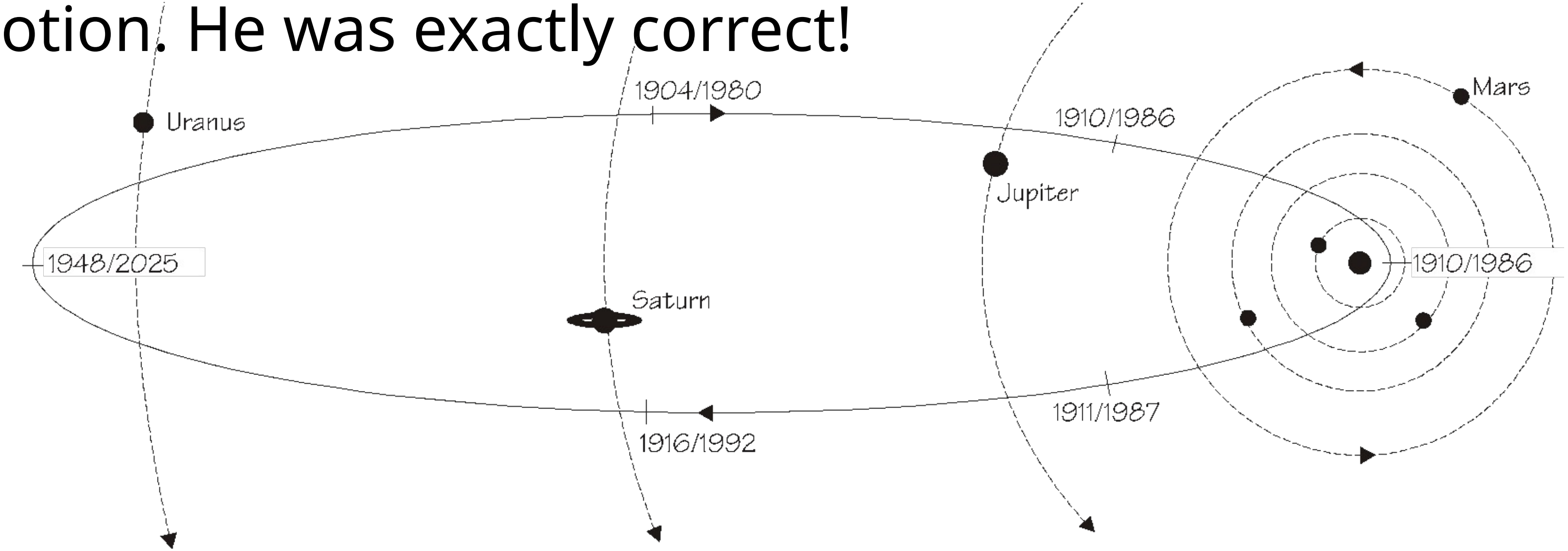
Newton’s theories were published in 1688 (“Principia”). His Universal Law of Gravity combined with the Laws of Motion explain all three of Kepler’s Laws of planetary motion.

These laws represent the “perfection” of the Copernican model. All planetary motions are explained with one equation, **gravity**. Geocentrism is finally wiped-out.

Can Newton’s ideas be tested further?

Newton's Law and Gravity

Edmund Halley tracked part of the orbit of a comet, and predicted when it would return using Newton's laws of motion. He was exactly correct!



Newton’s Law and Gravity

The planet Uranus discovered in 1781 by William Herschel. However, Uranus did not move according to predictions made with Newton’s laws.

The inconsistencies could be explained by another massive object that was pulling on Uranus’s orbit. Using Newton’s laws of motion, a new planet was predicted to exist further from the Sun than Uranus. Neptune was found in 1845, less than 1° away from its predicted position!

Newton’s laws are not only **testable and verifiable,** they are **fruitful**. The discovery of Neptune is one the great stories of the scientific method. “If I have seen farther than other men, it is because I stood upon the shoulders of giants.”

Gravity on other planets

- Let’s start the Homework!