

Last time: Scales of the Universe

- The size of our solar system, galaxy, and Universe
- The Light Year (10^{13} km) as a fundamental distance unit
- Universe is mostly empty space (density = 10^{-23} g/cm³)
- Composition: 75% hydrogen; ~24% helium; < 1% “impurities”
- we are mostly “star stuff” produced in stars and supernovae
- Time scales of the Universe (age ~ 13.6 billion years)

Today: Astronomy as a catalyst for modern Science

- by watching the skies, humankind eventually uncovered the basic laws that govern the motions of the planets, stars, and galaxies
- Using Newton’s laws, we can measure the most fundamental property of things in the Universe - their mass
- Gravity and light are the two ‘messengers’ that astronomers use to learn about the Universe

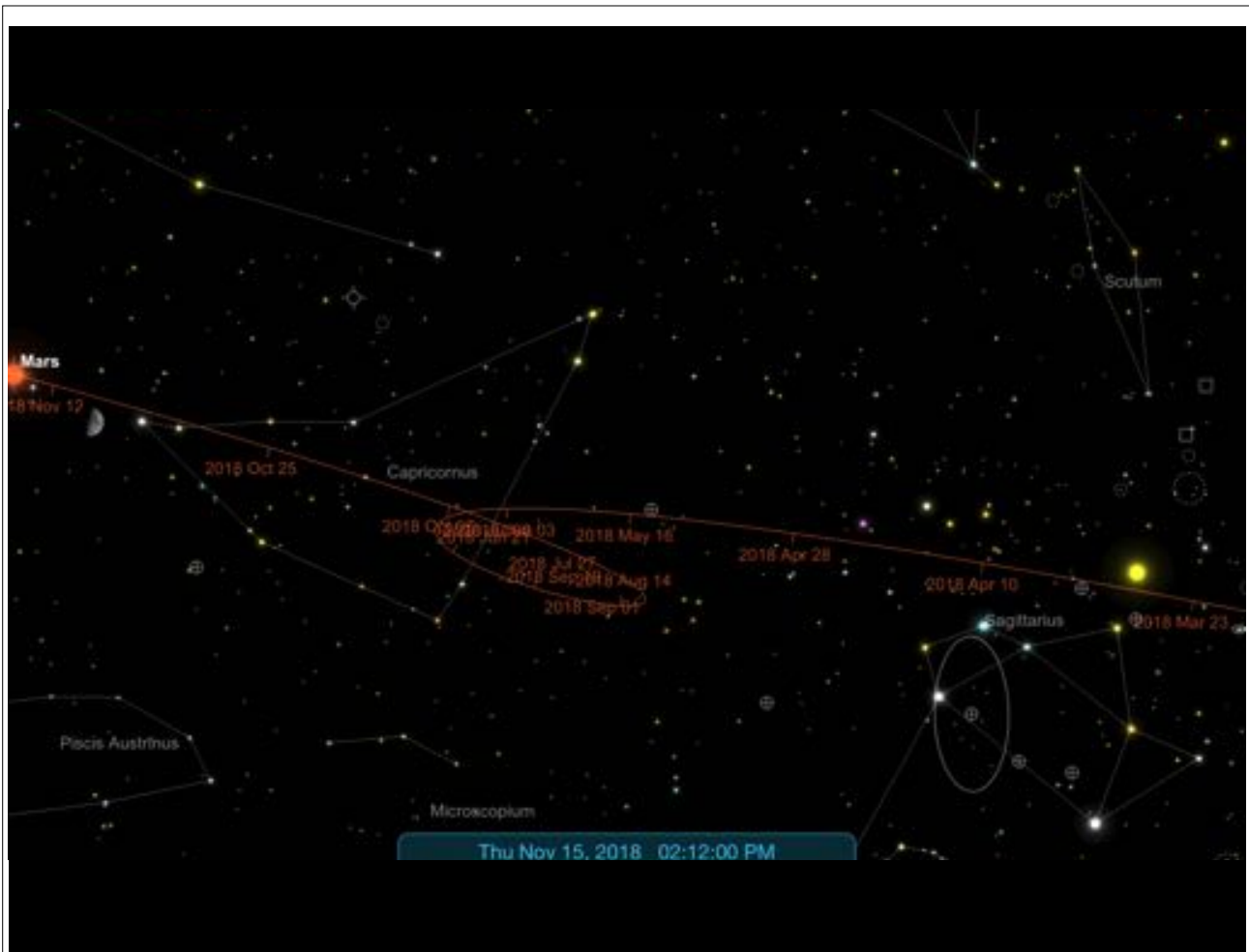
Occam’s Razor: William of Occam, 1340(!)

**“We take as Truth
the simplest explanation
that fits all of the data.”**

**This is the fundamental principle of
all modern science**

Today: The Discovery of Gravity

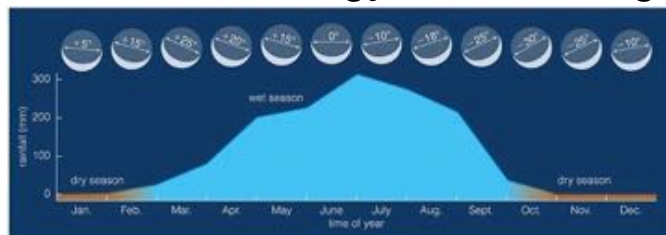
pre-history → Greeks → Copernicus → Tycho → Kepler → Galileo → Newton



The Early Days...

Astro 150 Fall 2020: Lecture 2 page 4

- Prehistoric Discoveries
 - **Motivation:** Calendar = survival
Cosmology = order = higher being



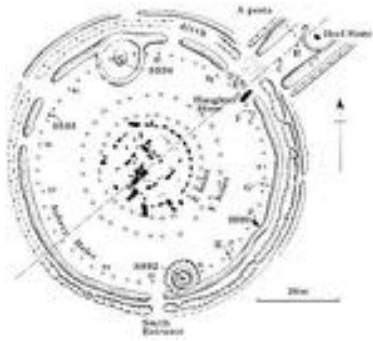
- **Ecliptic + Zodiac** paths of planets and Sun
- **Solstice** seasons
- **Saros cycle** eclipses



- Early Science: The (500 BCE - 150 CE)
 - spherical Earth (Pythagoras)
 - model of celestial motion (Aristotle)
 - relative dimensions of Sun, Moon, Earth (Aristarchus)

Ancient Calendars and Calculators

- Ecliptic / Equinox / Eclipse marker: Stonehenge



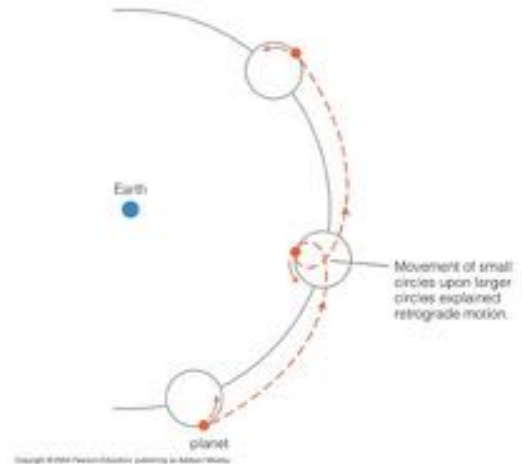
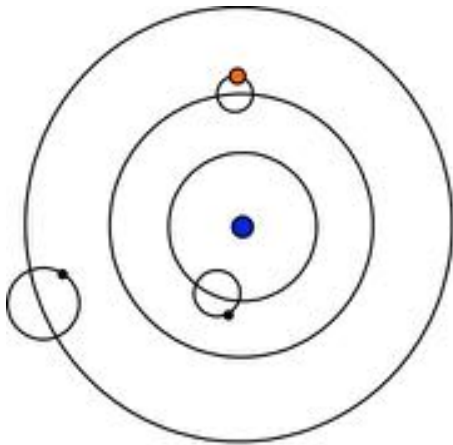
Ancient Calendars and Calculators

- Chichen Itza, Yucatan (Mexico): Annual



Philosophy + some observation culminated in

- Ptolemy's computational scheme for celestial motion
 - Earth -centered
 - Uniform, circular Motion
 - Epicycles



towards the modern view



- **1200s: Ptolemy's** method off by several degrees
 - response: add more epicycles . . .

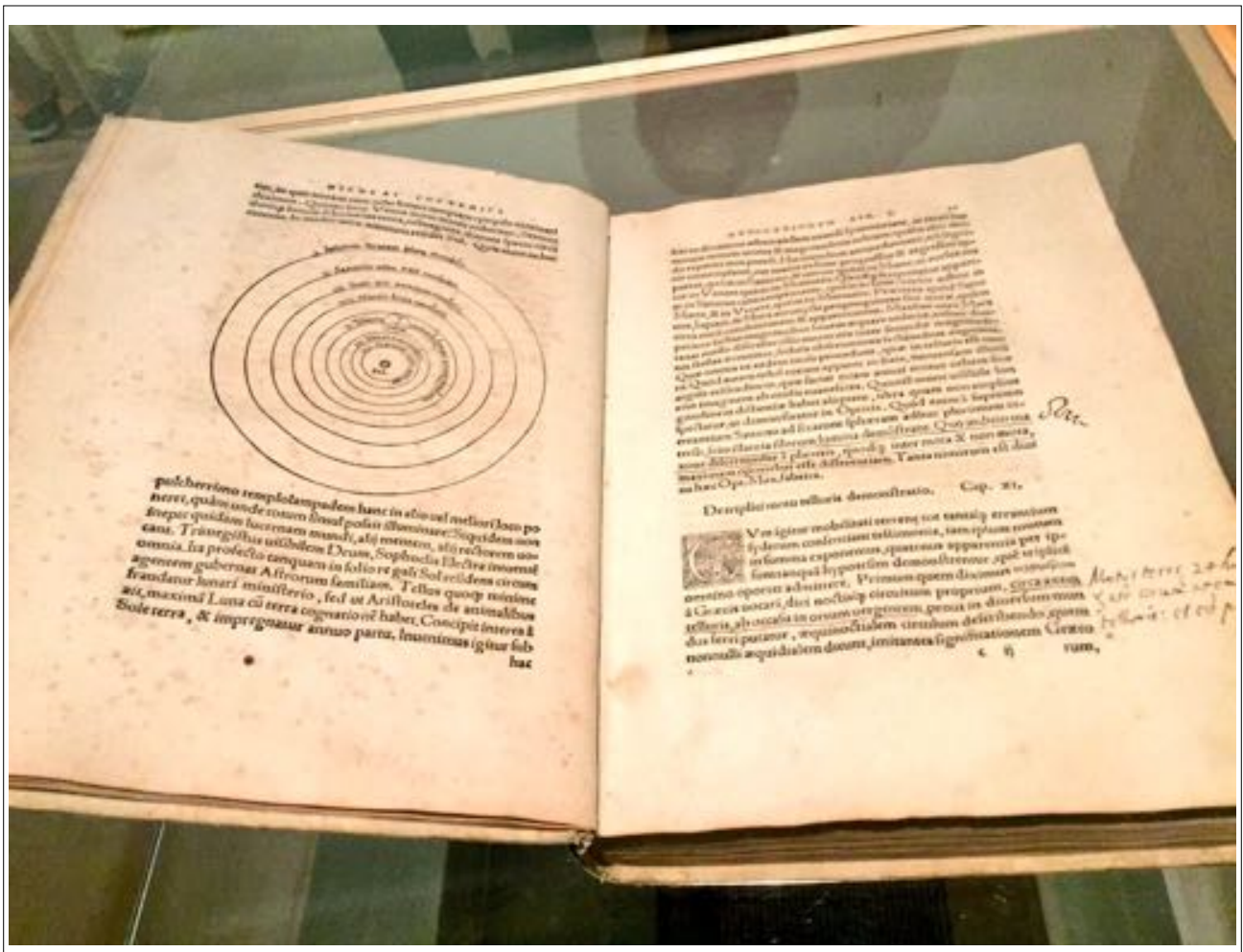


- **1543: Copernicus**
 - moved sun to center -----> Revolutionary!

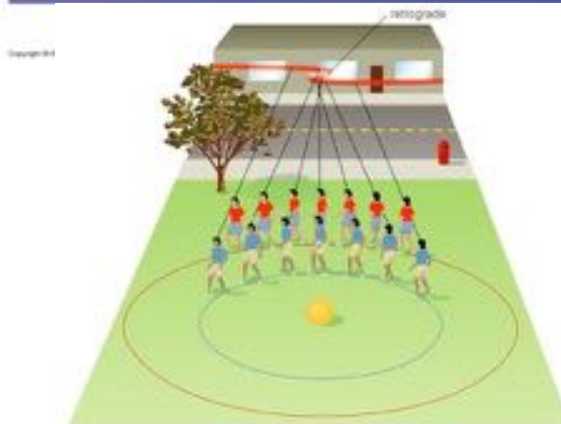
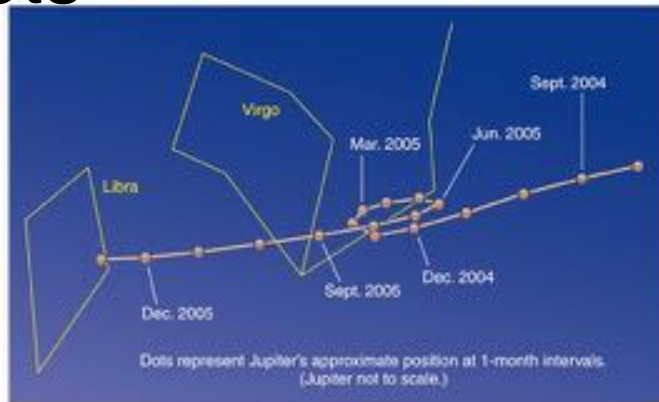
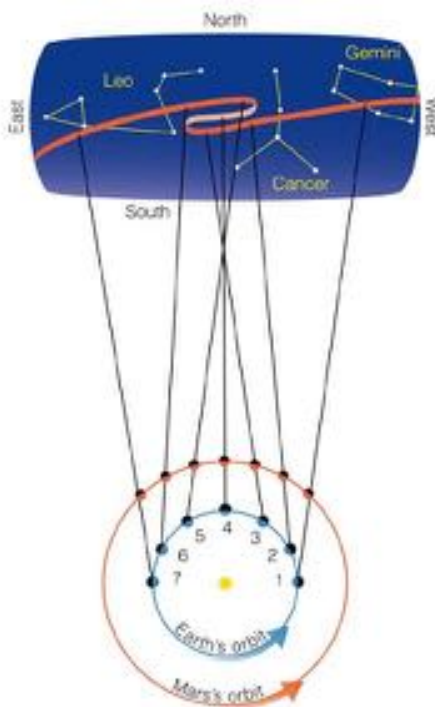
- **1580: Tycho Brahe**
 - precise positions of planets
 - stars are fixed, therefore very distant
 - sky is not immutable



- **1609: Galileo**
 - astronomer: telescopic studies show Copernicus was right
 - physicist: experiments with Gravity



Looping Planets



towards the modern view



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-
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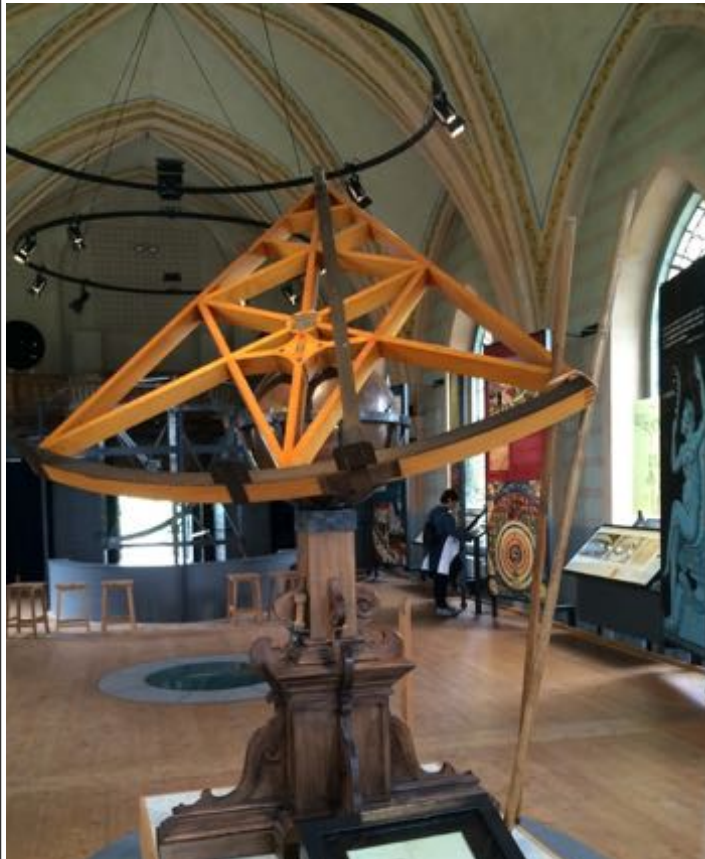


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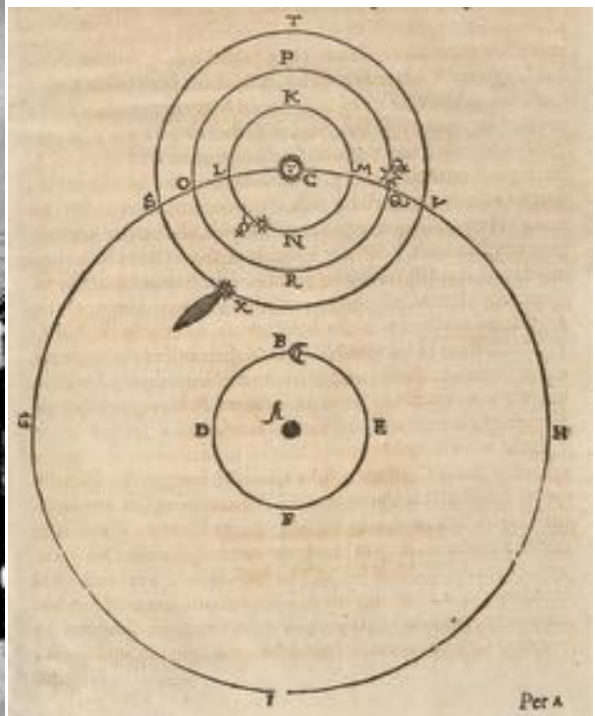
Brahe's Tools and Ideas



Brahe's Tools and Ideas

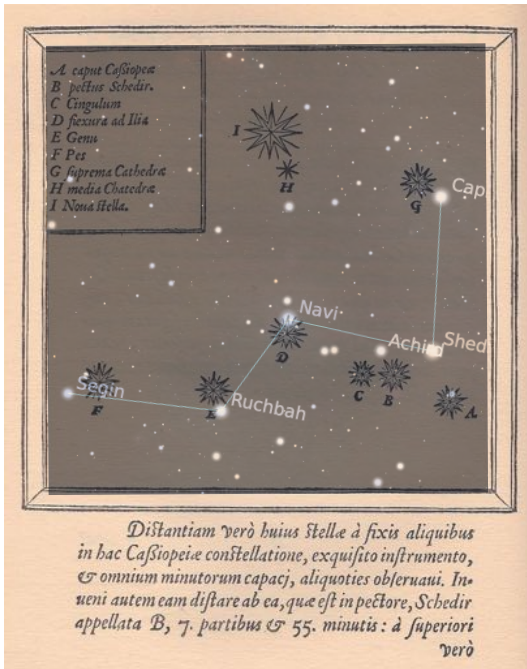


Brahe's Tools and Ideas

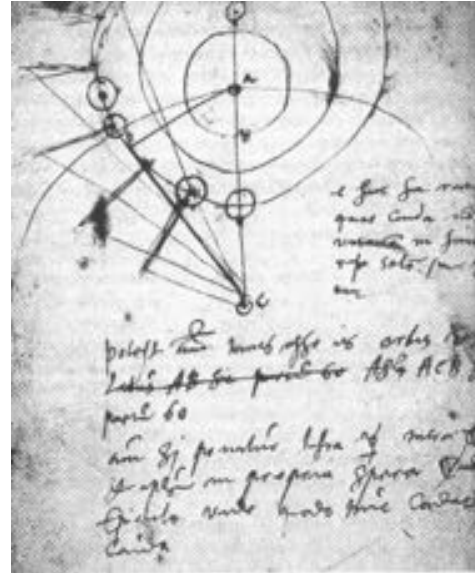


Brahe's demonstrations of the *non*-immutable heavens

Supernova in Cassiopeia in 1572



The Great Comet of 1577: not in our atmosphere, but farther than the Moon



towards the modern view



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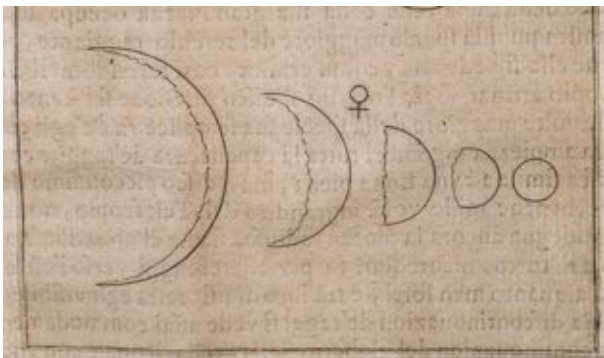
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Galileo's observations

- full set of phases of Venus
- Jupiter's system of moons (the Galilean satellites)



Observations Jupiter
1610

2. Jovis mar. H. 12	○ **
30. mar.	** ○ *
2. Apr.	○ ** *
3. mar.	○ * *
3. Apr.	* ○ *
4. mar.	* ○ **
6. mar.	** ○ *
8. mar. H. 17.	* ** ○
10. mar.	* * * ○ *
11.	* * ○ *
12. H. 4. Apr.	* ○ *
17. mar.	* ** ○ *
14. Apr.	* ** ○ *

a famous experiment 1612 (?)



1971



1610 - Johannes Kepler

mathematician and klutz

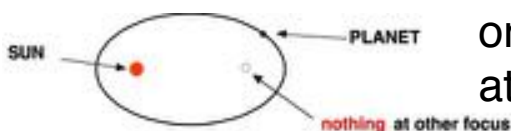


used Tycho's data on the motion of Mars:
with no circular motion bias
to discover

Kepler's Laws of Planetary Motion

These are simple empirical laws explaining planetary motion, derived from data only, with no preconceptions.

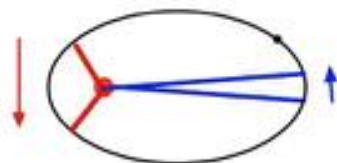
Kepler's Law #1



- Planets orbit the sun in **ELLIPTICAL** orbits around the sun, with the sun at one 'focus' of the ellipse.

- non-circular motion

Kepler's Law #2



- A line joining the planet to the Sun sweeps out **equal areas in equal times**... so planet moves faster when closer to the Sun

- non-uniform motion

Kepler's Law #3

- The Law of Periods:

$$\text{Period}^2 = (\text{semimajor axis})^3$$

$$P^2 = a^3$$

(P in years, a in A.U.)

Bigger orbit (larger a) → longer Period

Kepler's 3rd Law

Planet	P[y]	a[a.u.]	P ²	a ³	P ² /a ³
Mercury	0.241	0.387	0.0581	0.0580	1.0021
Venus	0.615	0.723	0.3782	0.3779	1.0008
Earth	1	1	1	1	1
Mars	1.881	1.524	3.5382	3.5396	0.9996
Jupiter	11.86	5.203	140.66	140.85	0.9986
Saturn	29.42	9.539	865.54	867.98	0.9972
Uranus	84.01	19.19	7057.7	7066.8	0.9987
Neptune	164.8	30.06	27159	27162	0.9999

1627: Kepler's Rudolphine Tables



- Final publication of Tycho's star catalog
- Planetary position tables computed with Kepler's laws
- Recipes to allow users to calculate positions on their own



DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STUDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR. DVCA DI TOSCANA.

Due ne i congressi di quattro giornate si discorre
sopra i due

MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;

*Proponendo indeterminatamente le ragioni Filosofiche, e Naturali
tanto per l'una, quanto per l'altra parte.*

CON PRI



VILEGI.

IN FIRENZA, Per Gio. Batista Landini MDCXXXII.

CON LICENZA DE' SUPERIORI.

(1632)

1666: Isaac Newton

mathematician: Invented calculus as a youth . . .

SYNTHESIZED:

Galileo's Experiments

+

Kepler's Laws

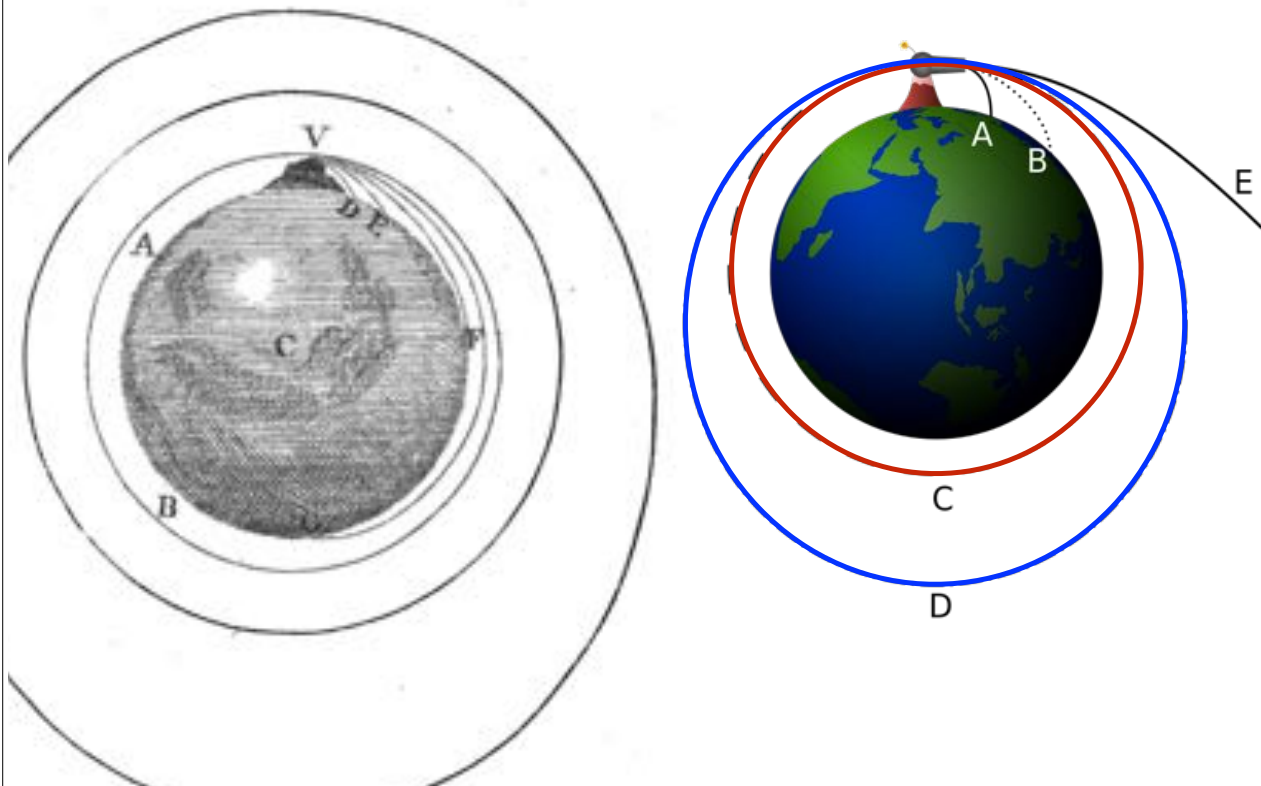
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Calculus

**into Physical Laws;
the basis of Modern Science**



Apple falls -> Earth and apple **attract each other**
Moon and Earth **attract each other**, too
**If moon moves sideways as it falls, it could forever
circle the Earth...**



Newton's Laws of Motion

- Newton #1: (the law of inertia)
 - bodies move at constant velocity unless acted upon by an unbalanced force
- Newton #2: (fisma)
 - Force = mass x acceleration (F=ma)
- Newton #3:
 - for every force on a body, there is an equal force acting in the opposite direction on another body
--- recoil & rockets

Newton's Law of Universal Gravitation

Gravity is

- a **central** force: strength drops with **distance²**
- a **universal** force: same form everywhere
- a **cosmic** force: inherent property of matter

Apple falls -> Earth and apple **attract each other**
Moon and Earth **attract each other**, too

If moon moves sideways as it falls, it could forever circle the Earth...

- **Force** of gravity pulls planets towards Sun
(Newton's 2nd law)
- without gravity, planets would fly away in straight lines
(Newton's 1st law)

Newton's Synthesis

- **Mathematics** - Calculus
 - how to define/formulate/calculate motion & acceleration
- **Physics** - definitions / laws
 - energy of interaction between masses
 - momentum - resistance to change in motion
 - *correspondence with mathematical definitions*
- **Universal Gravitation**
 - dependence of gravitational force on mass & distance
 - connecting Galileo's experiments and Kepler's Laws
 - successful synthesis of earthly & cosmic behavior
 - blueprint for modern physics

Newton's Legacy

- **Force of Gravity pulls planets towards Sun**
 - without gravity, planets would fly away in straight lines
- Newton's laws of motion and theory of gravity explain -**simply**- the orbits of the planets

Understanding motions of the planets was the principal discovery of astronomy from prehistory through 1700.

- Improved observations ("technology") **demand**ed more precise models of the Solar System
- **This precision was**
 - **approach**ed by complex models (epicycles, etc.) but
 - **achiev**ed by discovery of the underlying **simplicity: Gravity**