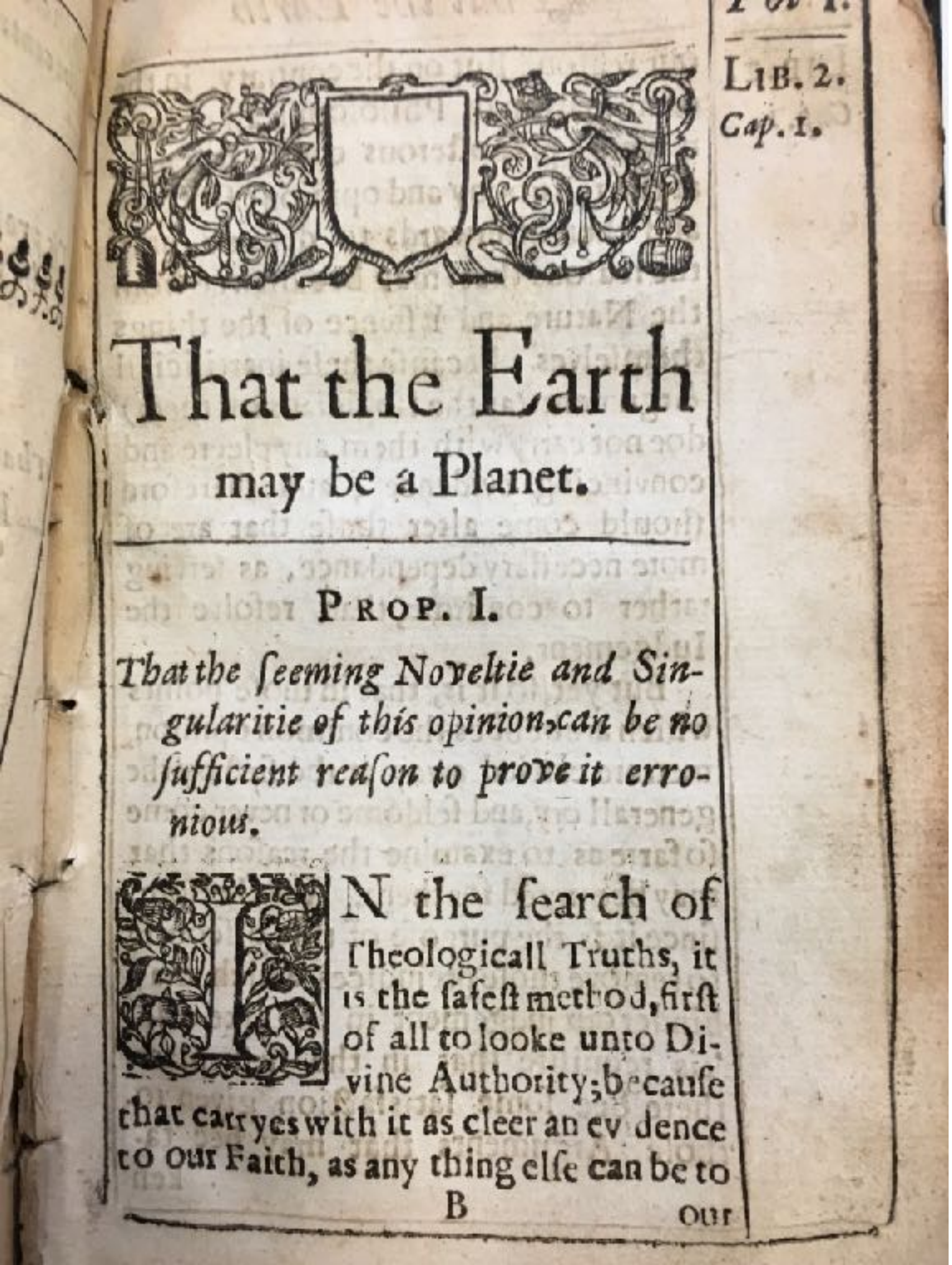
Today

- Planetary Motion
  - Tycho Brahe's Observations
  - Kepler's Laws of Planetary Motion
- Laws of Motion
  - in physics



That the Earth may be a Planet.

Prop. I.

That the ſeeming Noveltie and Singularitie of this opinion, can be no ſufficient reaſon to prove it erronious.

IN the ſearch of Theologicall Truths, it is the ſafeſt method, firſt of all to looke unto Divine Authority; becauſe that carryes with it as cleer an evidence to our Faith, as any thing elſe can be to

Page from 1640 text
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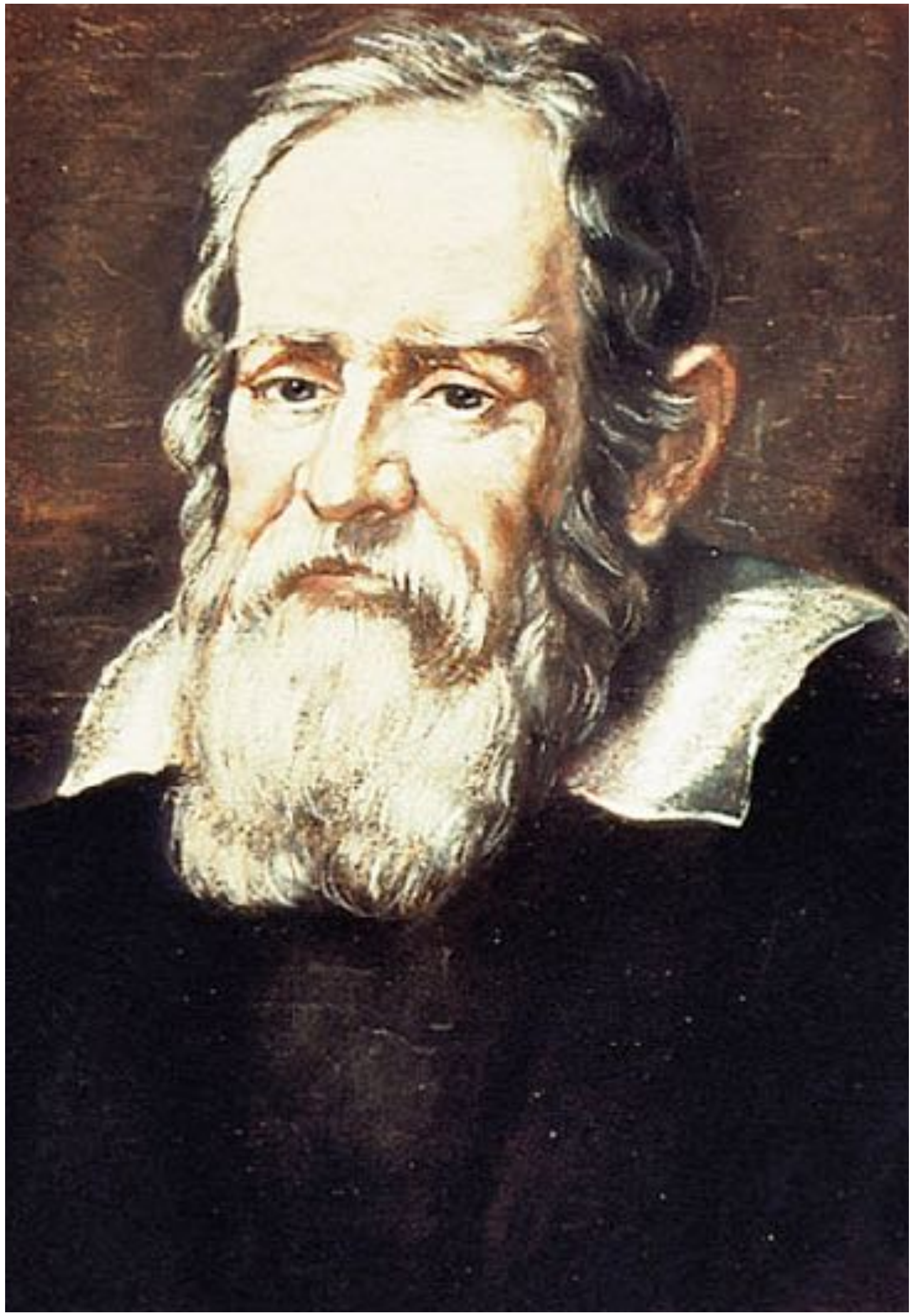
That the Earth
may be a Planet

the seeming novelty and singularity of this opinion can be no sufficient reason to prove it erroneous



Galileo Galilei

Galileo's work was important in part for refuting some important objections to the heliocentric system:

1. Motion is absolute with respect to the Earth.

Common misconception

2. Heavenly bodies are perfect, composed of an immutable ethereal substance.

Religious presumption

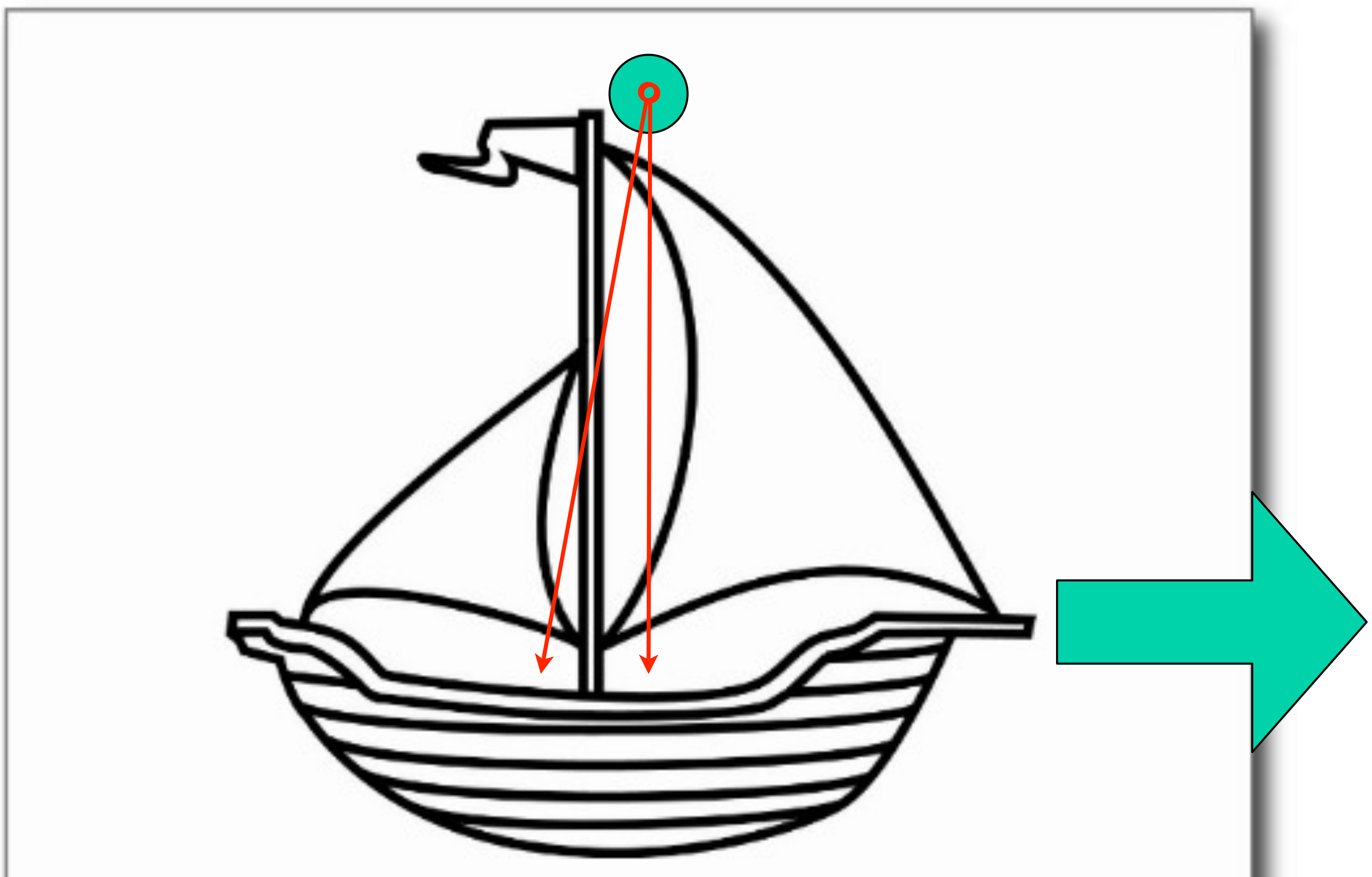
3. Parallax

Serious issue

Overcoming the first objection (nature of motion):

Galileo's experiments showed that objects in air would stay with a moving Earth.

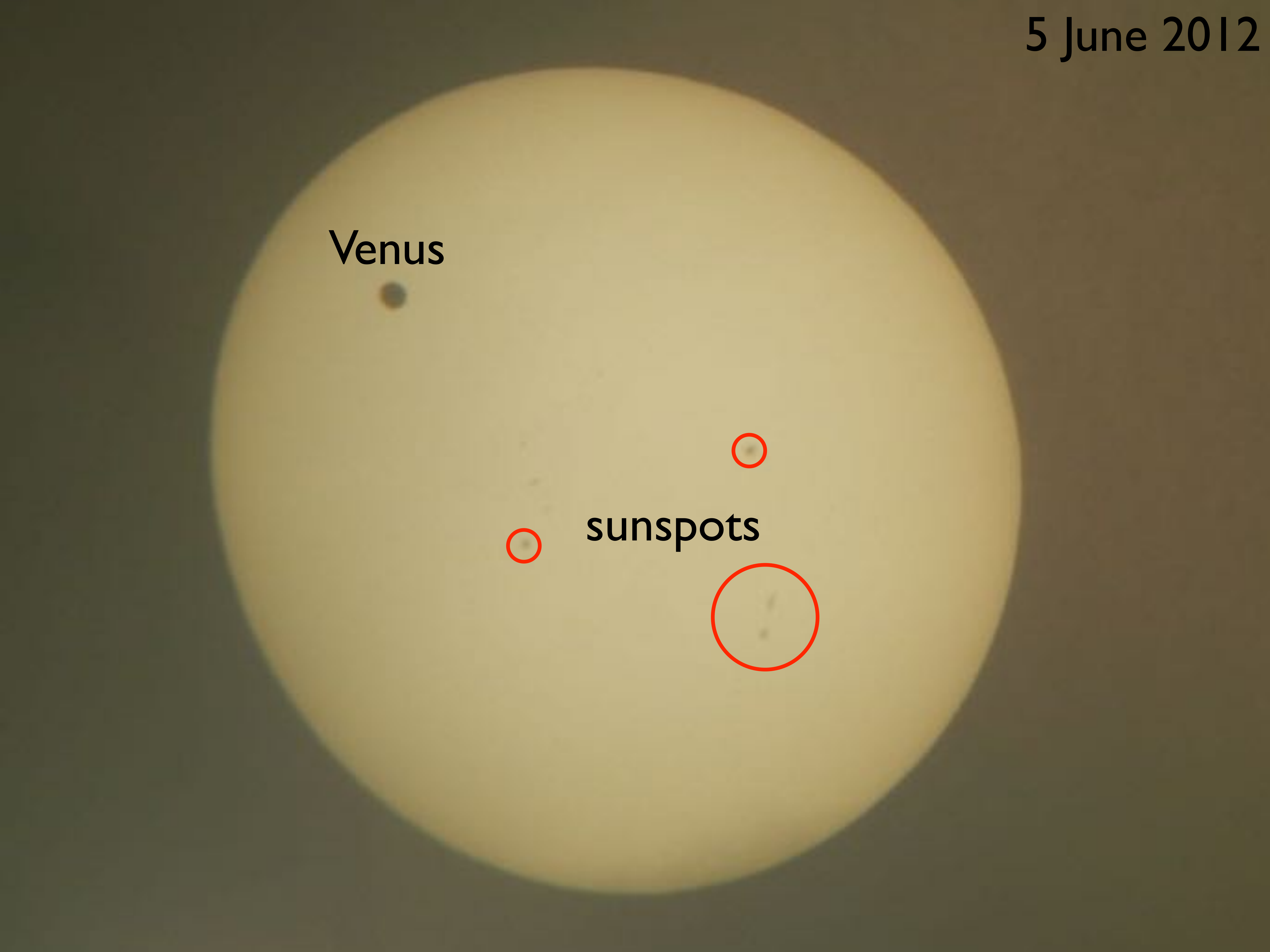
- Aristotle thought that all objects naturally come to rest.
- Galileo showed that objects will stay in motion unless a force acts to slow them down (Newton's first law of motion).



Overcoming the second objection (heavenly perfection):

In medieval cosmology, there was a distinction between the composition of the mortal & corrupt Earth (Four elements: earth, wind, water, & fire) and the perfect heavens, which were composed of a fifth, incorruptible element, aether.

- Tycho's observations of a comet and supernova already challenged this idea.
- Using his telescope, Galileo saw:
  - Sunspots on Sun ("imperfections")
  - Mountains and valleys on the Moon (proving it is not a perfect sphere)


5 June 2012
Venus
sunspots

Overcoming the third objection (parallax):

- Tycho *thought* he had measured stellar distances, so lack of parallax seemed to rule out an orbiting Earth.
- Galileo showed stars must be much farther than Tycho thought—in part by using his telescope to see that the Milky Way is countless individual stars.

? If stars were much farther away, then lack of detectable parallax was no longer so troubling.

How persuasive is this argument?

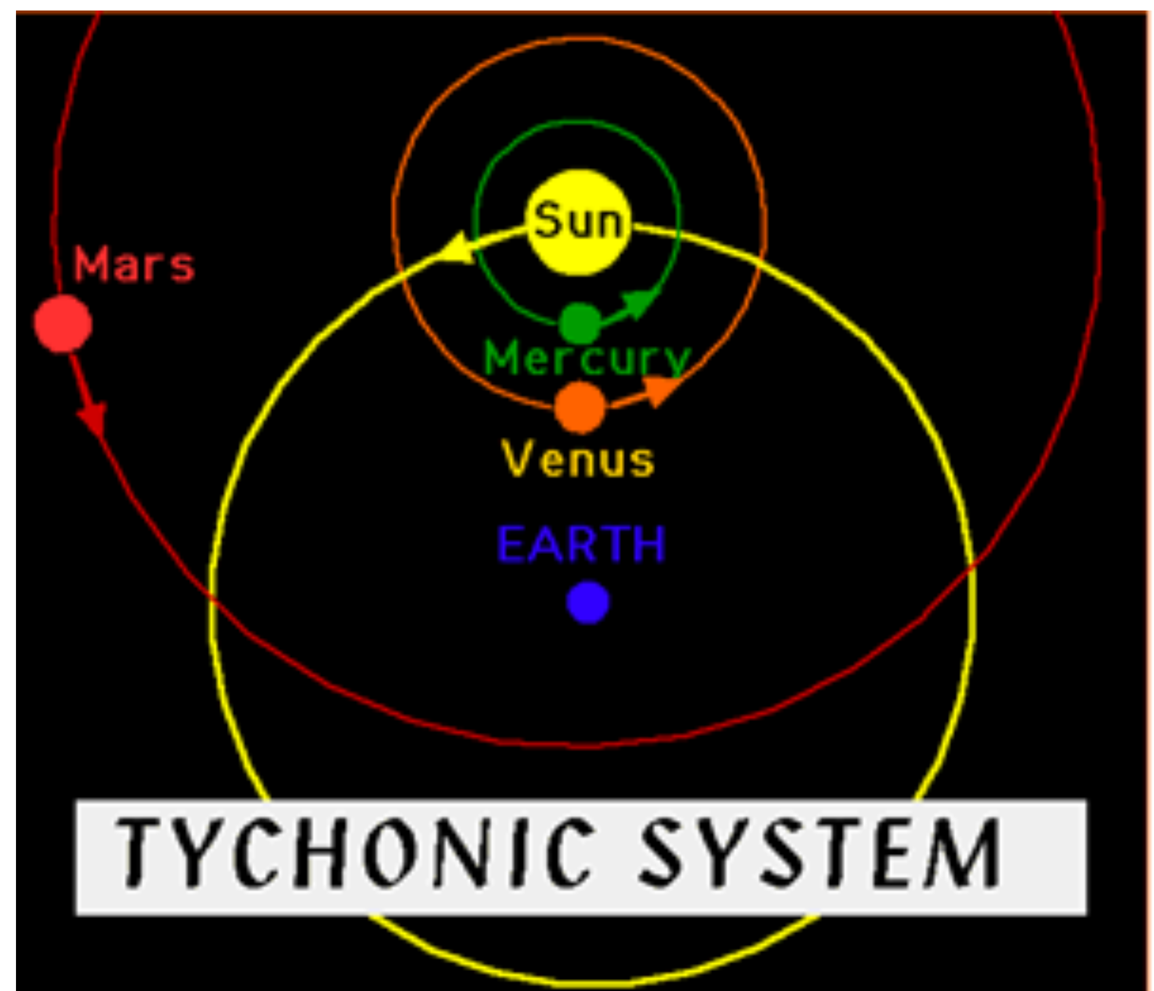
Tycho Brahe

the last great
naked-eye
observer

1546-1601

Tycho Brahe

- Brahe compiled the most accurate (one arcminute) naked eye measurements ever made of planetary positions.
- He still could not detect stellar parallax, and thus still thought Earth must be at the center of the solar system (but recognized that other planets go around Sun).



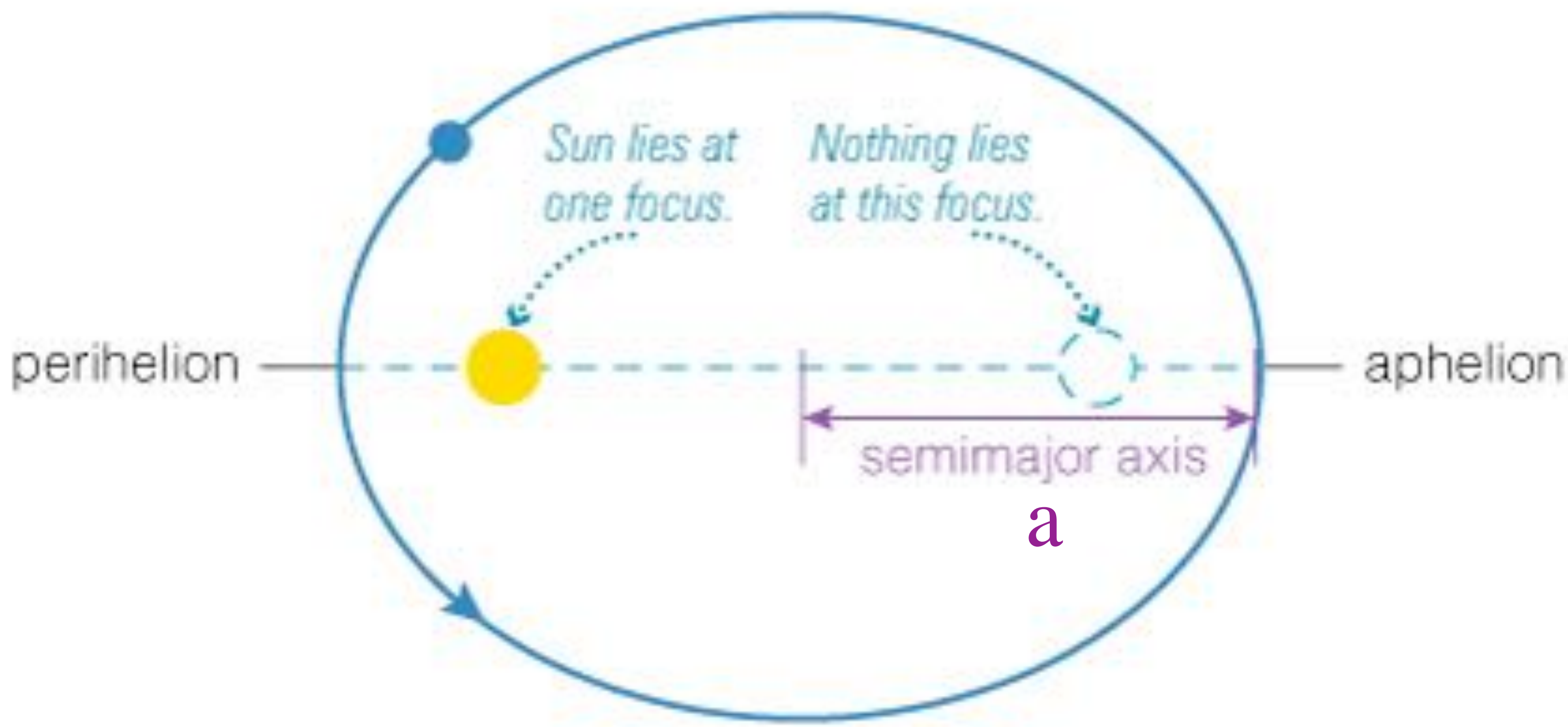
Johannes Kepler
(1571–1630)

- Kepler analyzed Brahe’s data
- Kepler first tried to match Tycho’s observations with circular orbits.
- But an 8-arcminute discrepancy led him eventually to ellipses.

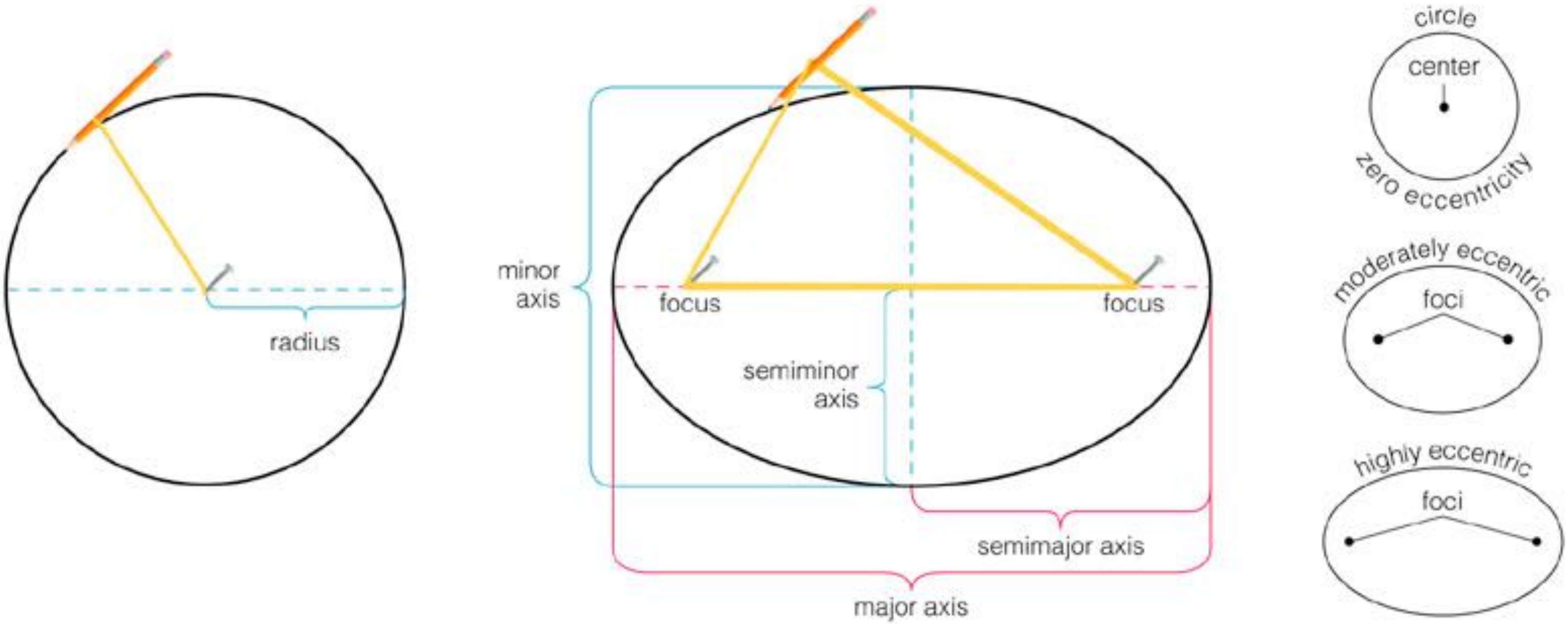
“If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, ***since it was not permissible to ignore****, those eight minutes pointed the road to a complete reformation in astronomy.”*

Kepler's Laws of planetary motion

Kepler's First Law: The orbit of each planet around the Sun is an ***ellipse*** with the Sun at one focus.



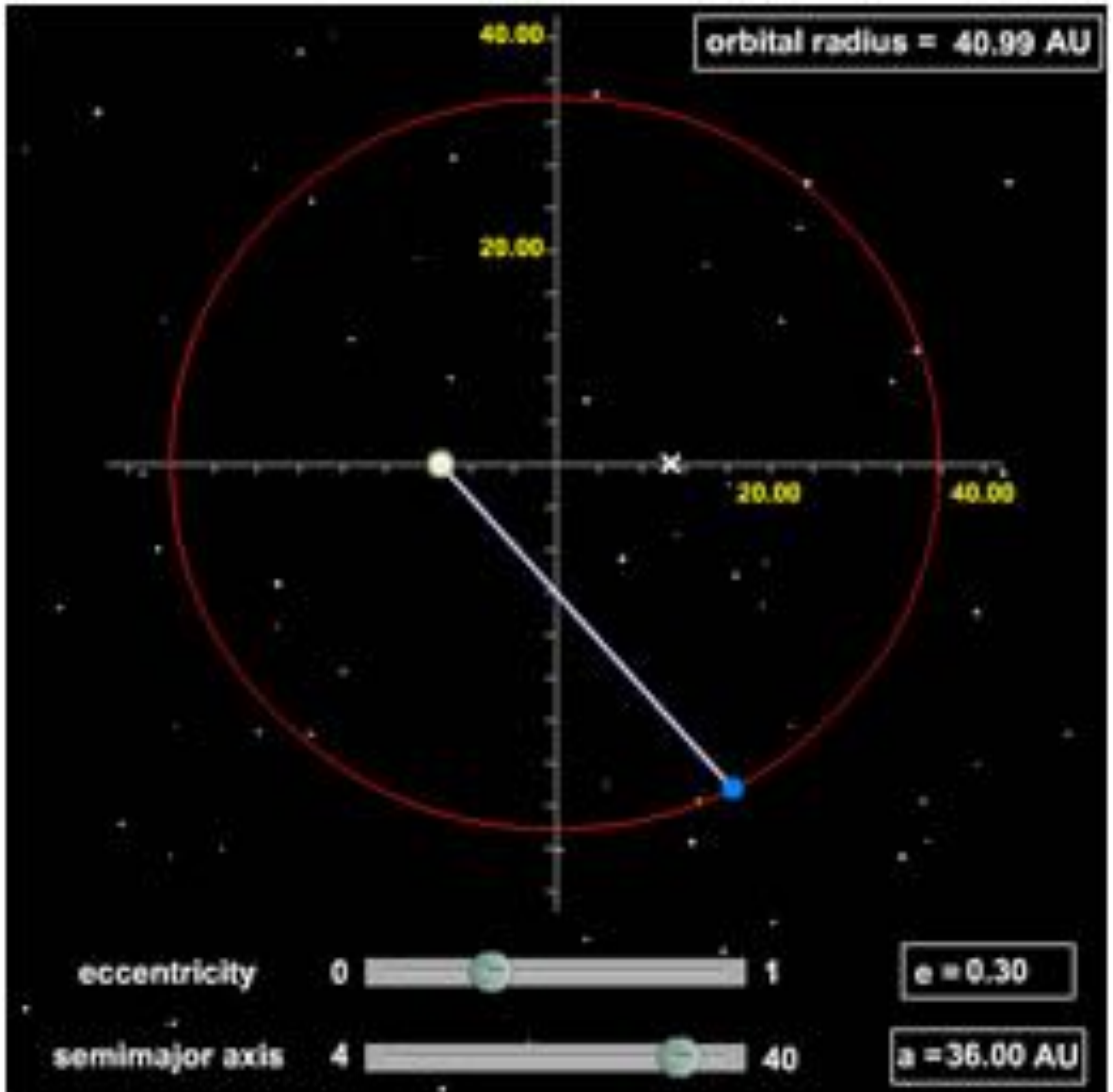
An ellipse is the shape that is equidistant from two **foci**. The **eccentricity** of an ellipse depends on the ratio of the long and short axes. Half of the long axis is the **semimajor axis, a**.



An ellipse looks like an elongated circle. Indeed, a circle is a special case of an ellipse where the two foci overlap.

PLAY 03_02DrawingEllipseWithString.swf

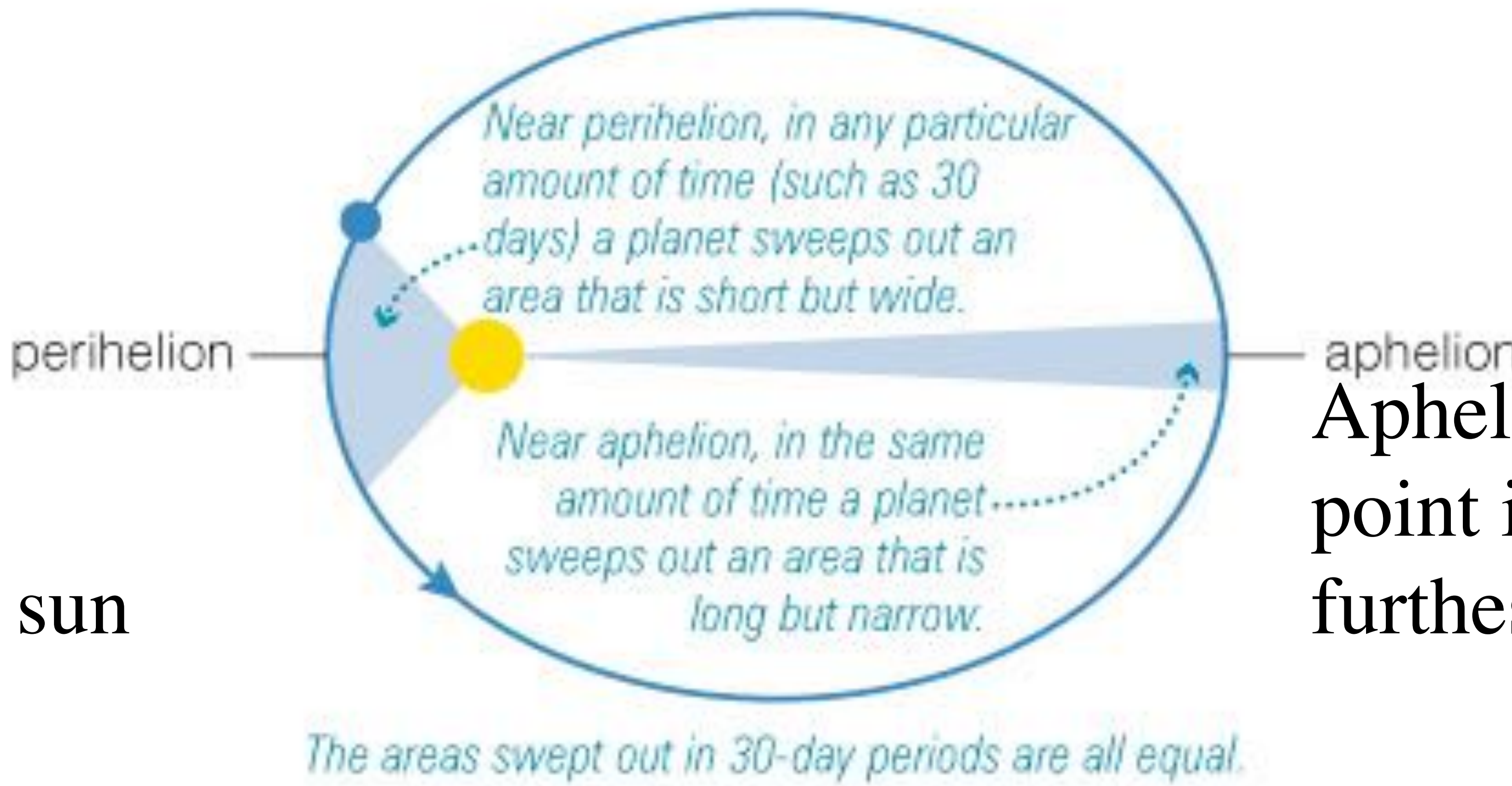
Eccentricity of an Ellipse



PLAY Eccentricity and Semimajor Axis of an Ellipse

Kepler's Second Law: As a planet moves around its orbit, it sweeps out equal areas in equal times.

Perihelion:
point in orbit
closest to the sun



Aphelion:
point in orbit
furthest from the sun

This means that a planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.

PLAY Kepler's 2nd Law

Kepler's Third Law

More distant planets orbit the Sun at slower average speeds, obeying the relationship

$$P^2 = a^3$$

p = orbital period in years
a = distance from Sun in AU
(semi-major axis of orbit's ellipse)

Earth: **P** = 1 year, **a** = 1 AU

Kepler's Third Law

- A worked example: Mercury: P = 0.24 year

$$P^2 = a^3$$

$$a = P^{2/3}$$

$$a = (0.24)^{2/3}$$

$$a = 0.39 \text{ AU}$$

Kepler's Third Law

- A worked example: Jupiter: a = 5.2 AU

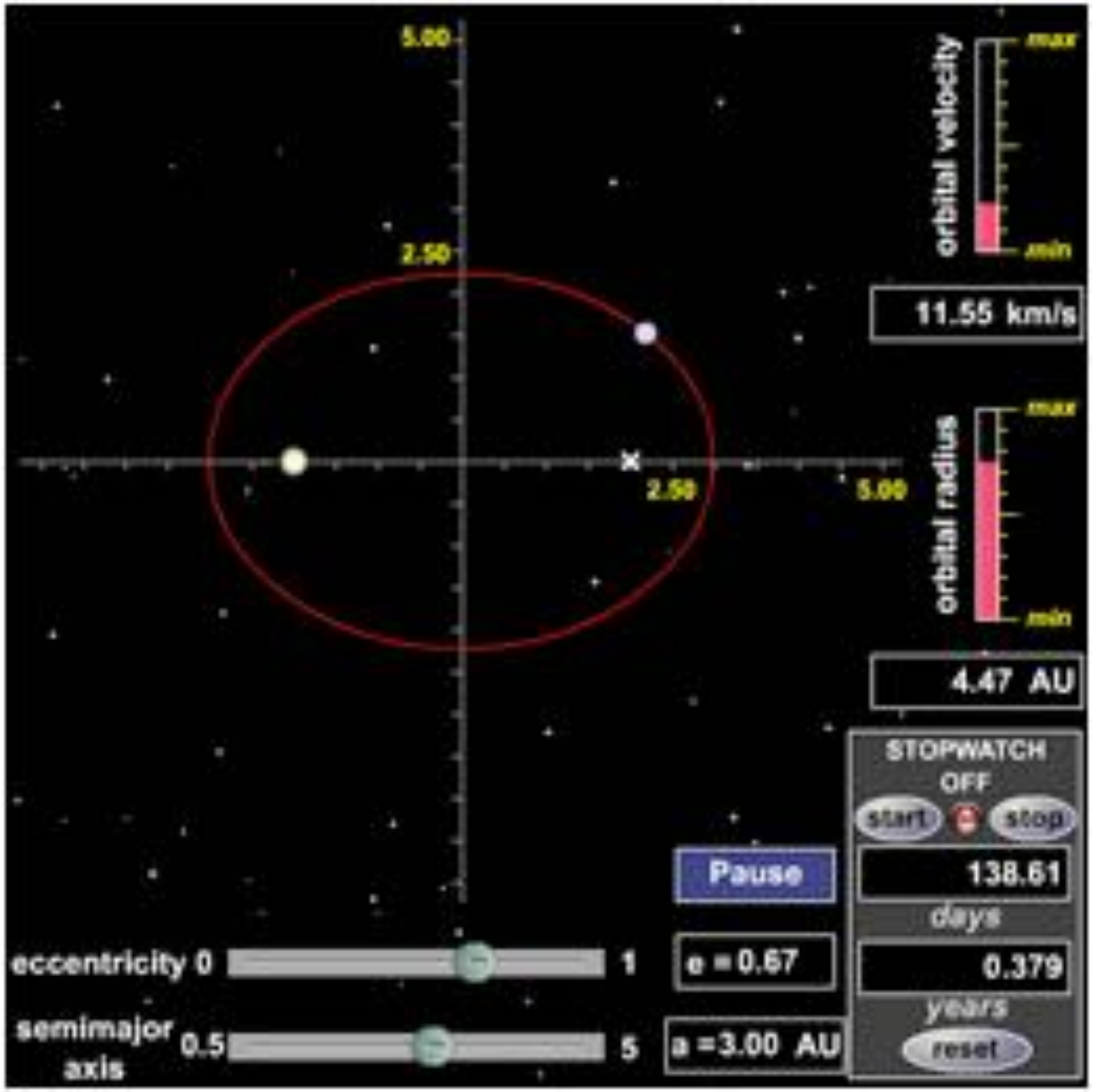
$$P^2 = a^3$$

$$P = a^{3/2}$$

$$P = \sqrt{(5.2)^3}$$

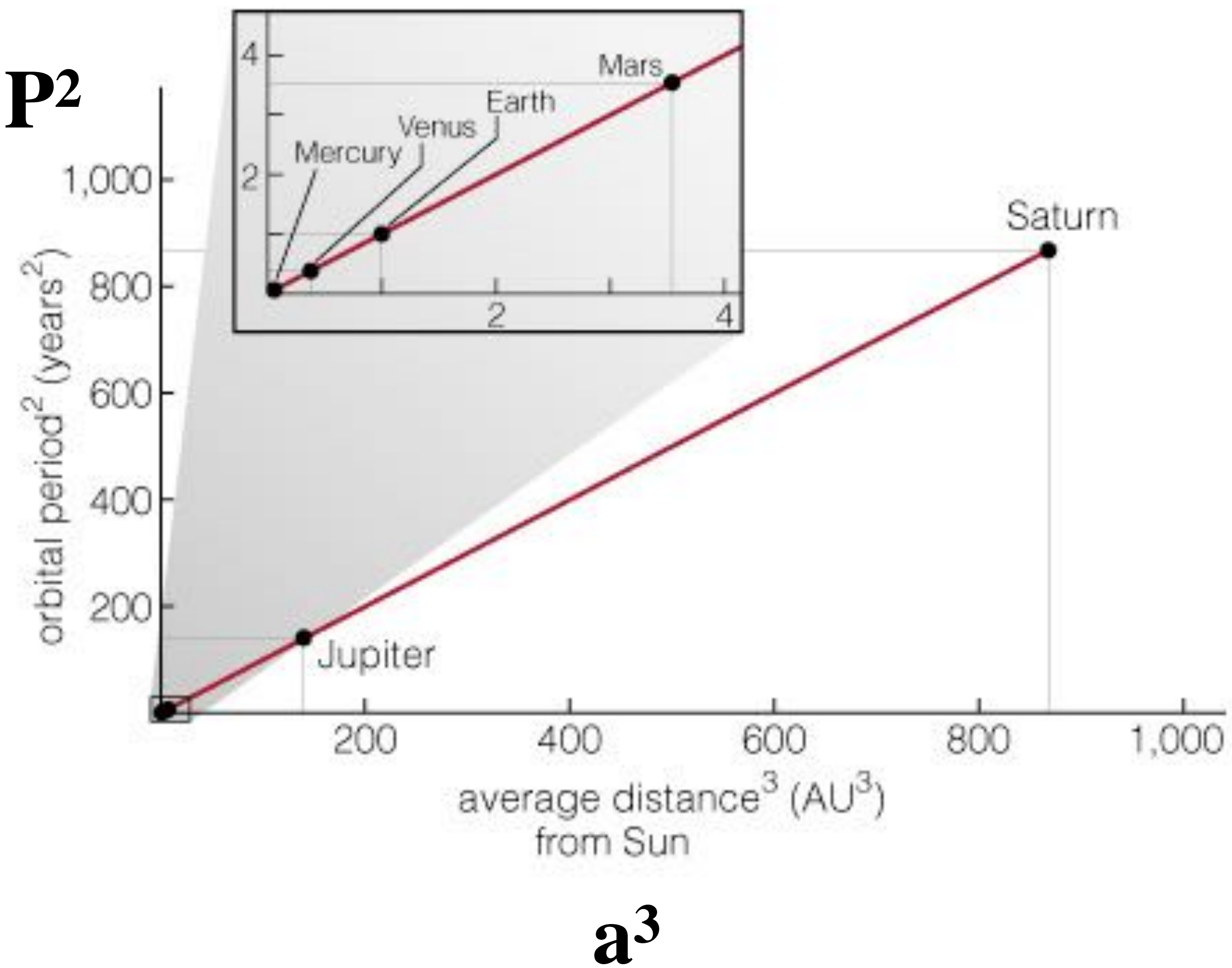
$$P = 11.9 \text{ years}$$

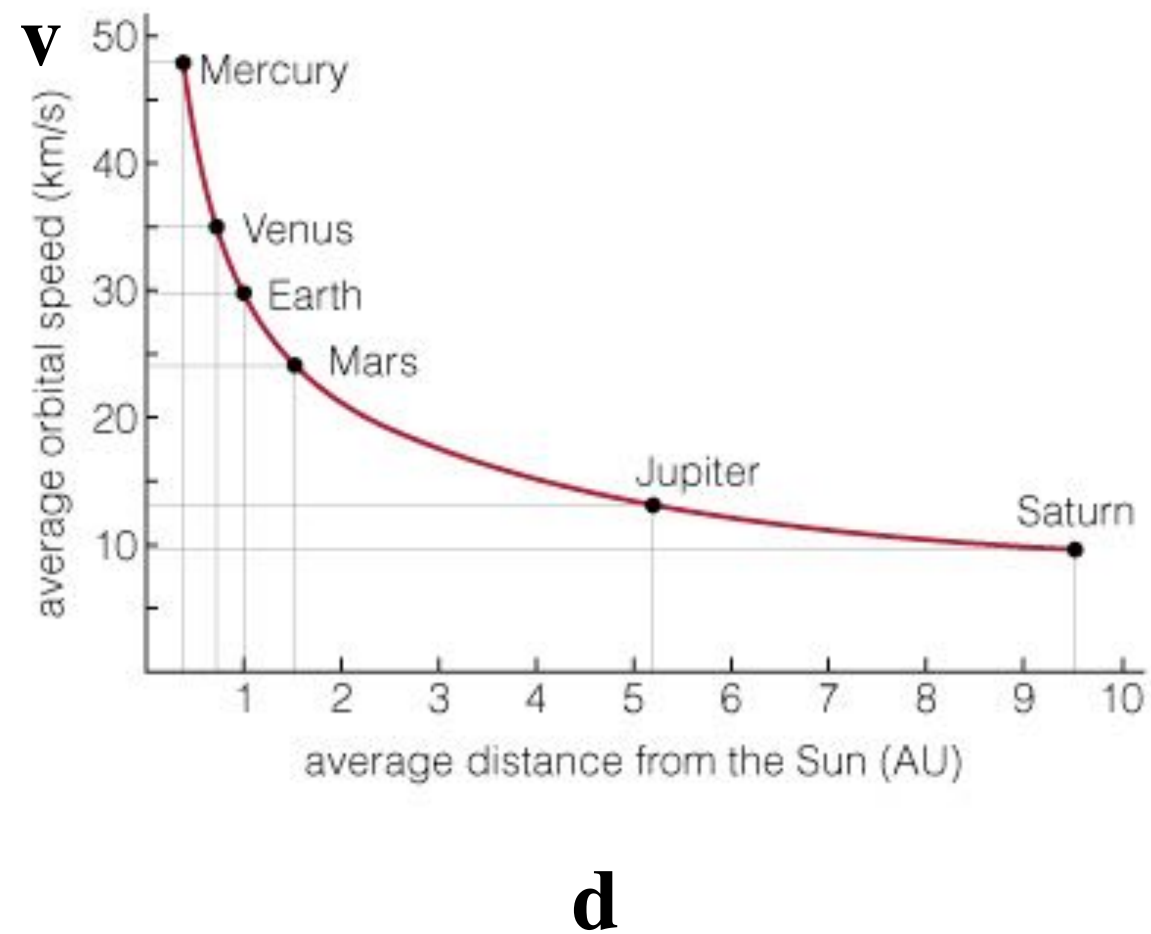
Kepler's Third Law



PLAY Kepler's 3rd Law

Graphical version of Kepler's Third Law



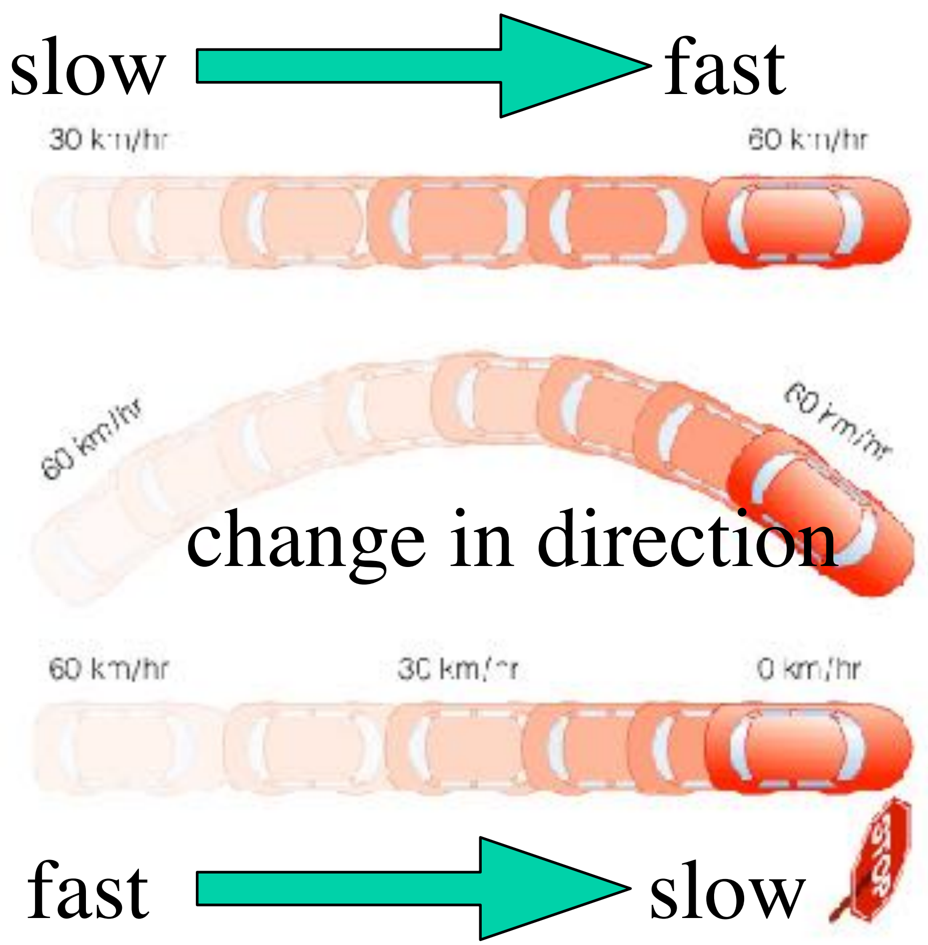


- Kepler's Laws:
  1. The orbit of each planet is an ellipse with the Sun at one focus.
  2. As a planet moves around its orbit it sweeps out equal areas in equal times.
  3. More distant planets orbit the Sun at slower average speeds: $p^2 = a^3$.

Major Figures in Copernican Revolution

- Copernicus: [Re]Invented Heliocentric model.
- Tycho Brahe: Collected large, accurate database on planetary positions & motions. Failed to detect parallax; suggested hybrid.
- Kepler: Used Brahe's data to discern his three Laws of planetary motion.
- Galileo: telescopic observations and physical arguments in favor of heliocentric model.

Laws of Motion (Physics)



Motion notions:

- **Speed**: Rate at which object moves

$$\text{speed} = \frac{\text{distance}}{\text{time}} \quad \left(\text{units of } \frac{\text{m}}{\text{s}}\right)$$

example: speed of 10 m/s

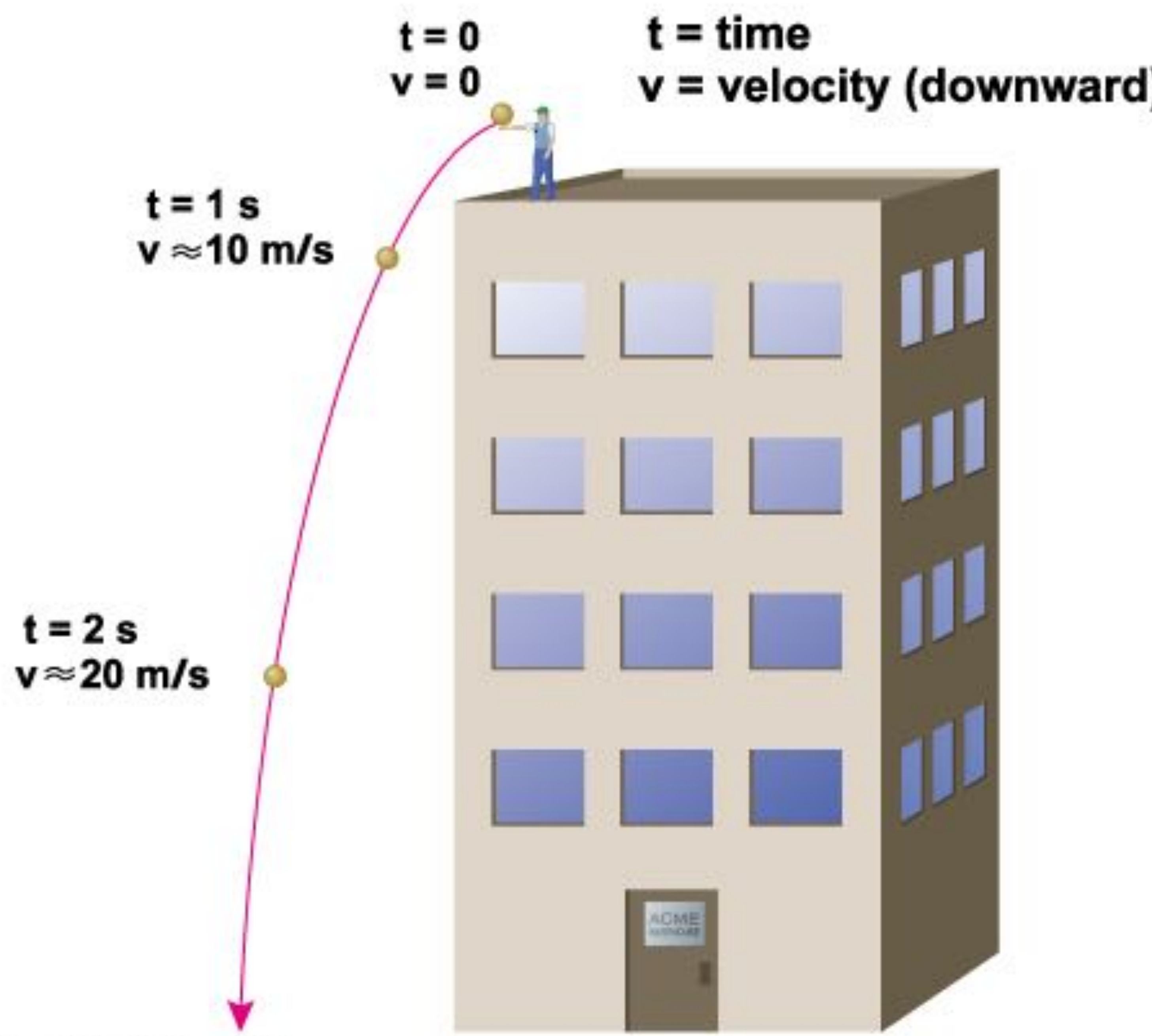
- **Velocity**: Speed and <u>direction</u>
  example: 10 m/s, due east

- **Acceleration**: Rate of change in velocity

$$\text{acceleration} = \frac{\text{speed}}{\text{time}} \quad \left(\text{units of } \frac{\text{m}}{\text{s}^2}\right)$$

Acceleration of Gravity

- All falling objects accelerate at the same rate (neglecting air resistance).
- On Earth, $g \approx 10$ m/s^2: speed increases 10 m/s with each second of falling.



Acceleration of Gravity (*g*)

- Galileo showed that *g* is the *same* for all falling objects, regardless of their mass.

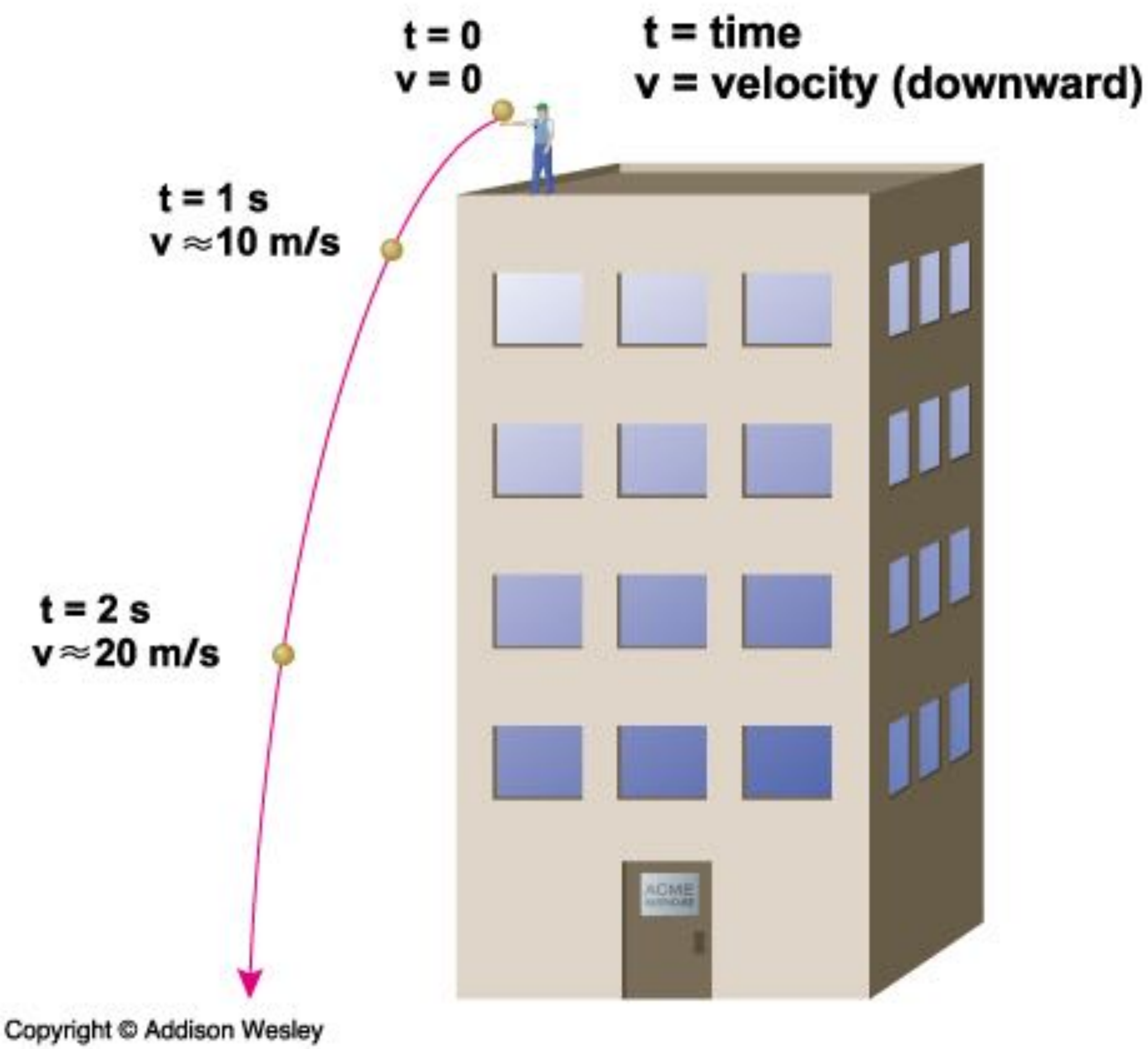
Apollo 15 demonstration

04_featherdrop_sound

also https://www.youtube.com/watch?v=-4_rceVPVSY
in contrast to https://www.youtube.com/watch?v=2OSrvzNW9FE

Vertical & Horizontal motion independent

- All objects accelerate at the same rate, regardless of whether
  - they fall straight down, or
  - are moving horizontally

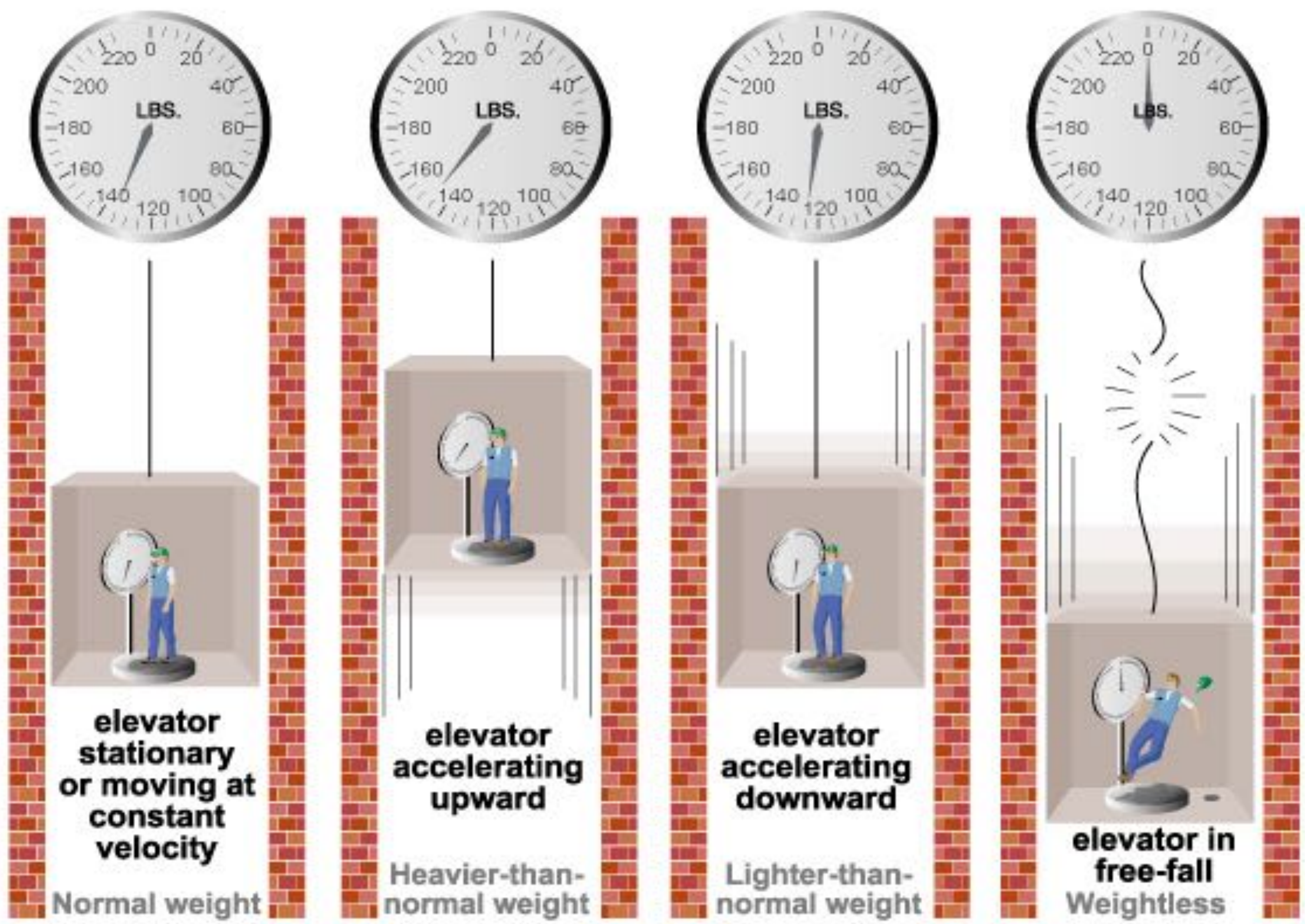


Momentum and Force

- Momentum = mass × velocity.
- A **net force** changes momentum, which generally means an acceleration (change in velocity).
- The rotational momentum of a spinning or orbiting object is known as **angular momentum.**

How is mass different from weight?

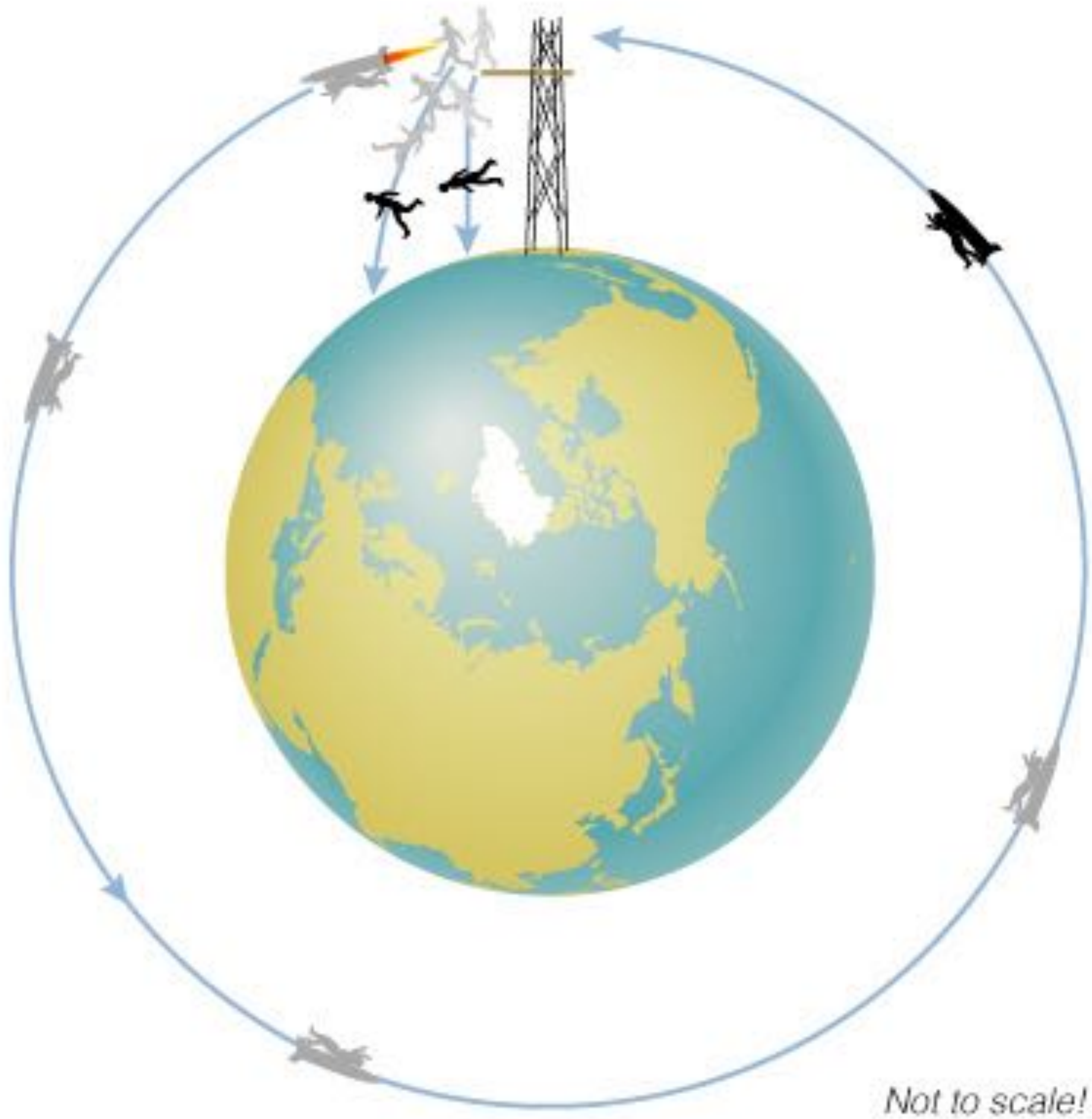
- **Mass**—the amount of matter in an object
- **Weight**—the *force* that acts upon an object



You are weightless in free-fall!

04_01ApparentWeight.swf

Why are astronauts weightless in space?



- There *is* gravity in space.
- Weightlessness is due to a constant state of free-fall.

What have we learned?

- How do we describe motion?
  - Speed = distance / time
  - Speed and direction => **velocity**
  - Change in velocity => **acceleration**
  - **Momentum** = mass × velocity
  - **Force** causes change in momentum, producing acceleration

What have we learned?

- How is mass different from weight?
  - Mass = quantity of matter
  - Weight = force acting on mass
  - Objects are weightless in free-fall