What are the key quantities of astronomy and how do we measure them?

• Distance/Size	**Lecture 2**
• Angular Size	**Lecture 2**
• Time	**Lecture 2**
• Speed/Velocity	
• Mass	
• Flux	

However, distances within the Solar System get awkward with km

- The planets are much smaller than the distances between them
- Distance from the Sun to the Earth:

  $$d = 150{,}000{,}000 \text{ km} = 1.5 \times 10^8 \text{ km}$$

- So one approach is to use scientific notation
- Here is a case where we make up a new unit to deal with all of those zeros:

  1 AU = Sun-Earth distance = 1.5×10^8 km

The astronomical unit was originally conceived as the average of Earth's aphelion and perihelion
$1.49597870700 \times 10^8$ km

Kepler’s Laws, Newton’s Laws, and Gravity

Understanding why the planets orbit around the Sun the way that they do

Chapters 3.3-3.5, 4.1-4.2, 4.4

Vocabulary for motions

- Speed

  - How fast something is moving regardless of direction

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Vocabulary for motions

- Speed
  - How fast something is moving regardless of direction
- Velocity
  - A speed plus a direction
- Acceleration
  - A change in velocity (i.e., a change in speed or direction, or both)
- Orbit
  - The path through space that one object takes as it moves around another object

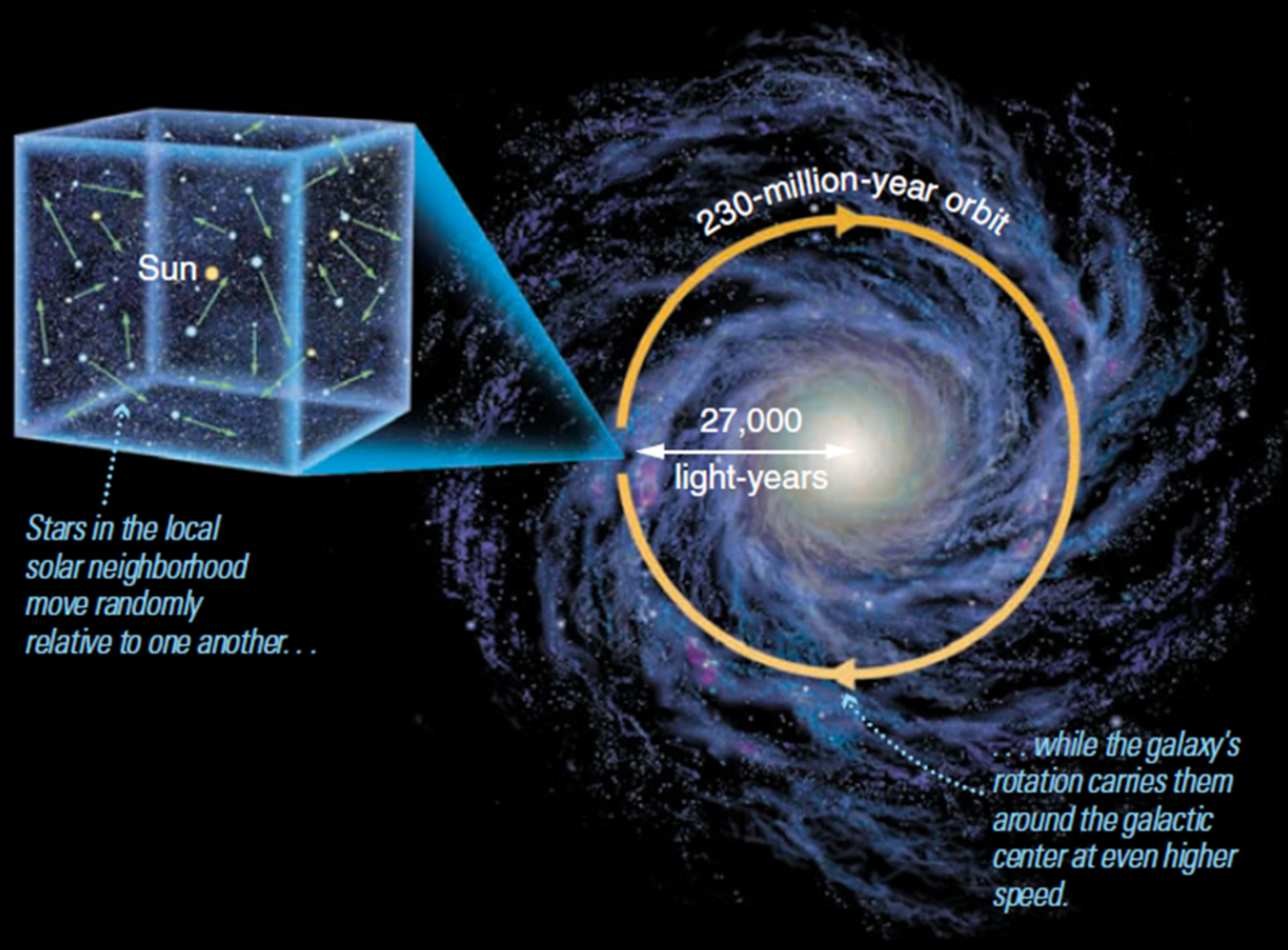
Units for speeds and velocities

- In astronomy, we use metric units
- Kilometers per second (km/s)
- Or, meters per second (m/s)
- 1 km/s = 2250 mph!

For more on the metric system, see appendix C.4 in your textbook

Speeds

- Planets around a star
  ~10 km/s or
  ~22,500 miles/hr!
- Stars relative to the center of the galaxy
  ~200 km/s



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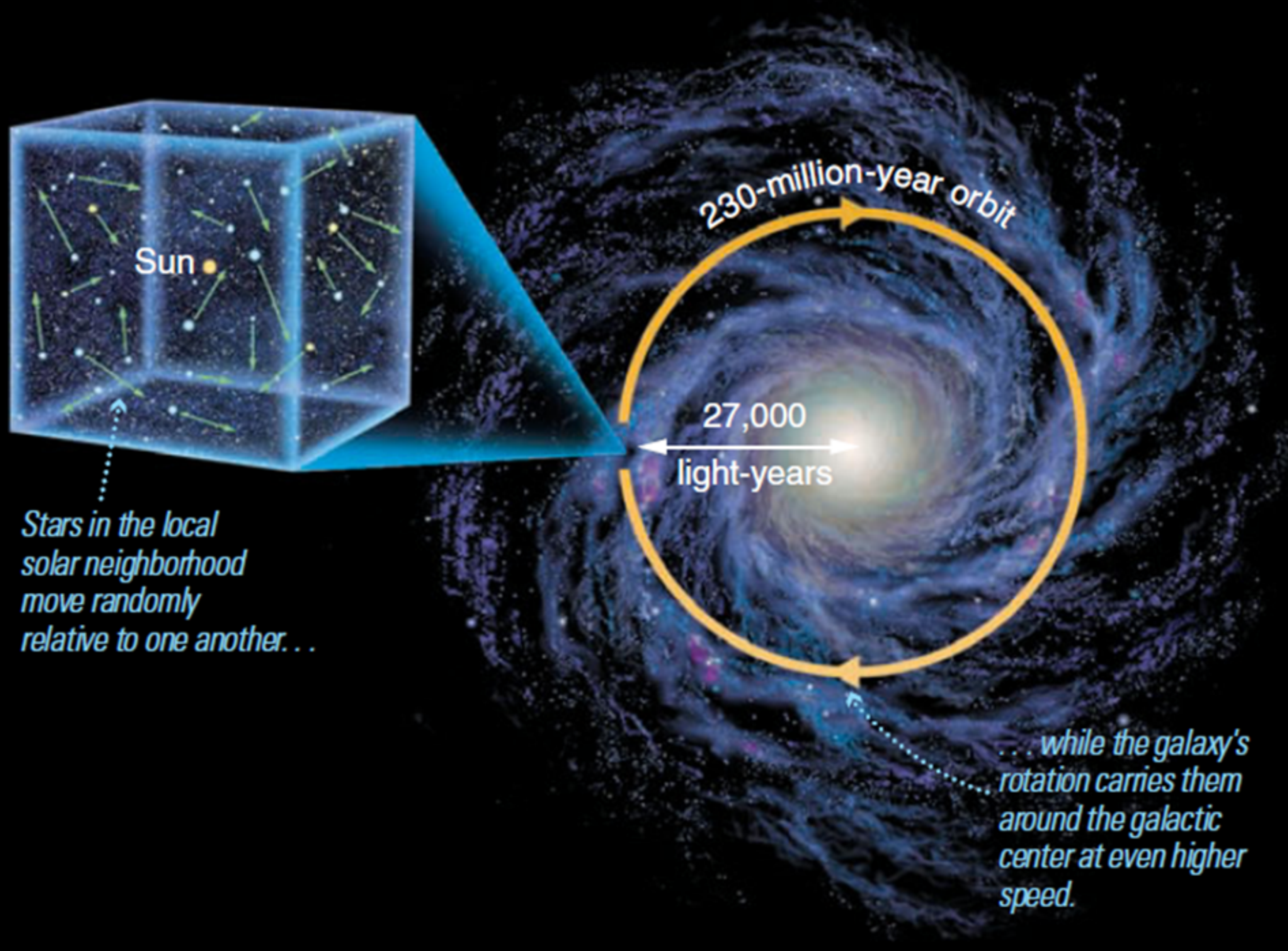
Speeds

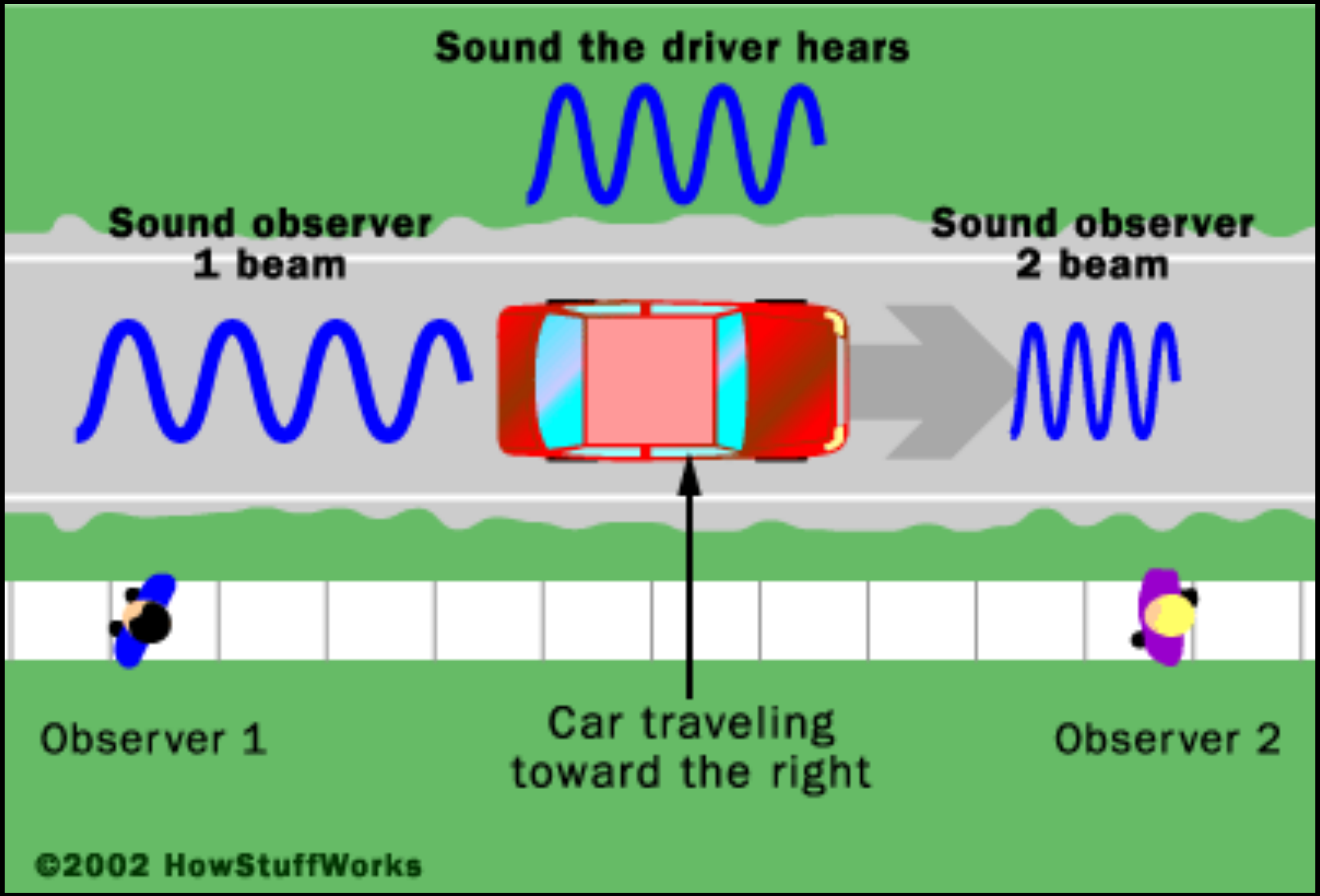


1 km/s = 2250 mph

- Planets around a star ~10 km/s or ~22,500 miles/hr!
- Stars relative to the center of the galaxy ~200 km/s
- Galaxies relative to other galaxies hundreds to ~1000 km/s
- Speed of light 3×10^5 km/s

How do we measure speeds?

- We use the Doppler shift of light
- We'll discuss this when we discuss spectroscopy in a few lectures.



The same process works for light.
Higher frequency (blue) means that the object is moving toward you.

Lower frequency (red) means that it is moving away

$$v = c\,(\lambda - \lambda_0) / \lambda_0$$

To understand motions, we also need to discuss mass

This woman has a weight (on Earth) of about 120 lbs

... or a mass of about 54 kg.

In astronomy, one of the typical units of mass is the kilogram (kg)

Mass vs Weight

Mass – a measure of the amount of matter in an object

Weight – the *force* that a scale measure exerts upon an object

Mass vs Weight

Mass – a measure of the amount of matter in an object

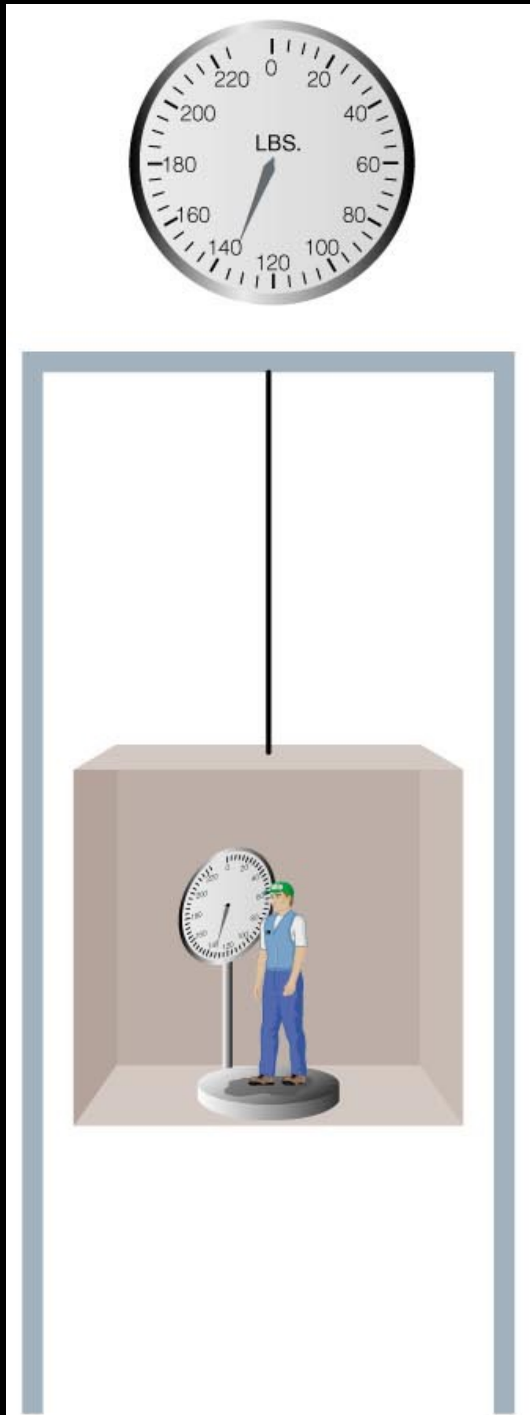
Weight – the *force* that a scale measure exerts upon an object

For example

Your mass – the amount of mass in your body

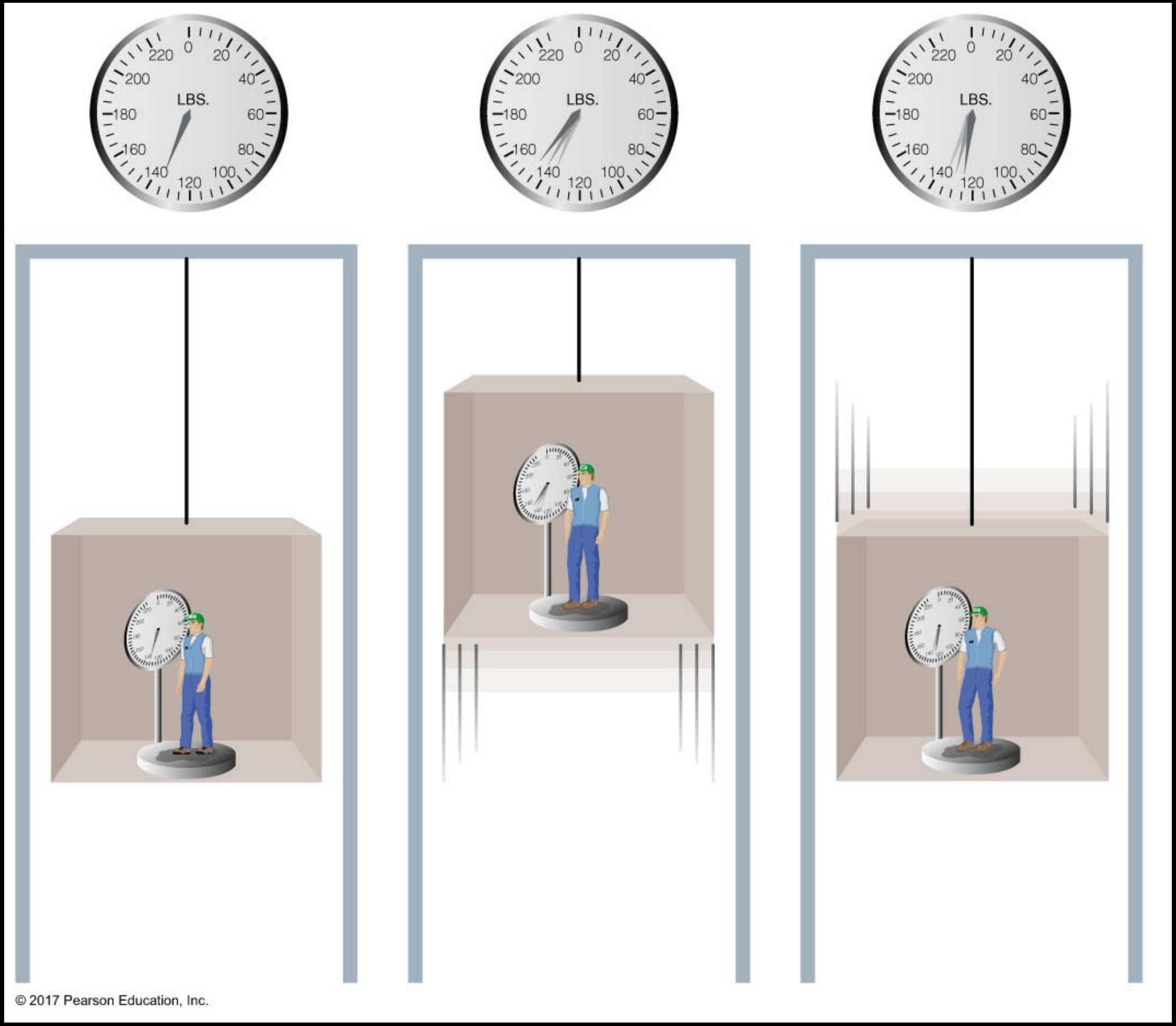
Your Weight – the *force* that a scale measure when you stand on it

Mass vs Weight



What is your mass in an elevator ?
What is your weight?

Mass vs Weight



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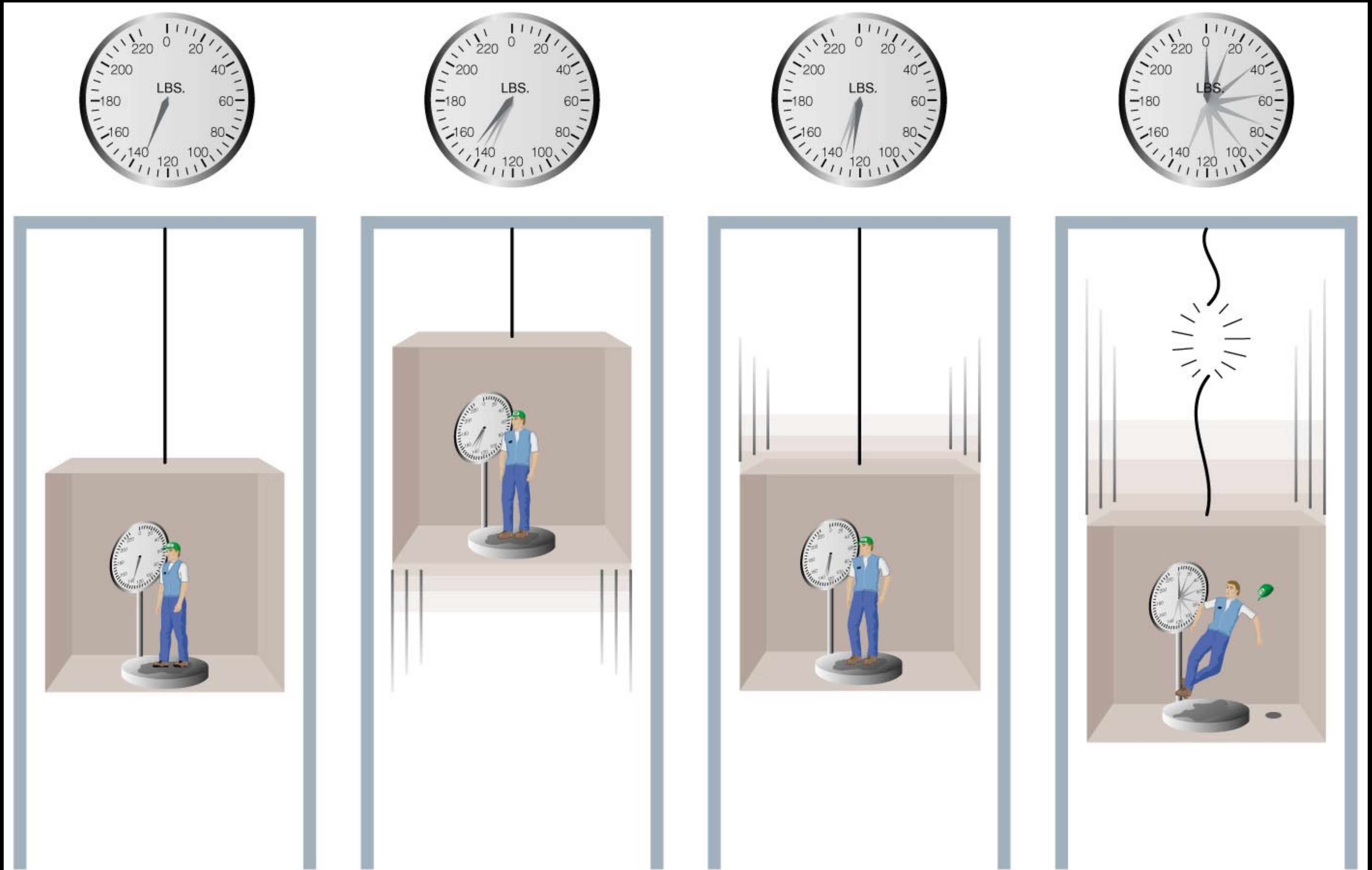
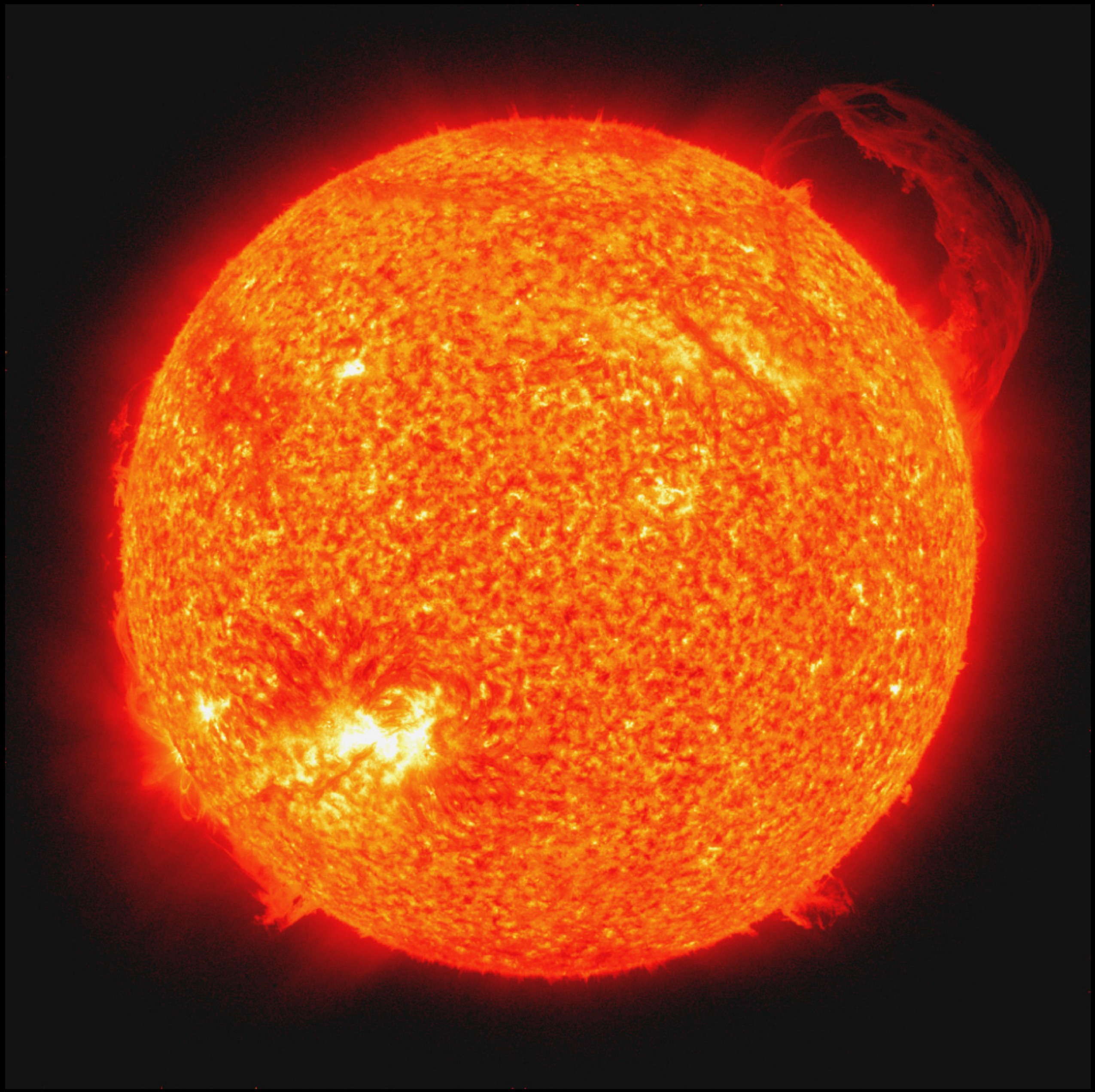


What is your mass in an elevator ?
What is your weight?

But what is mass?

- The amount of matter in an object
- Equivalently, mass is a measurement of how hard it is to move something
- Huh? See discussion of Newton's Laws coming up

Mass -- STARS



This star, our Sun, has a mass of about

2,000,000,000,000,000,000,000,000,000,000

kilograms

That's a lot of zeros, so instead, we'll make a new unit called the **SOLAR MASS**.

$$\boxed{1M_\odot = 1 \text{ Solar Mass} = 2 \times 10^{30} \text{ kg}}$$

How do we measure mass?

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- We look at the speed of small things orbiting around the object that we want to study

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- We look at the speed of small things orbiting around the object that we want to study
  - Satellites around the Earth
  - Planets around a star
  - Gas around a star
  - Stars within a galaxy
  - Galaxies within a cluster
- To understand how this works, we need some more tools.

Understanding motions in the Universe

The first question: How do astronomical objects (planets, stars, gas, etc.) move?

Understanding motions in the Universe

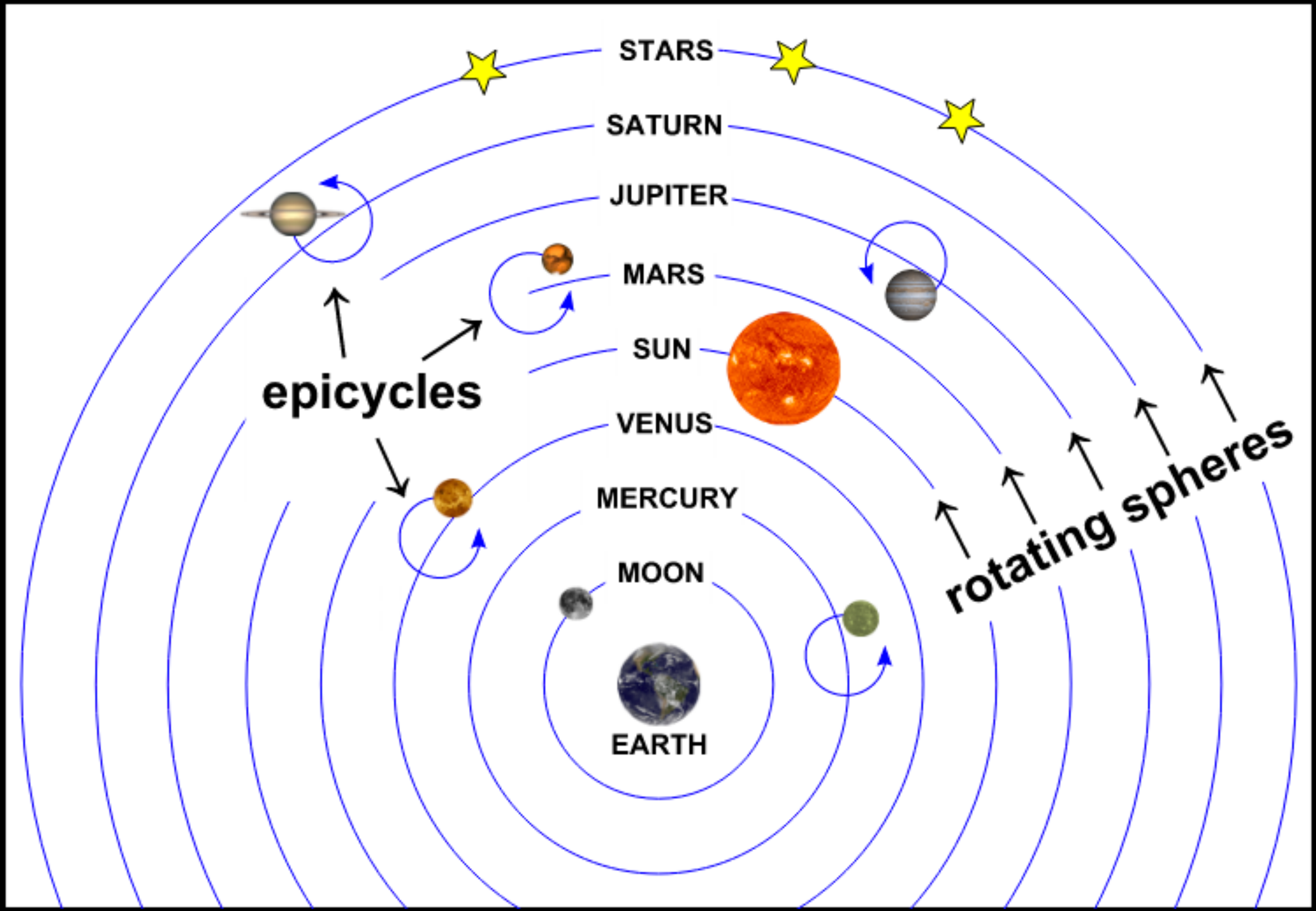
The first question: How do astronomical objects (planets, stars, gas, etc.) move?

The next question: Why do they move the way they do?

– This is where the physics really comes in

Ptolemaic model

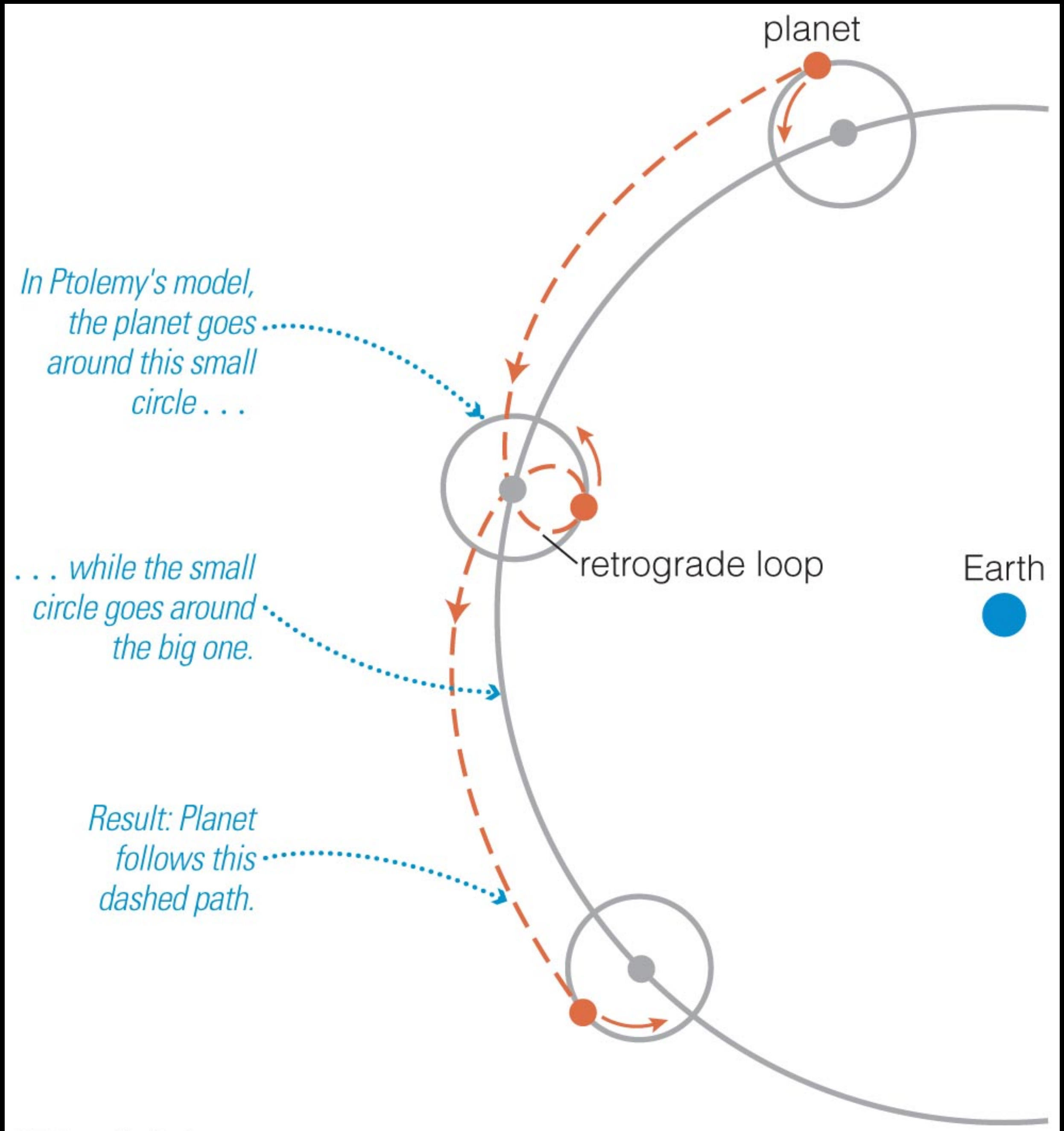
The most sophisticated geocentric model was that of Ptolemy (A.D. 100–170)



Sufficiently accurate to remain in use for 1,500 years.

Ptolemaic model

Retrograde motion of Mars



We will see this in the next slides

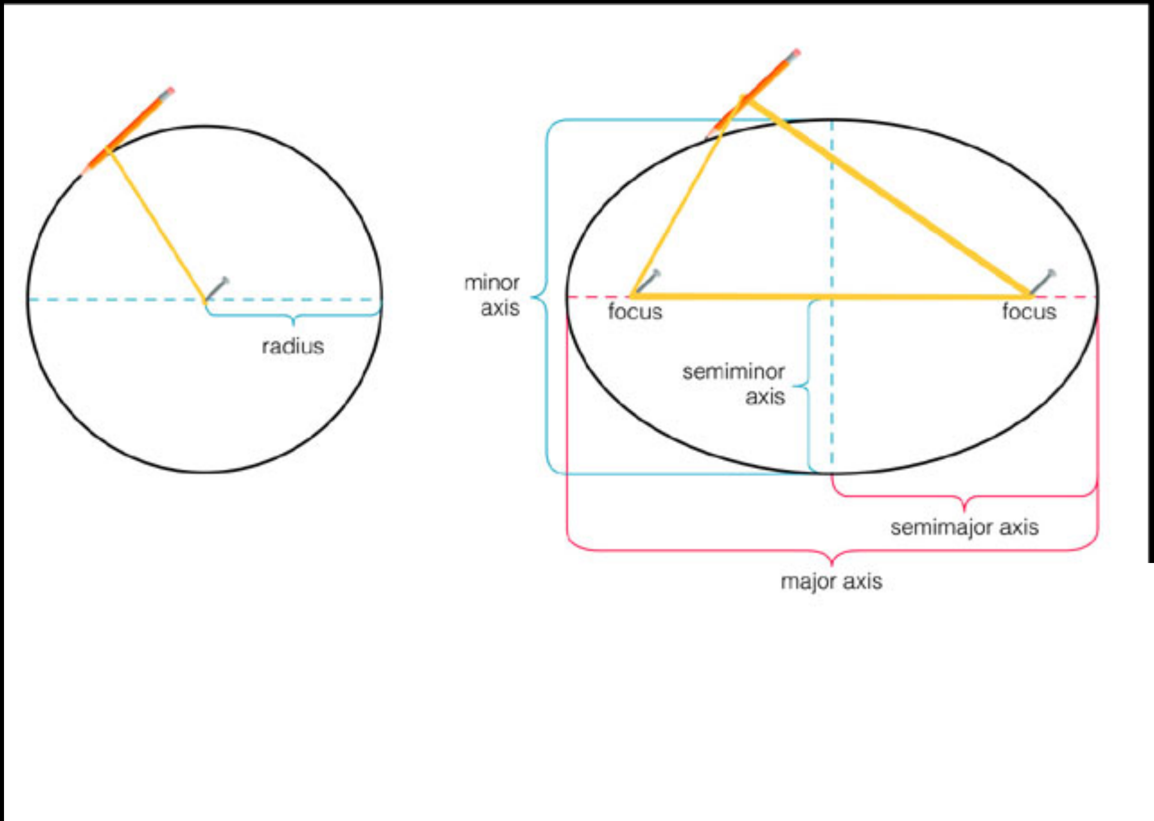
An example of how things move: Kepler's Laws

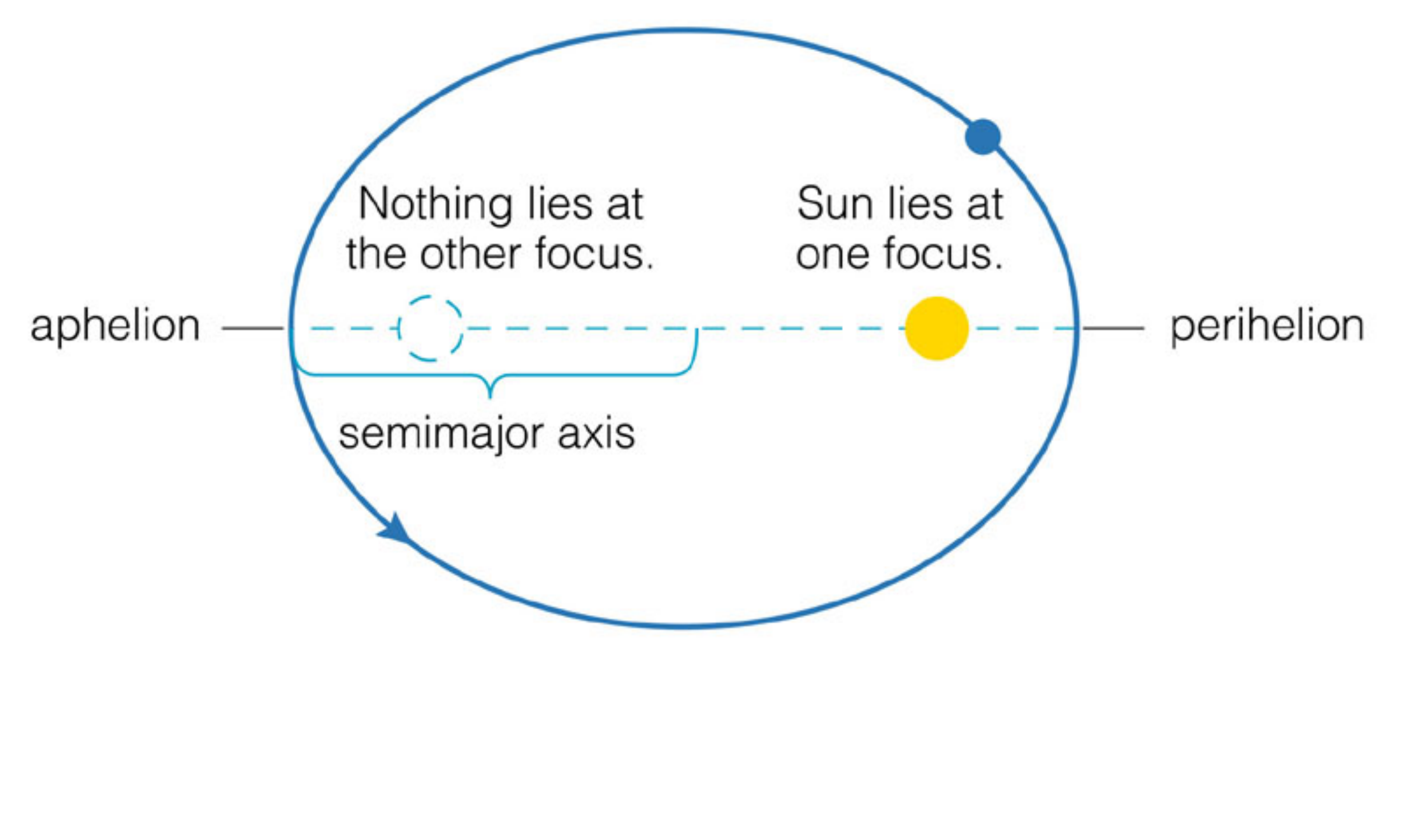
Copernicus, Tycho, Kepler and Galileo challenge the Earth-centered model

- Lots of very careful observations of motions of the planets in the Solar system
- Results brought together by Kepler in 3 laws of planetary motion

Kepler's first law

- Orbits are ellipses with Sun at one focus

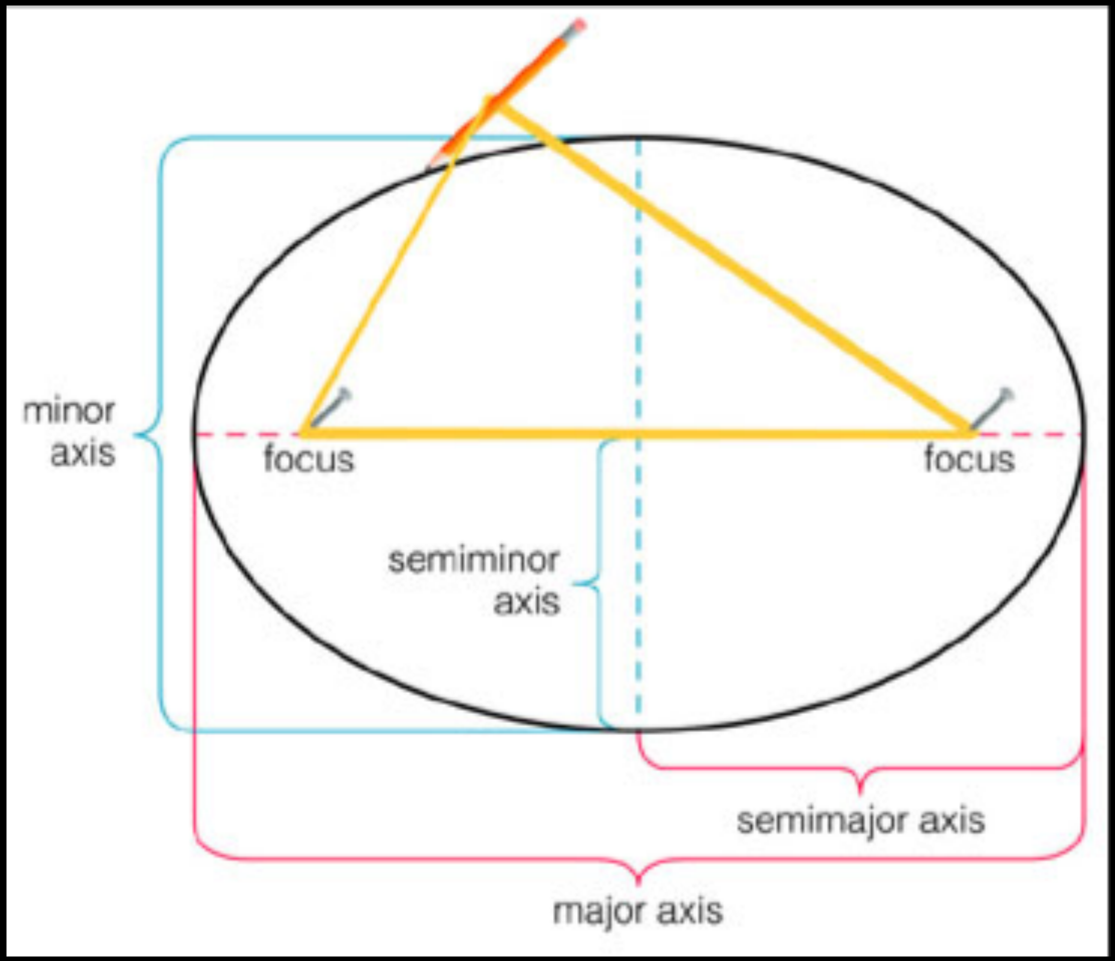




Describing ellipses

An ellipse has a center and two foci (focuses)

- Major axis: the long axis
  – the axis that goes through the center and the foci
- Minor axis: the short axis
  – perpendicular to the major axis
- Semimajor axis (a): 1/2 the length of major axis
- Semiminor axis (b): 1/2 the length of minor axis
- How "squished" is an ellipse?
  – Look at axis ratio (b/a)
  – What is the axis ratio of a circle?
  – Alternatively, look at eccentricity

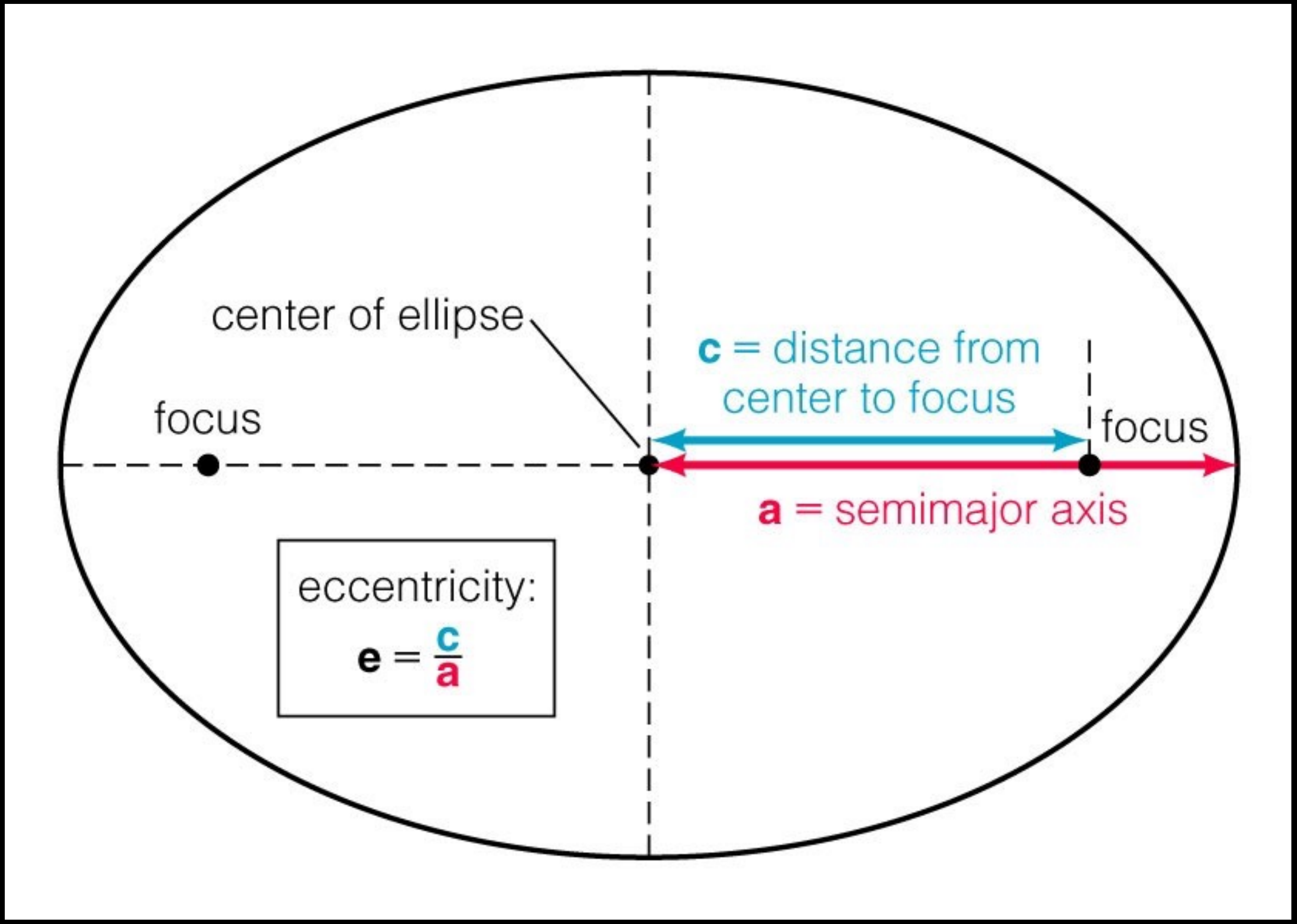


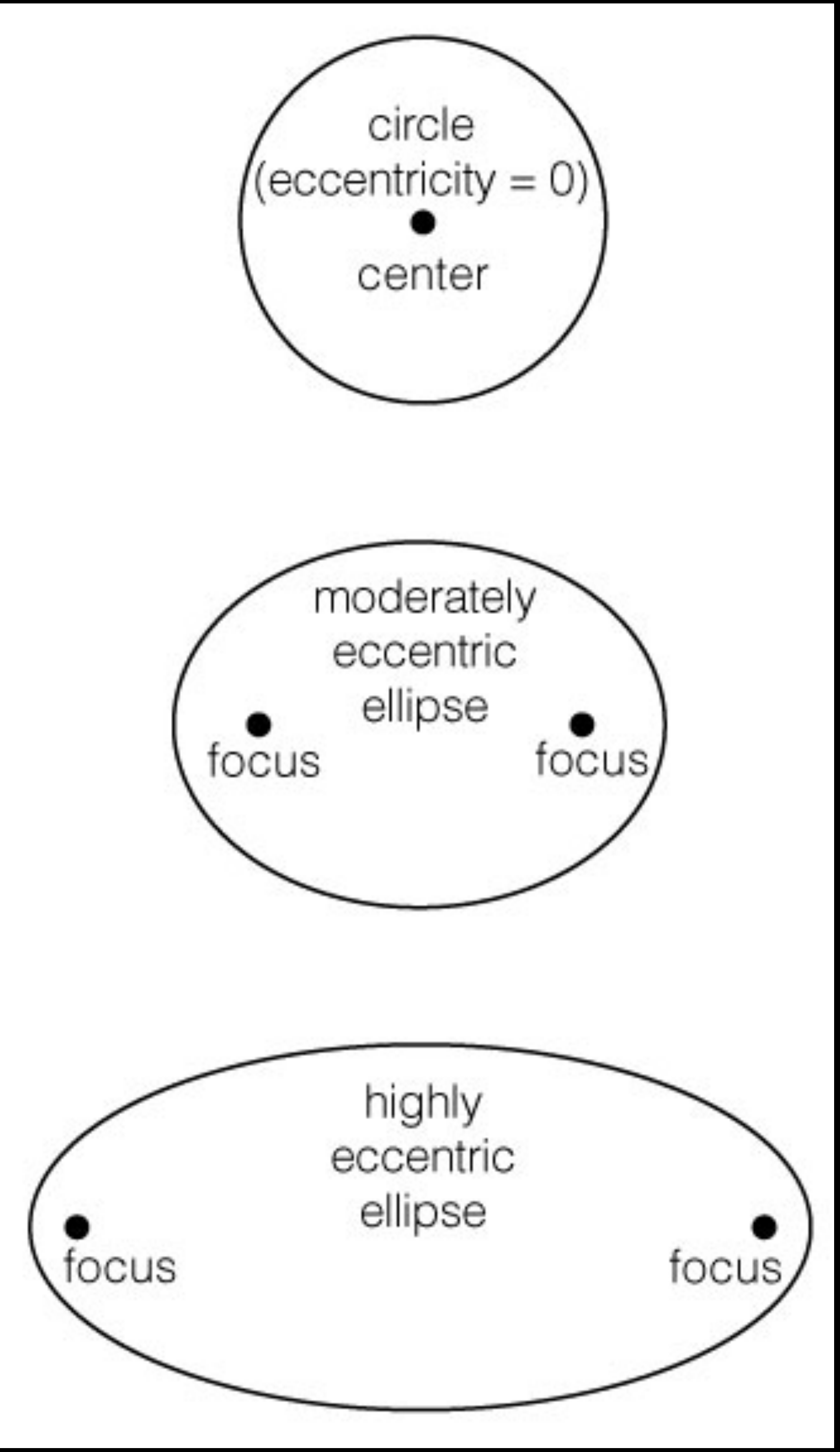
Eccentricity

Eccentricity is defined as e=c/a, where c is the distance between the center and one of the foci.

– A circle has e=0

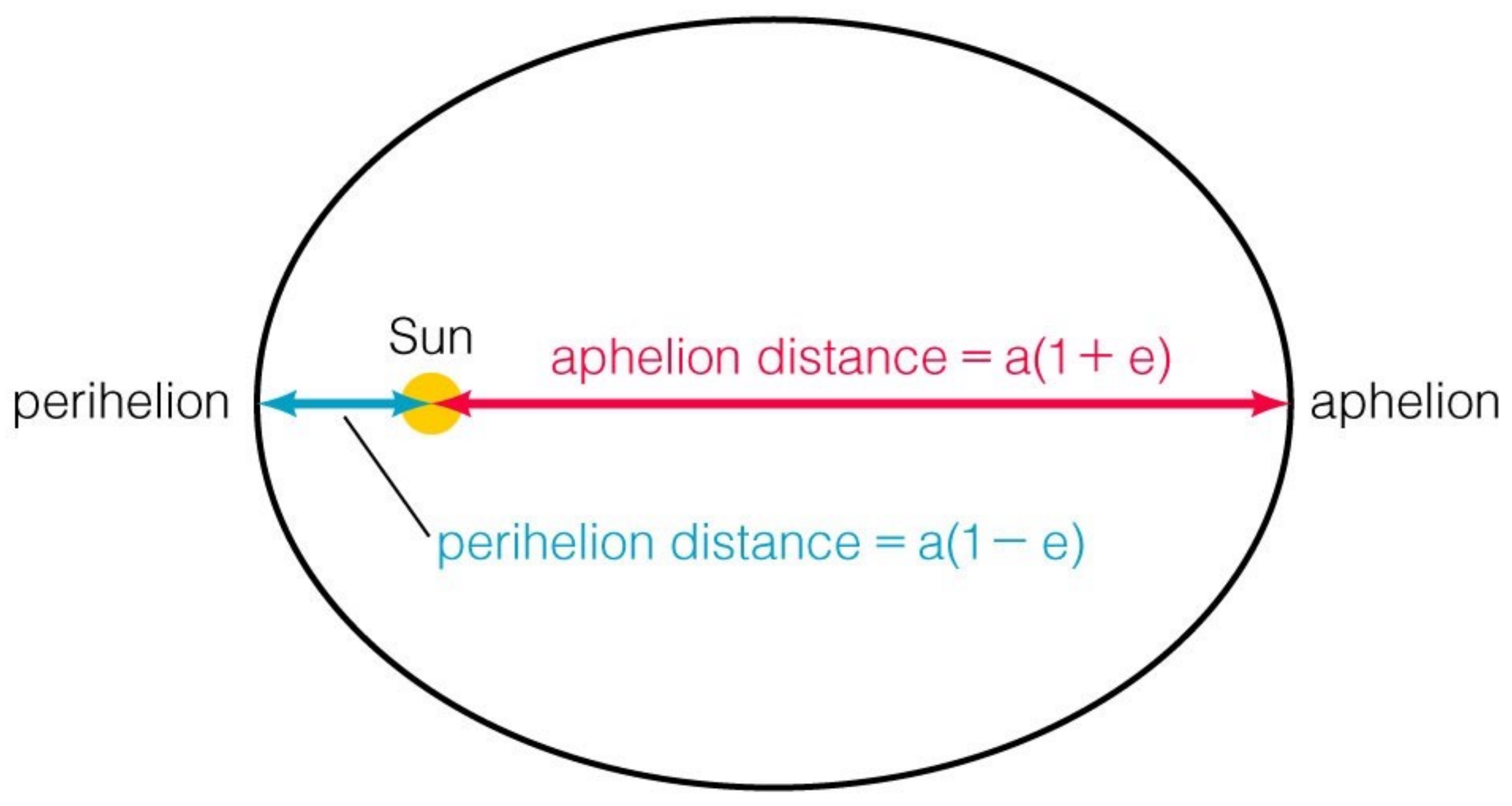
– Earth's orbit has e=0.017





Perhelion and aphelion

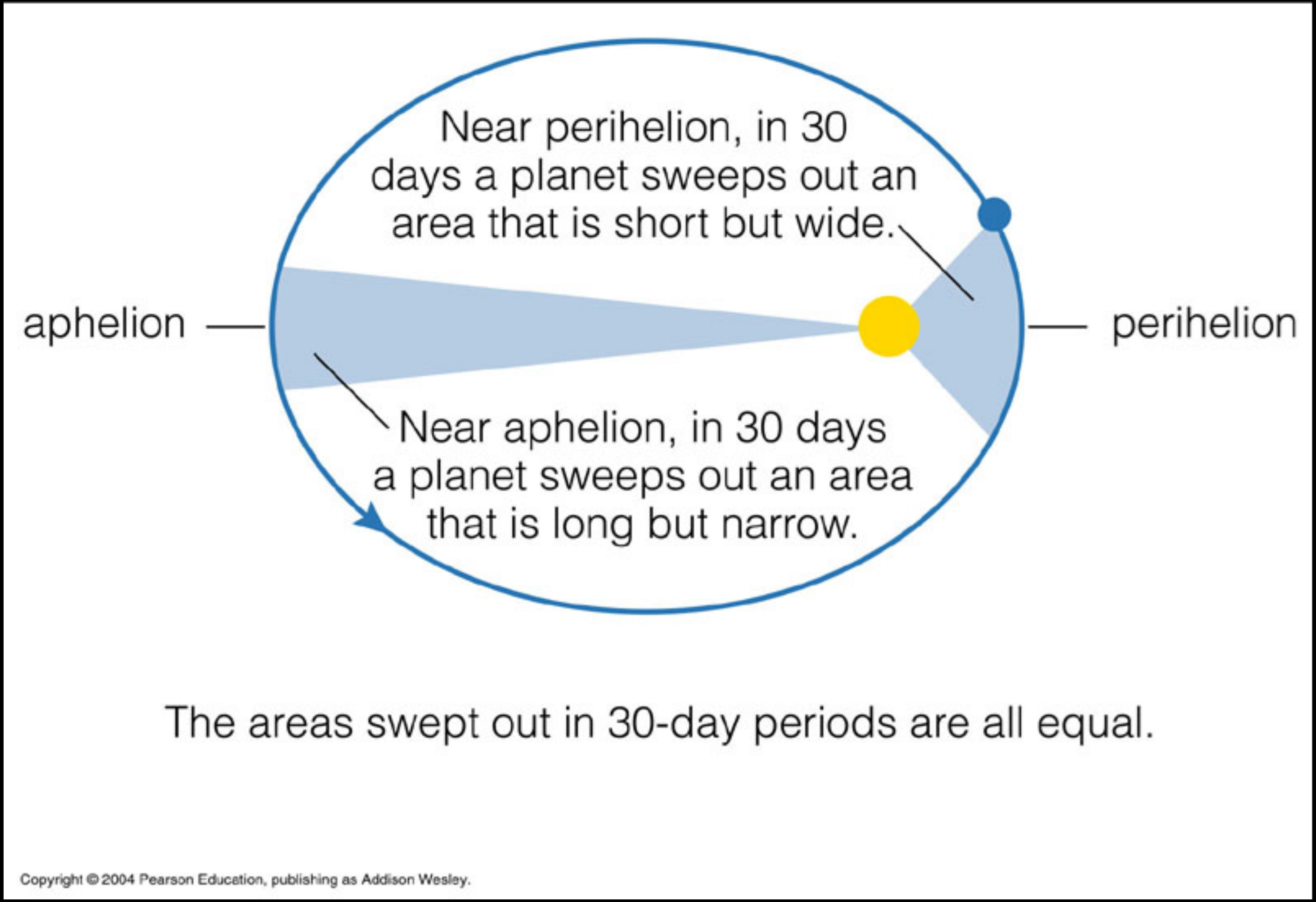
- Perihelion: Closest approach to the Sun
- Aphelion: Farthest point of the orbit
- You can calculate the perihelion and aphelion distances from the semimajor axis length and the eccentricity



Kepler's second law

Equal areas in equal times

– (planets move faster when they are closer to the Sun)



Toward Kepler's third law

- Use careful measurements of:
  - The semimajor axes (a) of the planets' orbits
  - The period (P) of the planets' orbits

    Period = time it takes to go around the Sun once

Toward Kepler's third law

- Use careful measurements of:
  - The semimajor axes (a) of the planets' orbits
  - The period (P) of the planets' orbits

    Period = time it takes to go around the Sun once
- Plot these quantities versus each other

  Measure semimajor axes in astronomical units (AU)

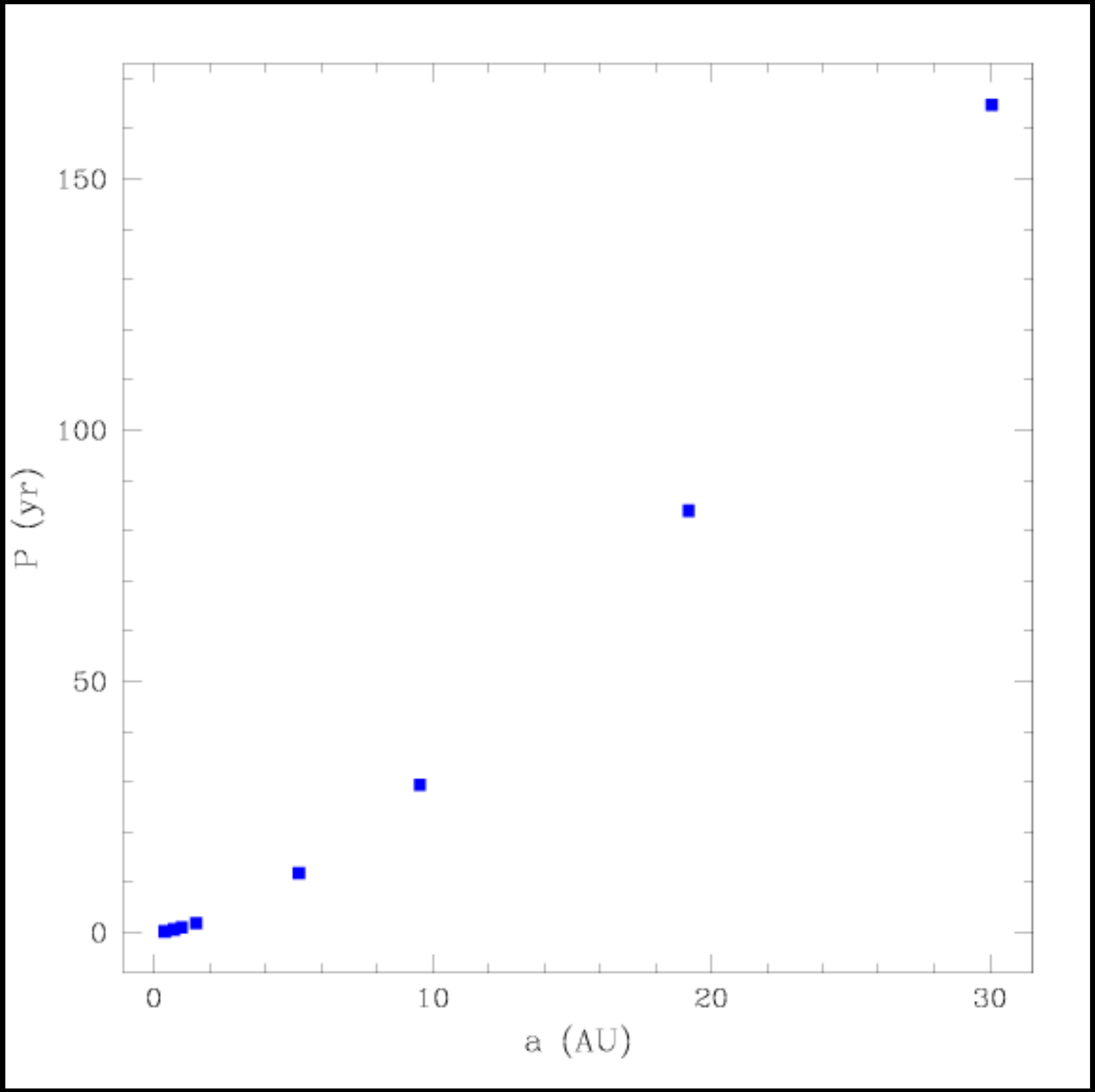
  1 AU = distance between the Earth and Sun

  Measure period in years

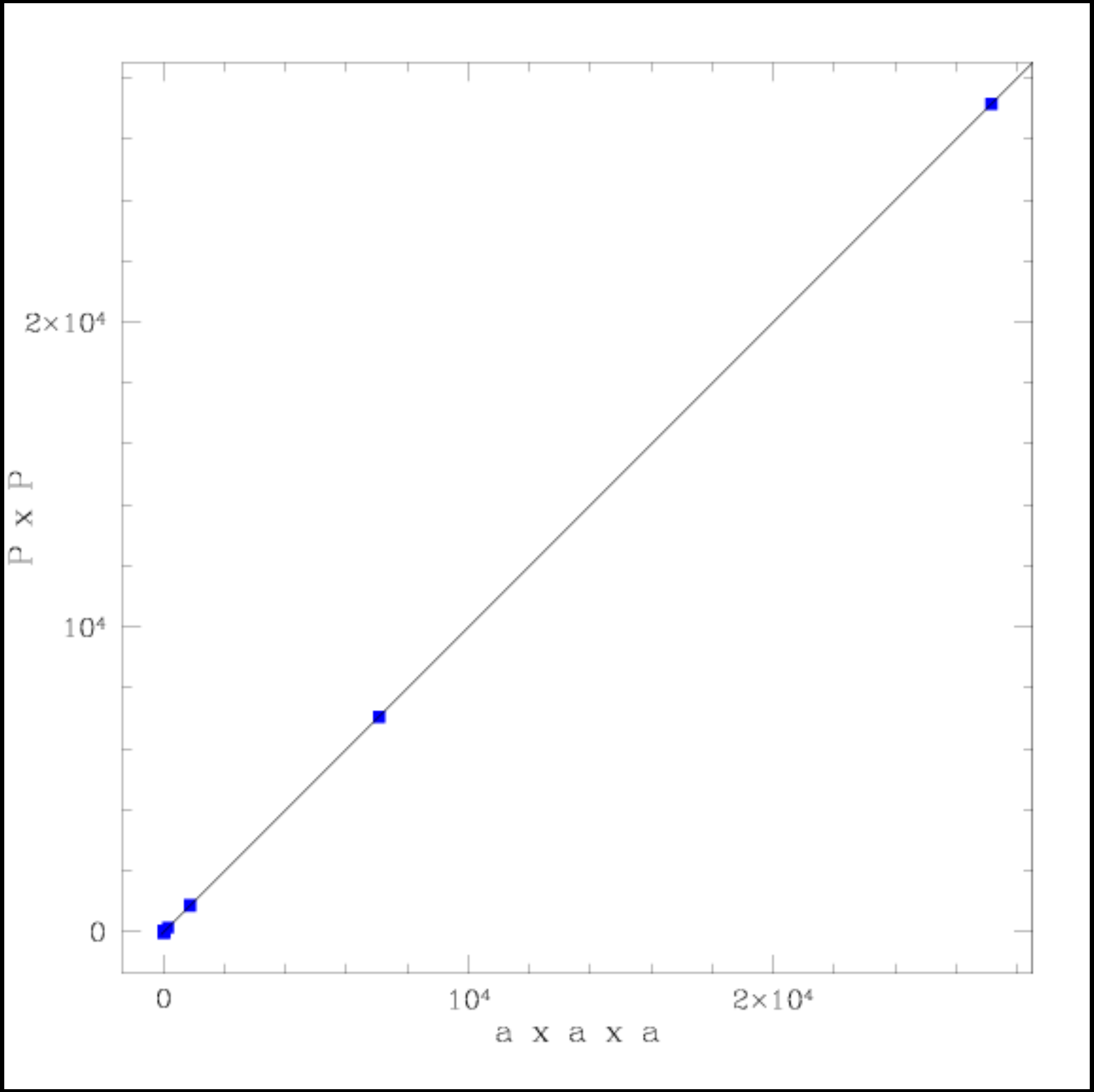
Toward Kepler's third law

Planet	distance	Period
	(A.U.)	
Mercury	0.387	87.969 d
Venus	0.723	224.701 d
Earth	1.000	365.256 d
Mars	1.524	686.98 d
Jupiter	5.203	11.862 y
Saturn	9.537	29.457 y
Uranus	19.191	84.011 y
Neptune	30.069	164.79 y

Toward Kepler's third law



Toward Kepler's third law



Toward Kepler's third law

- A clear relation between semimajor axis of ellipse (a) and the period of the orbit (P)

$$\boxed{P^2 = a^3}$$

P measured in years

a measured in AU

– Period: time it takes planet to go around once

– This relationship could be defined even without knowing what the actual distances were

- use ratios instead
- defined a new unit: the Astronomical Unit (AU)
- 1 AU = distance between the Sun and the Earth

– This law leads to an understanding of what causes the planets to move - more later…

Why do objects move the way that they do?

Why do objects move the way that they do?

- The answer is that objects move in response to the forces acting on them

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- The answer is that objects move in response to the forces acting on them
- In astronomy that force is usually due to GRAVITY

Why do objects move the way that they do?

1. Newton's Laws and Gravity

Talk about FORCES we must!

In terms of physics, a force is a push or a pull that affects the motion of an object.

Newton's laws relate forces and the resulting motions, in terms of accelerations (changes of speed or direction)

Newton's 1st Law

- Nature is lazy

Newton’s 1st Law

- Nature is lazy
- Or, with better phrasing:

“An object at rest tends to stay at rest”
And
“An object in motion keeps the same speed and direction”

UNLESS A NET FORCE ACTS UPON IT

- “Net force” means that the forces on the object do not cancel out
- In other words: no net force means no acceleration

FORCES

speed changes
or
direction changes

→ There must be a net force acting on the object

Both speed and direction are constant

→ All the forces are in balance

Newton's 2nd Law of Motion:

If you apply a net force to an object, the amount of acceleration is directly proportional to the size of the force

Force = mass X **acceleration**

Or in shorthand

F = m a

F=ma –or– a=F/m

Massive things are harder to accelerate

A Thought Experiment

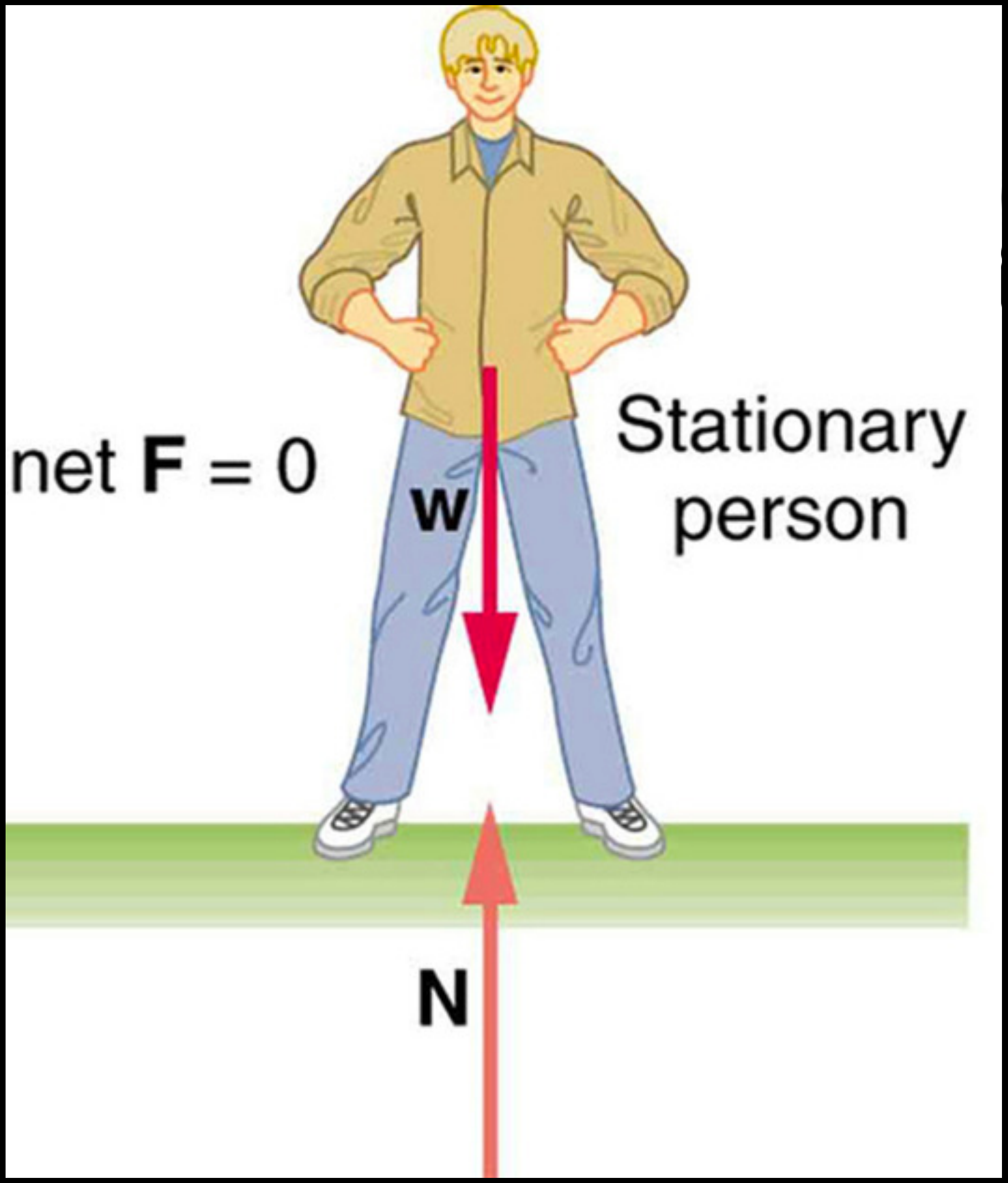
What are the forces acting on:

- Me?

A Thought Experiment

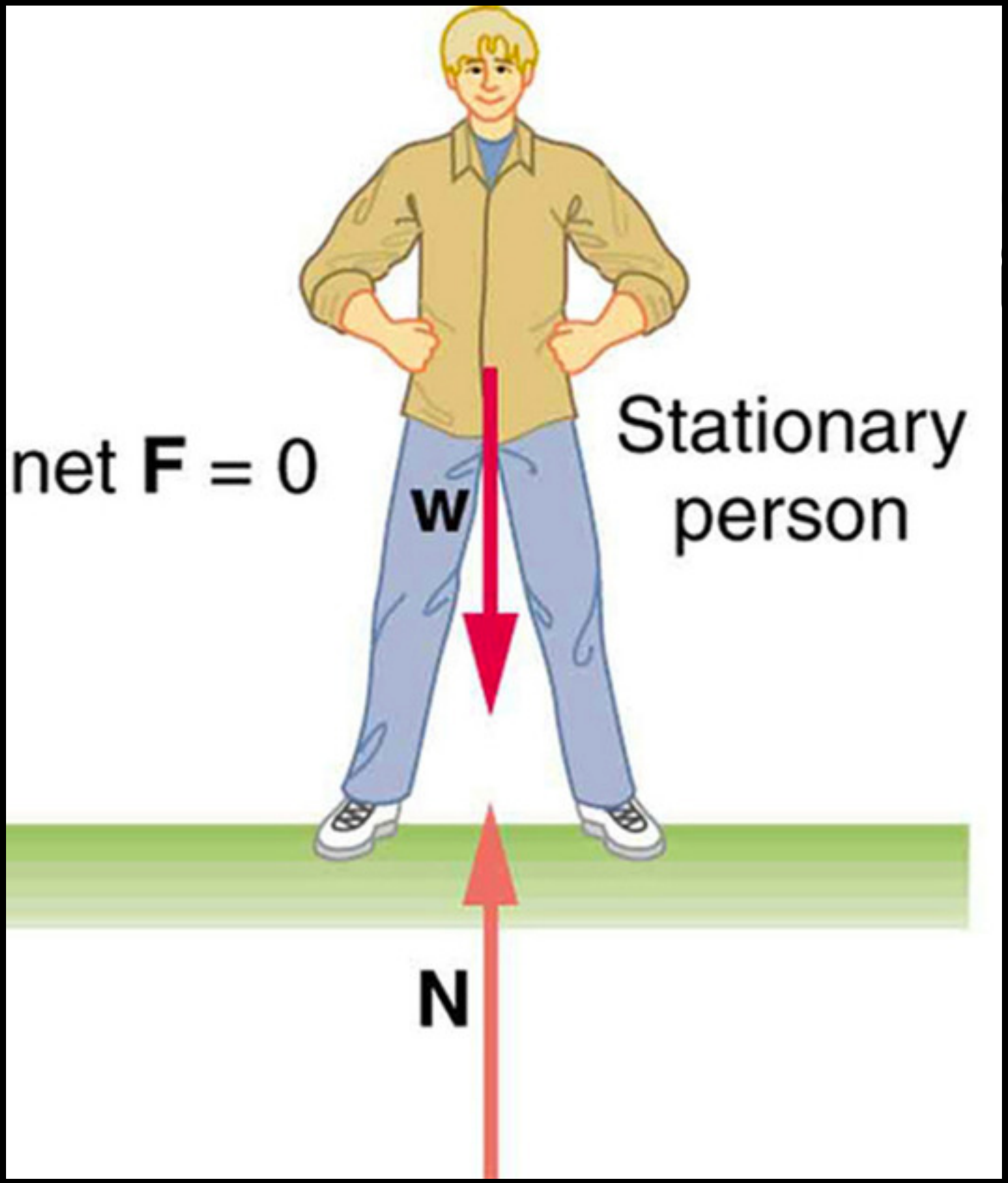
What are the forces acting on:

- Me?



Newton's 3rd:

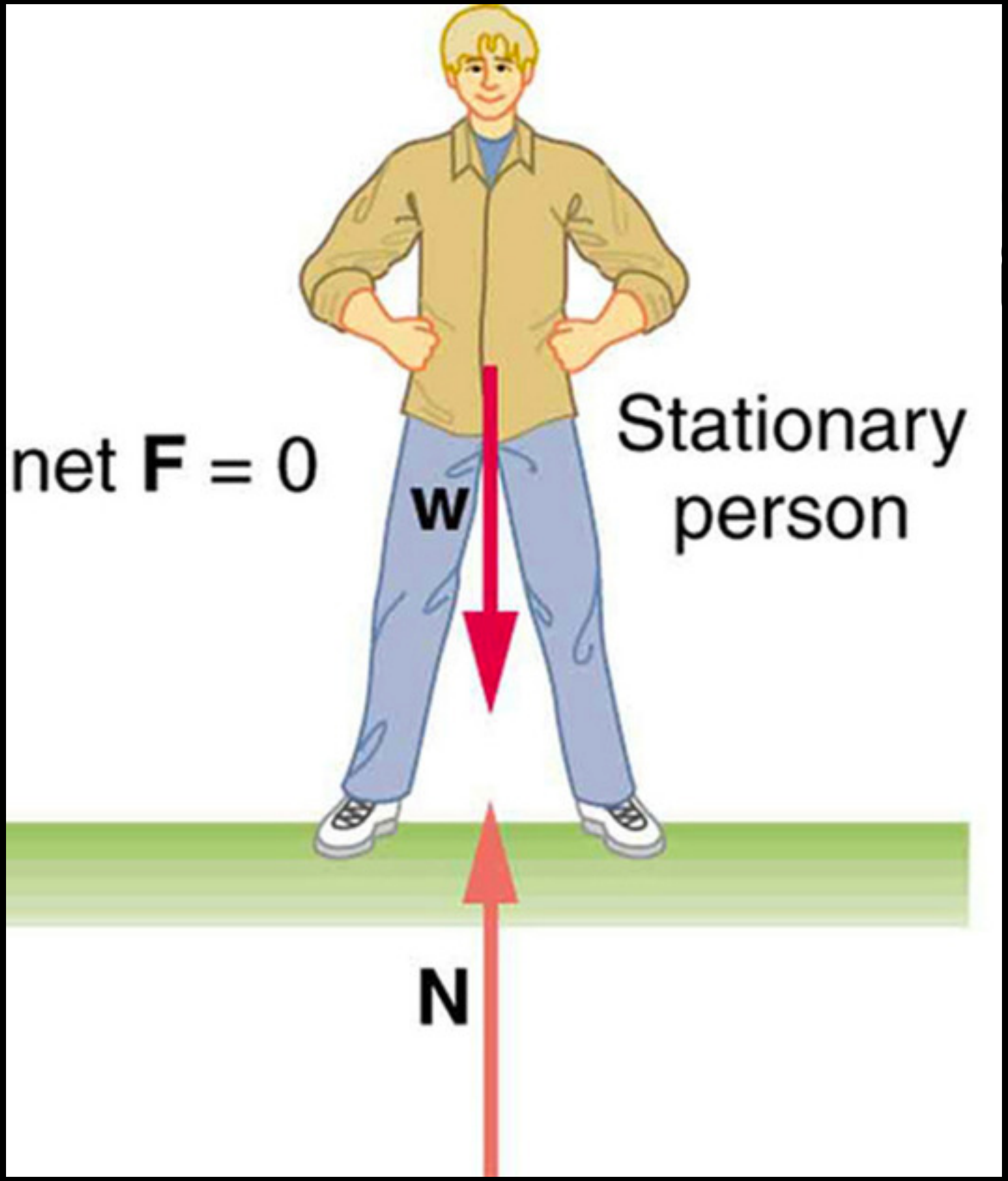
For any force there is always an equal and opposite reaction force.



Newton's 3rd:

For any force there is always an equal and opposite reaction force.

Example: A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.

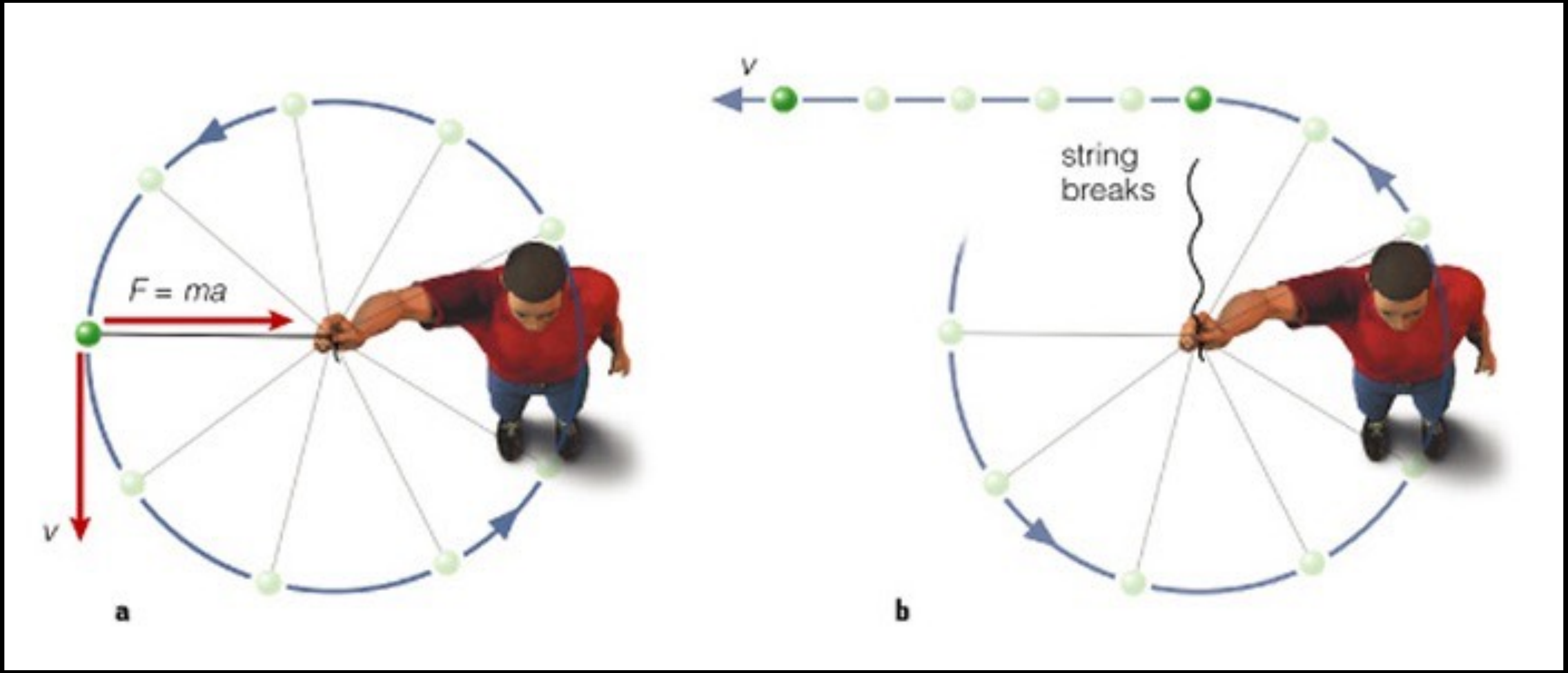


A Thought Experiment

What are the forces acting on:

- Me?
- A ball on a string, swung in a circle?

There are "central forces" acting on objects moving in circles (or other curved paths)

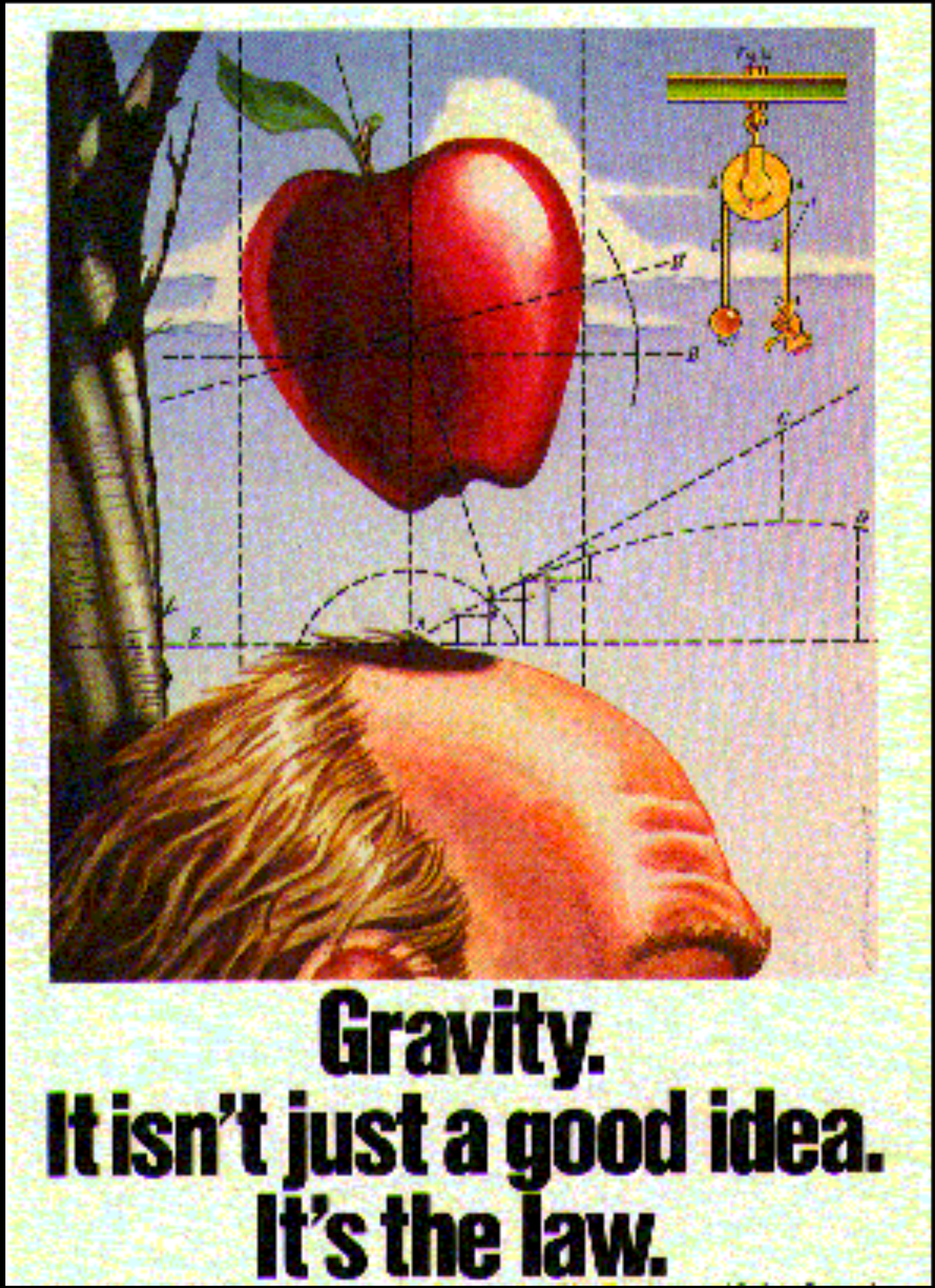


Many things in astronomy travel on approximately circular paths

- Moons around planets
- Planets around stars
- Stars around the center of galaxies

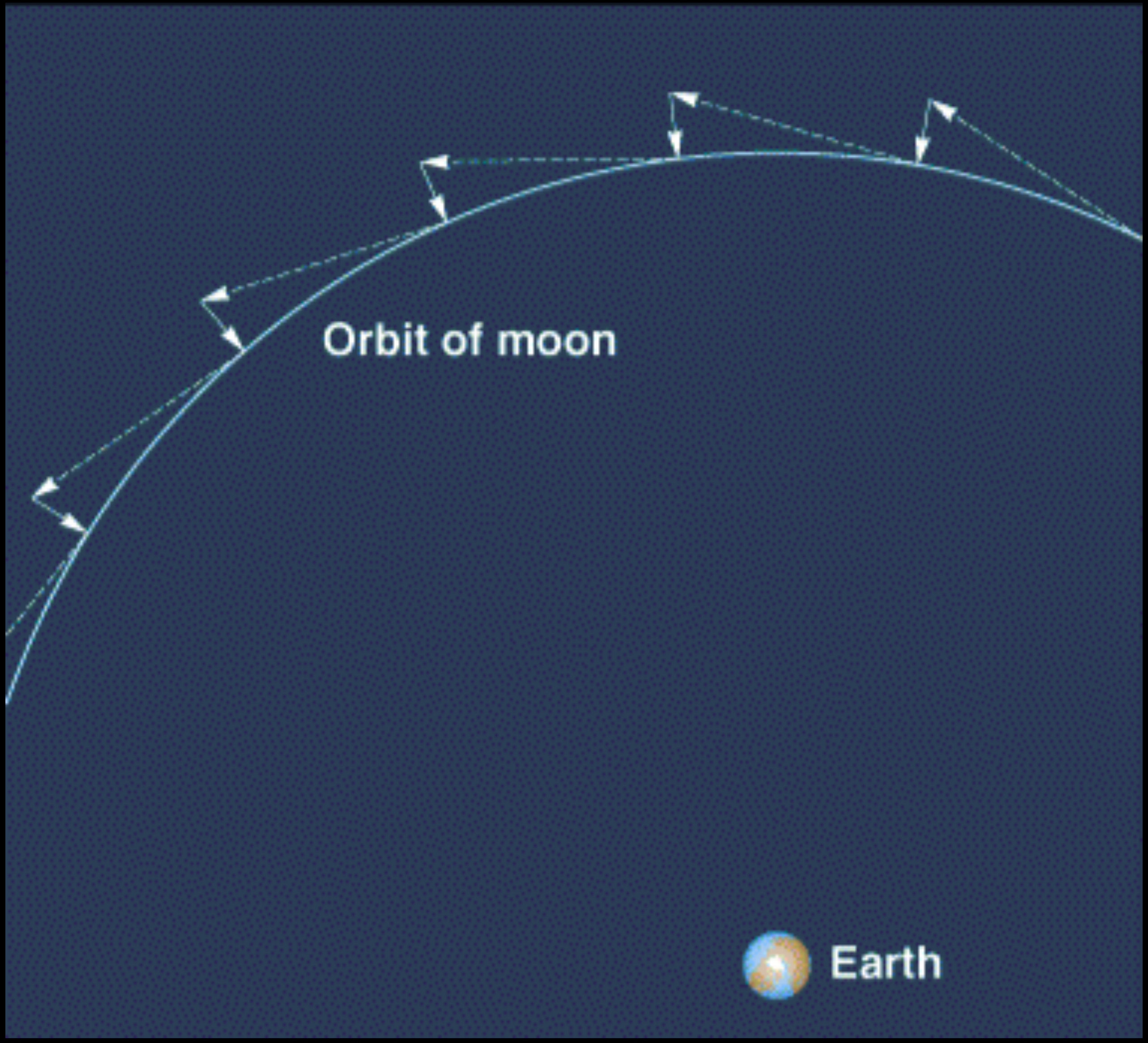
- A change of direction means an acceleration means that a net force is being applied

Elliptical orbits imply that there is some central force keeping the moon/ planet/star from going in a straight line



GRAVITY

Why does gravity lead to roughly circular orbits?



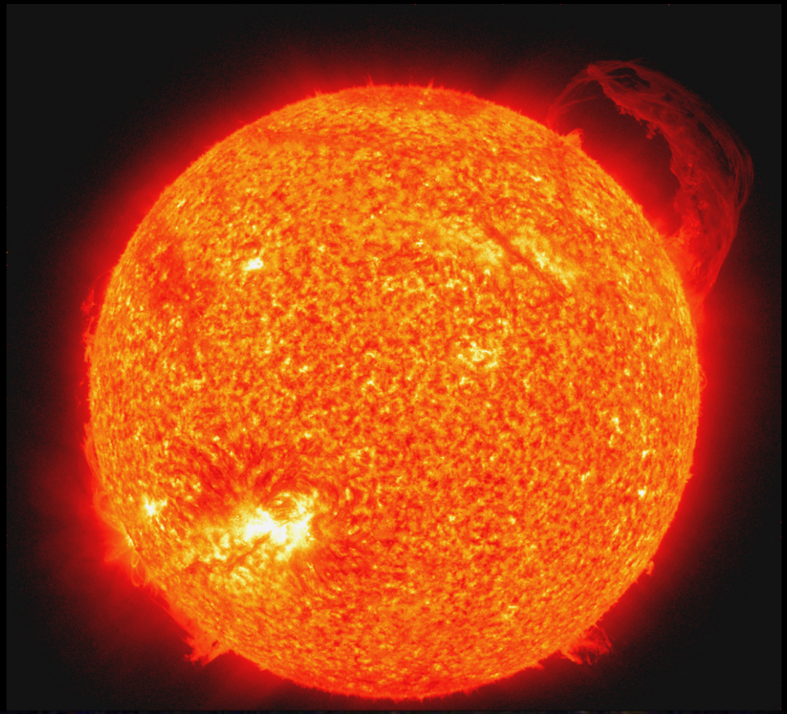
The Moon tries to travel in a straight path (Newton's 1st Law), but the gravitational pull of the Earth keeps tugging it back onto a circular path (Newton's 2nd Law).

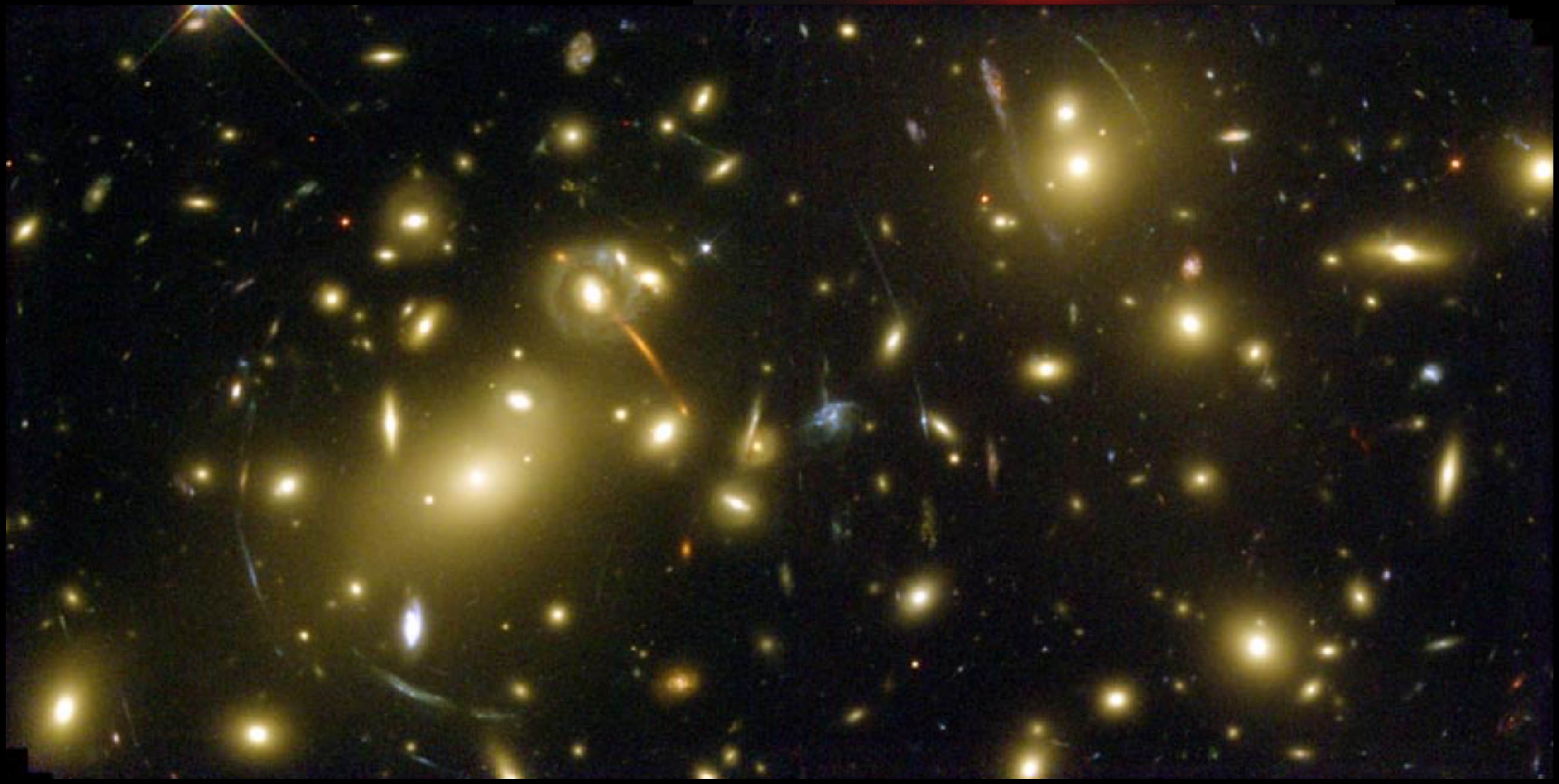
So the Moon is constantly

FALLING toward the Earth

It's the same for the Earth around the Sun, or the Sun around the center of the Galaxy.

Gravity also keeps astronomical objects bound together





Nature has FOUR fundamental forces...

1. **Gravity**
2. **Electromagnetic**
3. **Strong**
4. **Weak**

Gravity is the one that matters most for astronomy!

(Even though it is the weakest of the four)

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- Strong and Weak Nuclear forces have very short ranges ($<10^{-12}$ cm).

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Gravity is the one that matters most for astronomy!

(Even though it is the weakest of the four)

- Strong and Weak Nuclear forces have very short ranges (<10^{-12} cm).
- Electromagnetic force has a long range, but astronomical objects are not charged (for the most part).

BUT IN CONTRAST

- Gravity operates over any range, and affects anything with mass.

Nature has FOUR fundamental forces...

	relative strength	Range (m)
1. Gravity	1	∞
2. Electromagnetic	10^{36}	∞
3. Strong	10^{38}	$\sim 10^{-12}$
4. Weak	10^{25}	$\sim 10^{-12}$