Announcements

- Results of clicker questions from Monday are on ICON.
- First homework is graded on ICON.
- Next homework due one minute before midnight on Tuesday, September 6.
- Labs start this week. All lab sections will be in room 665 VAN.
- If you need help:
  - Find a friend or group of friends to study with
  - Office hours in 702 VAN, Tuesday 1–3 pm, Wednesday 10-11 am, or by appointment.
  - Astronomy tutorial in 310 VAN, Tuesday 3-5 and 7-9 pm.

How big is the Universe and where are we in it?

- Orbits of the planets
- Is the Earth or the Sun at the center of the Universe?
- Kepler's laws of planetary motion
- Newton's laws of gravitation
- How to measure large distances?
- Sizes of astronomical objects
- How big is the Universe?

The ratio of the size of the observable universe to the size of a proton is about

- Need to find sizes of observable universe and proton. Look on slides from lecture 1:
  - Size of universe = 10^{26} meters
  - Size of proton = 10^{-15} meters
- Now take ratio. Do universe/proton or proton/universe? First thing in ratio goes on top of fraction:
  - universe/proton = $10^{26}/10^{-15} = 10^{41}$
  - Closest answer is 10^{+40}
- Get 10^{-40} if your fraction is upside-down.
- Get 10^{25} if you forget to divide by 10^{-15}.
- Get 10^{-25} if you do both.

The ratio of volume of Jupiter to volume of solar system (inside orbit of Neptune)

- Want (volume of Jupiter) / (volume of Neptune's orbit)

$= (4/3)\pi(\text{radius of Jupiter})^3 / (4/3)\pi(\text{radius of Neptune's orbit})^3$

$= (\textbf{radius} \text{ of Jupiter})^3 / (\text{radius of Neptune's orbit})^3$

Lecture slide gives **diameters not radii**, need to divide by 2.

$= (7.1\times10^7)^3 / (4.5\times10^{12})^3 = (7.1\times10^7 / 4.5\times10^{12})^3 = 4.0\times10^{-15}$

- Get 3.2×10^{-14} if you use the diameter (forget to divide by 2)
- Get 1.6×10^{-5} if you forget to take the cubes.
- Get 3.2×10^{-5} if you do both.

If the tilt of the Earth's axis were zero degrees instead of 23.5 degrees then

A) There would be no seasons

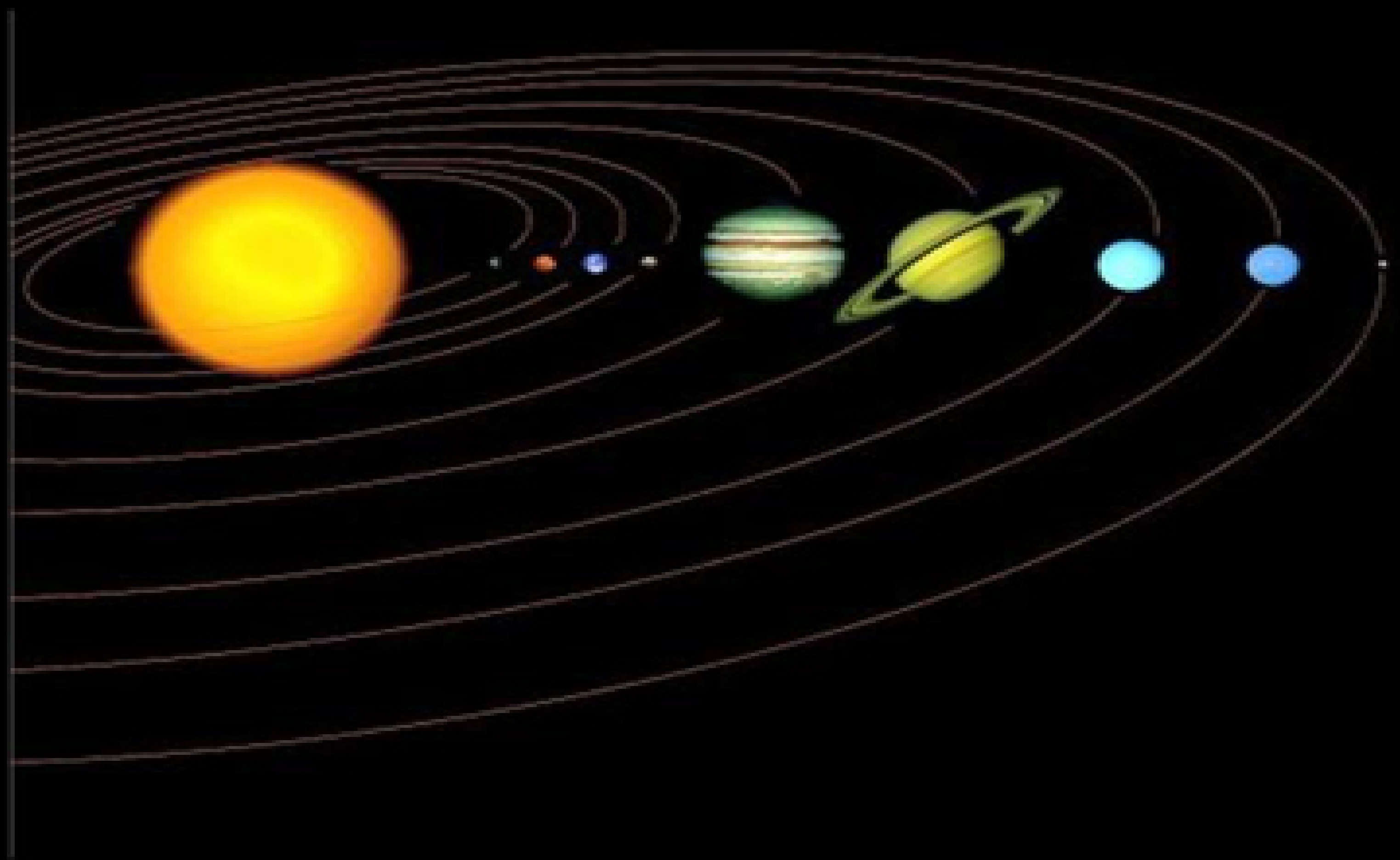
B) The Sun would always rise due east and set due west

C) The celestial equator and the ecliptic would be the same

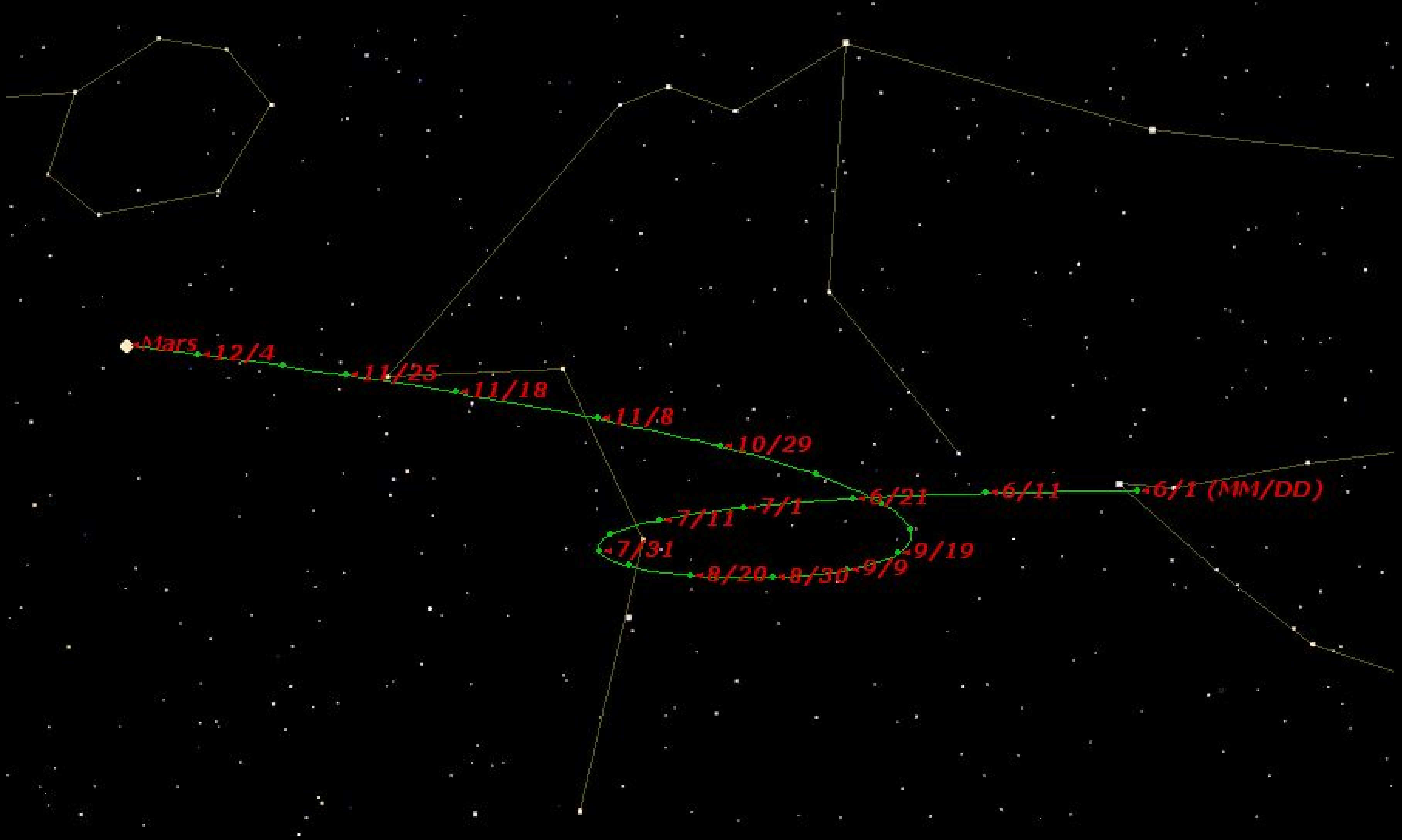
D) All of the above are true

E) No clue

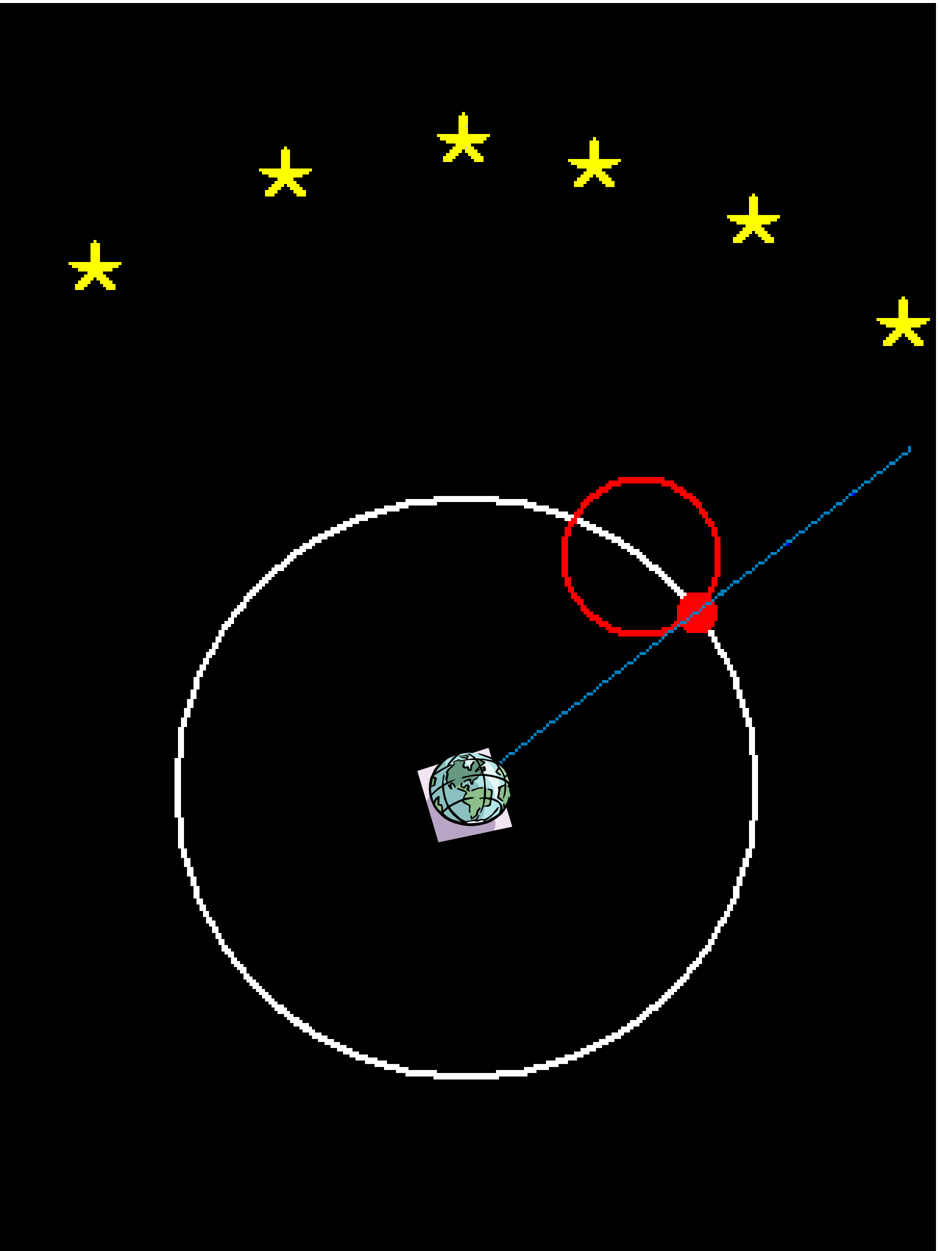
Orbits of the planets



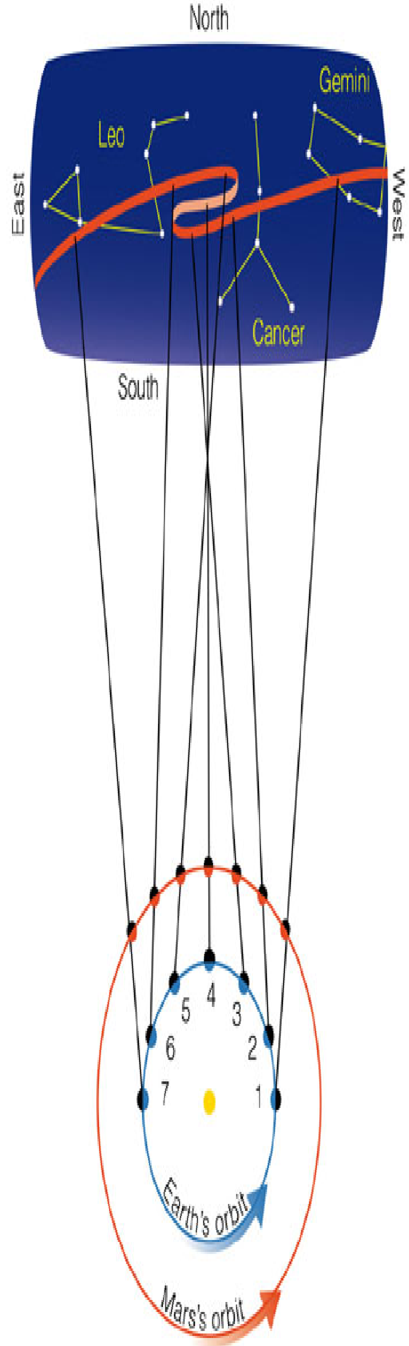
Motion of Mars on the Sky in 2003



Earth-Centered Model



Ptolemy (150 A.D.) introduced the idea of epicycles to explain the motion of the planets



Sun-Centered Model

Copernicus (1500 A.D.) suggested that it would be simpler to have the planets orbit the Sun. (demo 8A10.55)

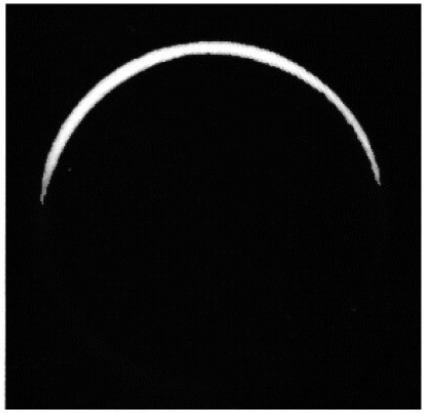
Moves Earth from center of Universe.

Copernican principle – we do not occupy a special place in the Universe.

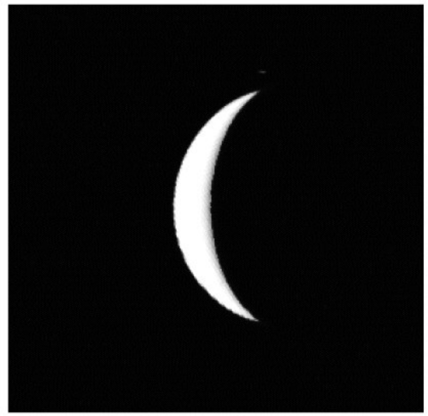
Any way to pick between models of Ptolemy vs Copernicus?

Predictions of the positions of the planets on the sky are essentially the same.

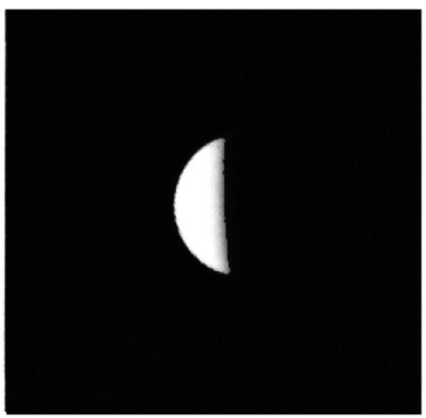
Galileo proved the planets orbit the Sun by observing Venus



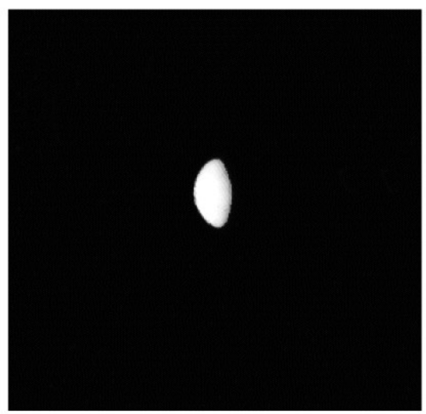
$\alpha = 58^\circ$



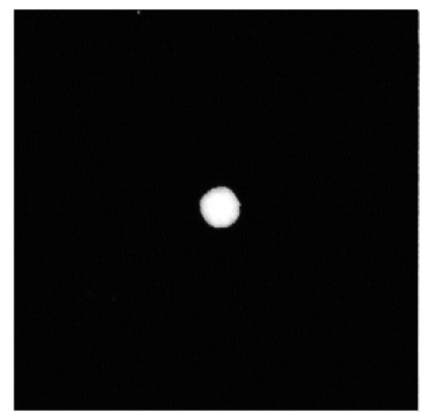
$\alpha = 42^\circ$



$\alpha = 24^\circ$



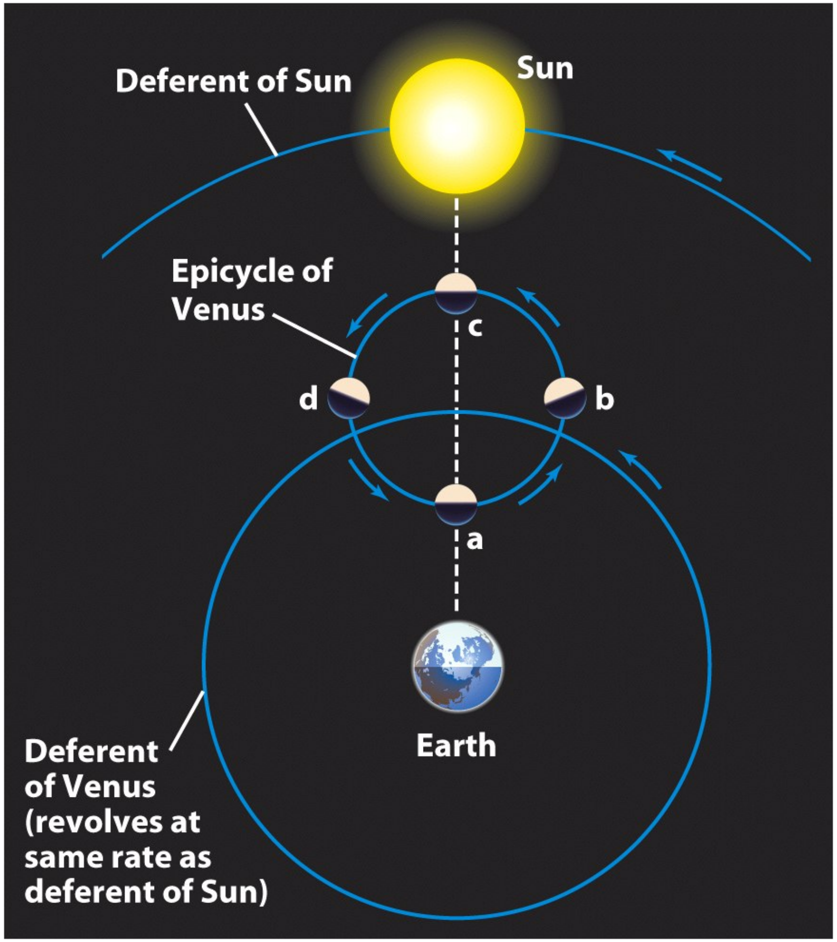
$\alpha = 15^\circ$



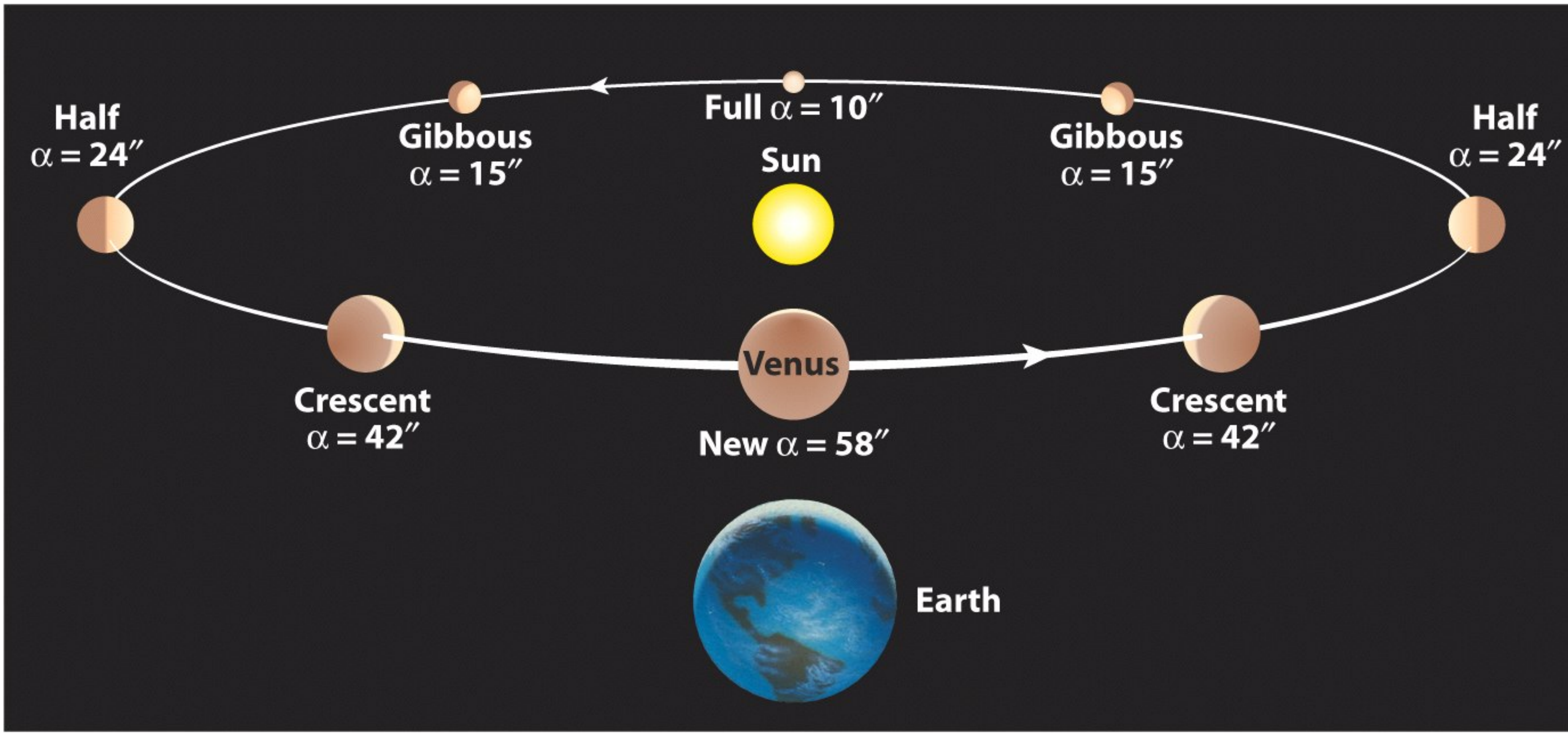
$\alpha = 10^\circ$

Earth-Centered Model

- Venus is never seen very far from the Sun.
- In Ptolemy's model, Venus and the Sun must move together with the epicycle of Venus centered on a line between the Earth and the Sun
- Then, Venus can never be the opposite side of the Sun from the Earth, so it can never have gibbous phases – no "full Venus".



Sun-Centered Model



- In a Sun centered model, Venus can show all phases – as Galileo observed.

Retrograde motion is explained in the Copernican (sun-centered) model of the solar system as

A) a result of planets moving in circles in constant speed around the Sun

B) an illusion that takes place when a planet is at its maximum distance from the Sun

C) when a planet slows down when at large distances from the Sun

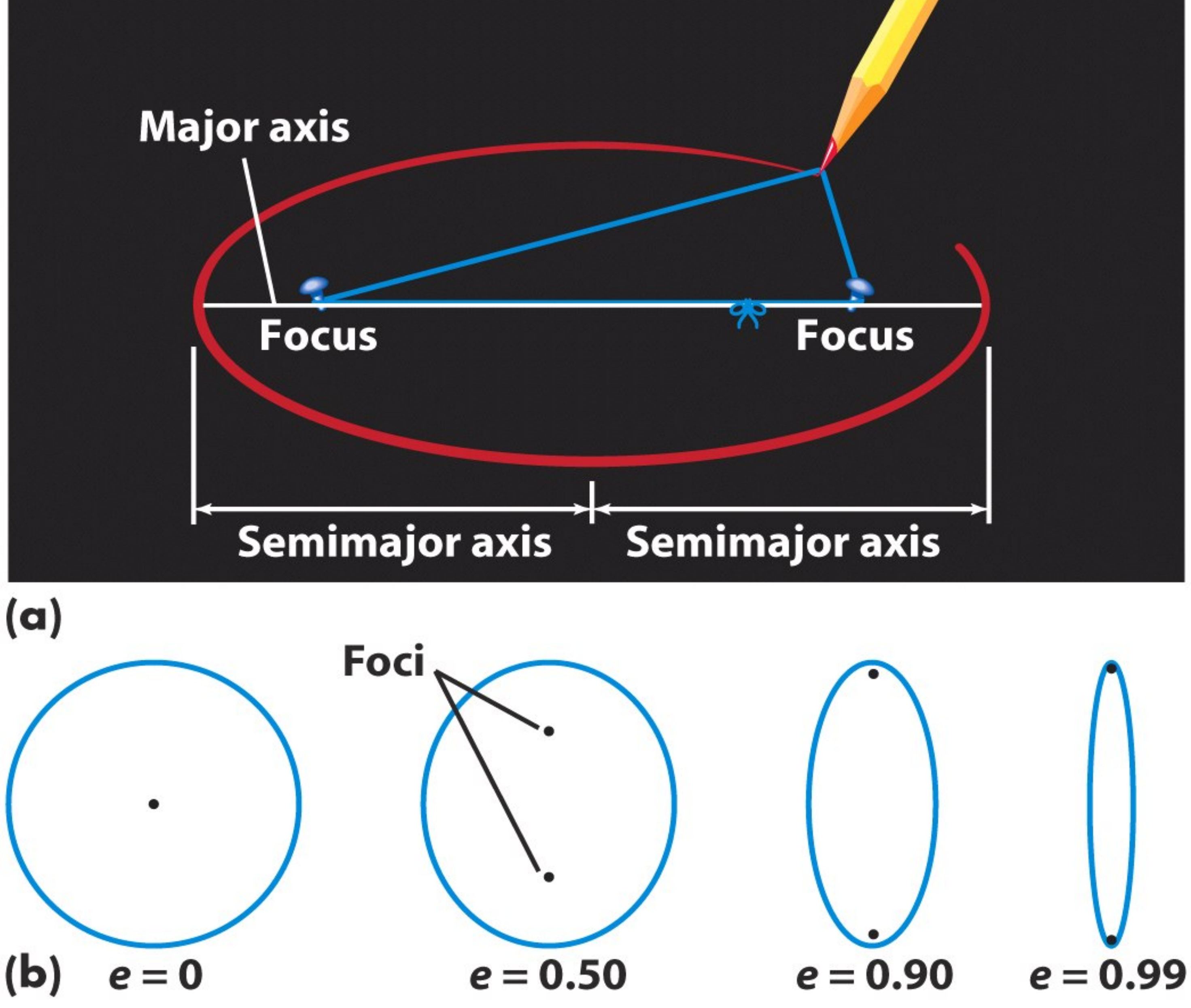
D) a dance move

Kepler’s Laws of Planetary Motion

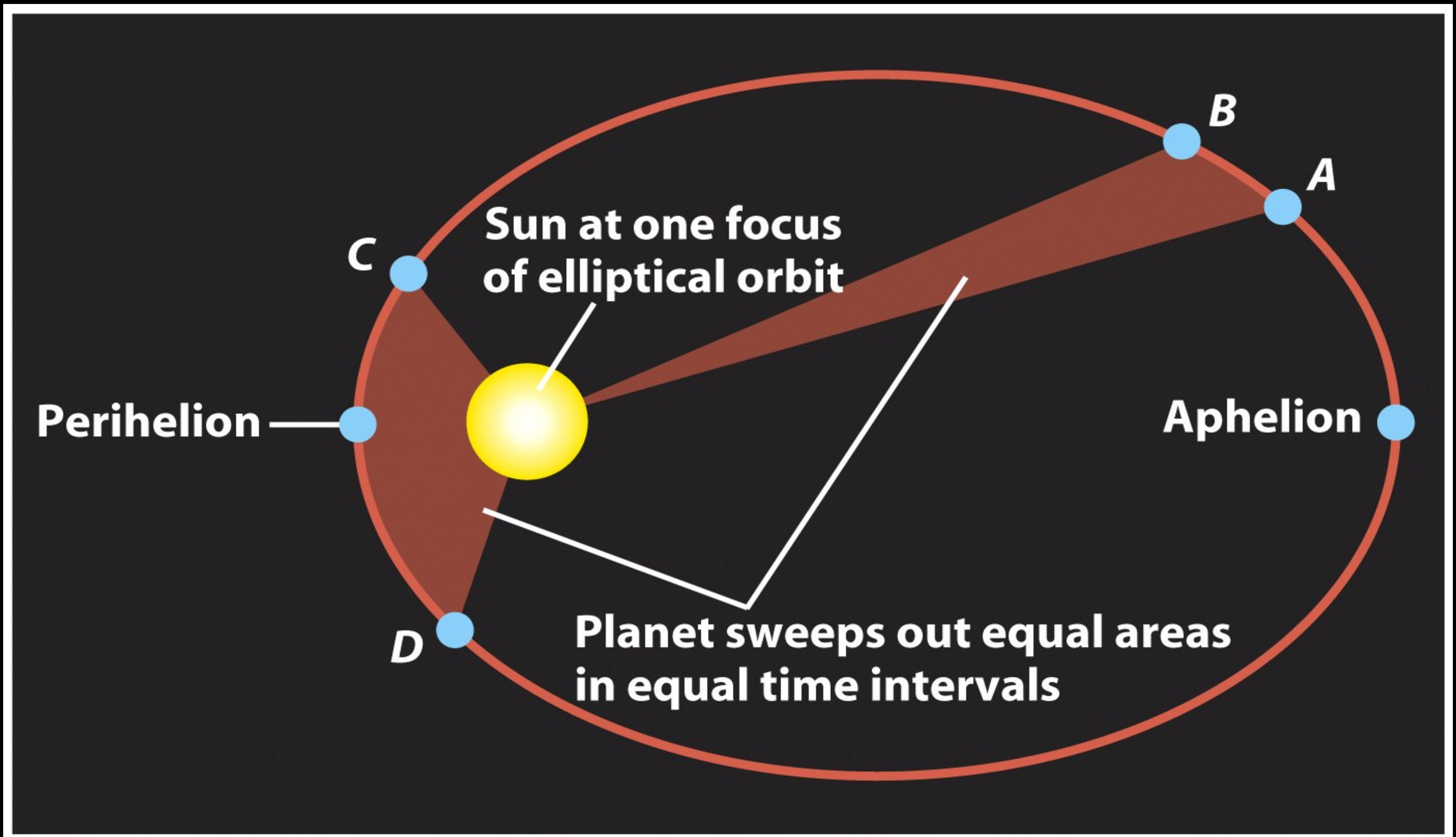
- Copernicus' model makes slightly wrong predictions about the positions of the planets in the sky.
- Using precise measurements of the positions of the planets in the sky collected by Tycho Brahe, Johannes Kepler deduced three laws of planetary motion:

  - The orbits are ellipses.
  - Planets move faster when closer to the Sun and slower when farther away.
  - Planets farther from the Sun take longer to orbit.

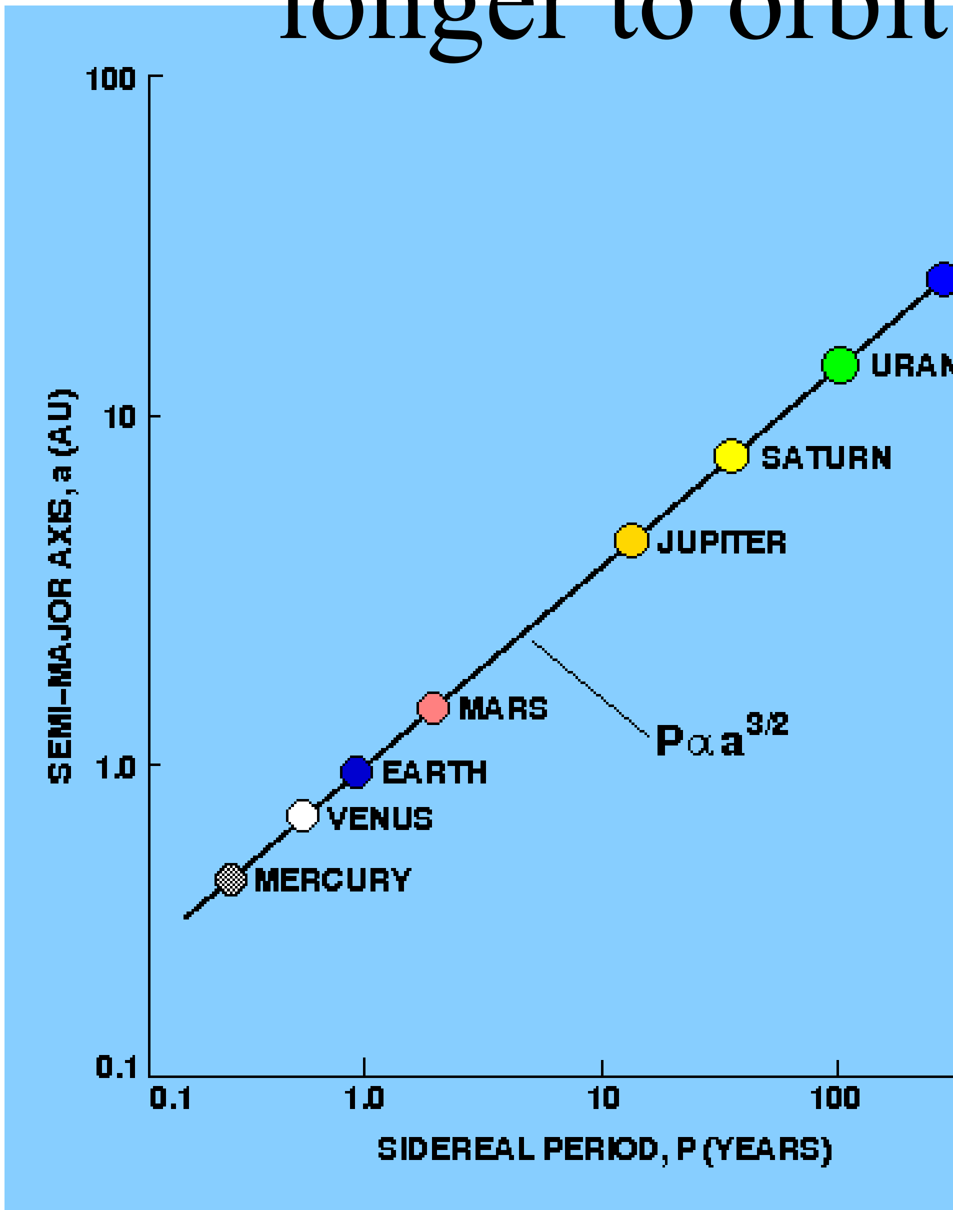
Orbits are ellipses



Planets move faster when closer to the Sun



Planets farther from the Sun take longer to orbit



The inner planets have smaller orbits and move faster

Near which letter does Halley's comet spend the most time?

A

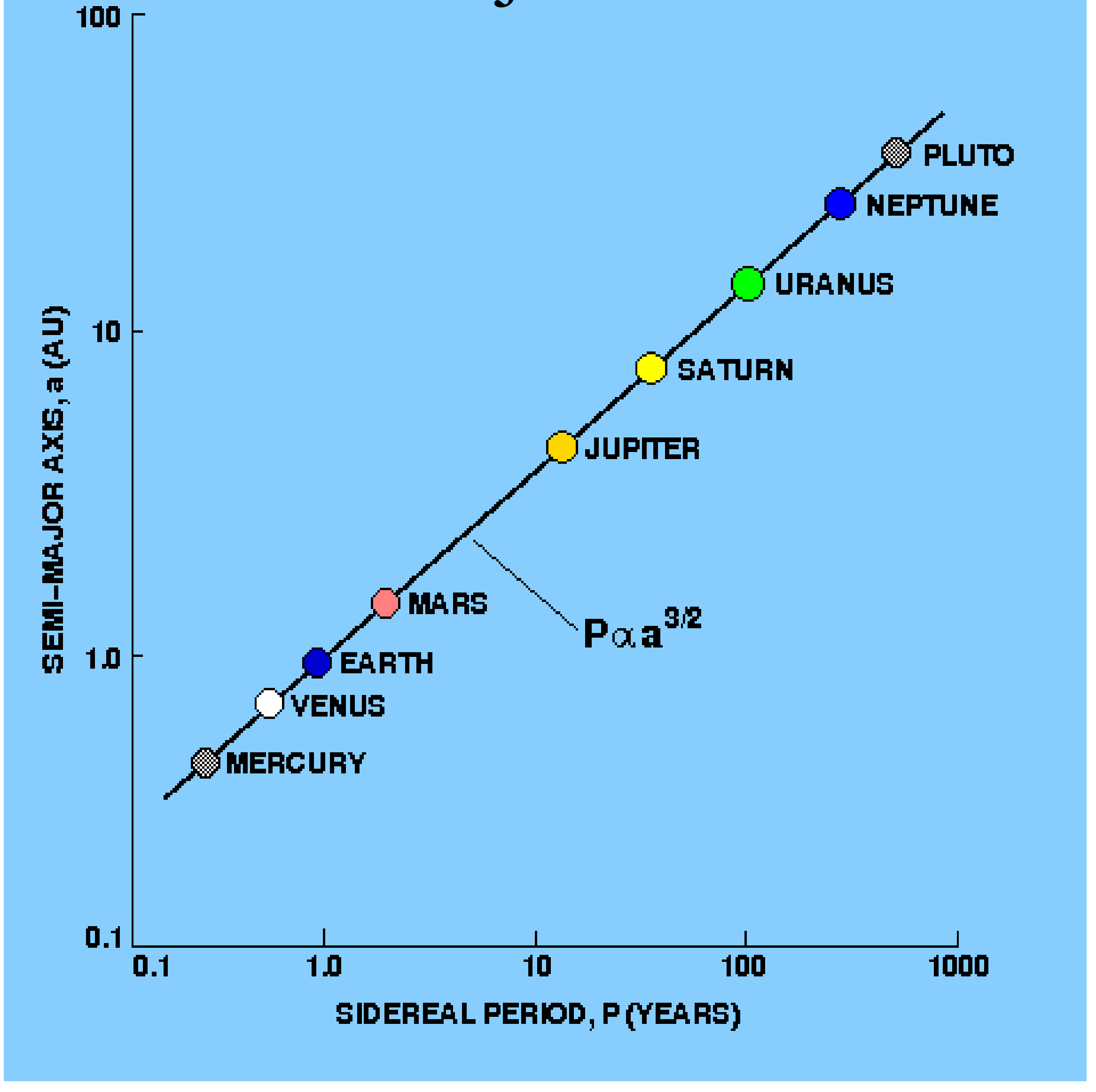
B

D

C

Halley's comet has an orbital period of about 80 years. What is the semi-major axis of the orbit?

A) 0.2
B) 2 AU
C) 20 AU
D) 200 AU
E) No clue



Isaac Newton

- Newton realized that the same physical laws which apply on Earth also apply to the Sun, Moon, and planets.
- He formulated laws that described the motion of objects both on Earth and in space (the heavens).
- He also invented calculus.

Newton’s laws

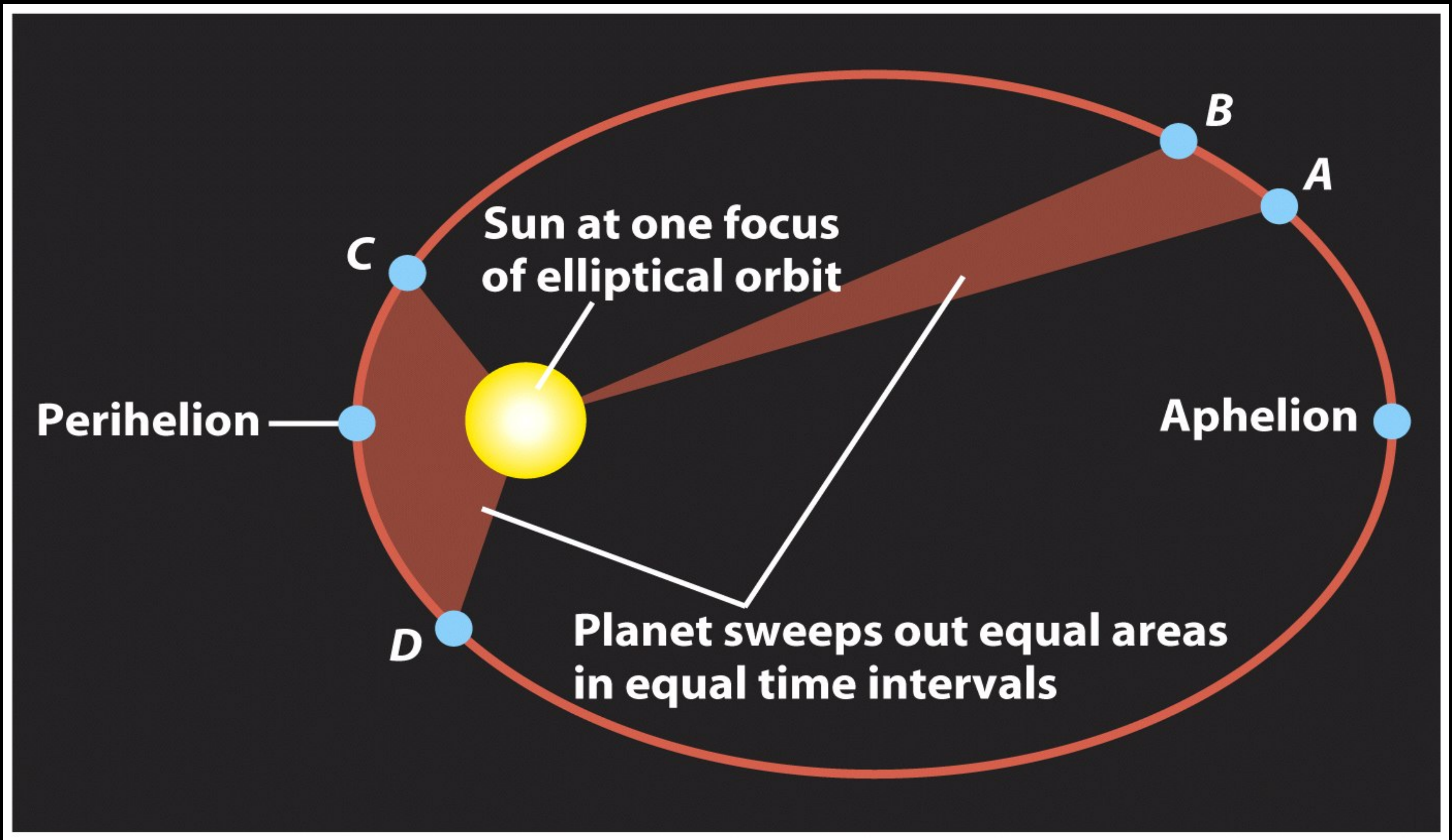
1. The law of inertia: a body remains at rest, or moves in a straight line at a constant speed, unless acted upon by an outside force
2. The force on an object is directly proportional to its mass and acceleration.
3. The principle of action and reaction: whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first body.

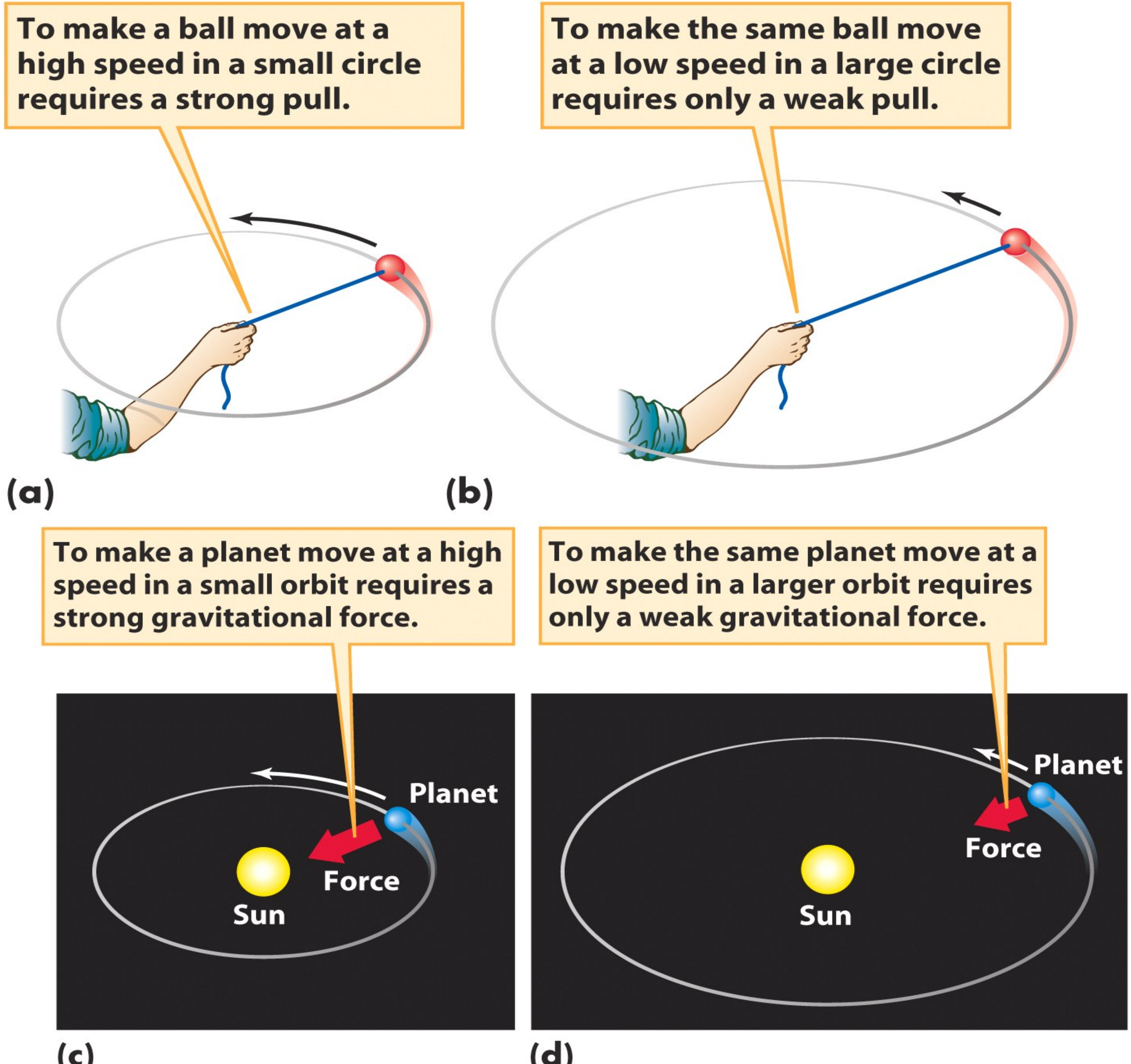
Newton's Law of Gravitation

- The gravitational force exerted by an object is proportional to its mass
- The gravitational force exerted by an object decreases with the square of the distance
  - If person B is twice as far away from the Sun as person A, then the force of gravity on person B is only ¼ of that on person A.

Newton's laws explain Kepler's laws

Planets move faster when closer to the Sun




To make a ball move at a high speed in a small circle requires a strong pull.
To make the same ball move at a low speed in a large circle requires only a weak pull.
(a)
(b)
To make a planet move at a high speed in a small orbit requires a strong gravitational force.
To make the same planet move at a low speed in a larger orbit requires only a weak gravitational force.
Planet
Force
Sun
Planet
Force
Sun
(c)
(d)

Where is the force of gravity on Halley's comet strongest?

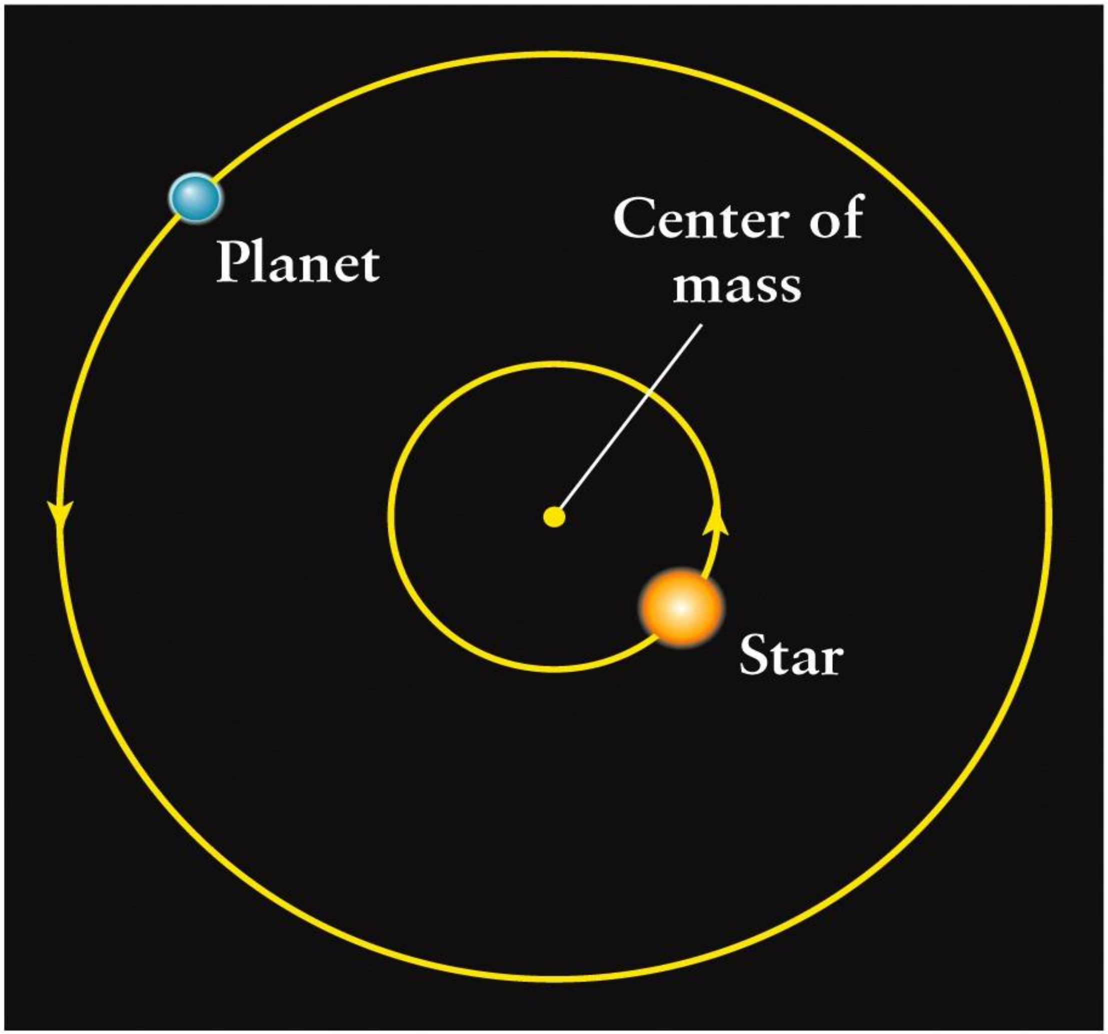
A

B

D

C

Mutual orbits of planet and star



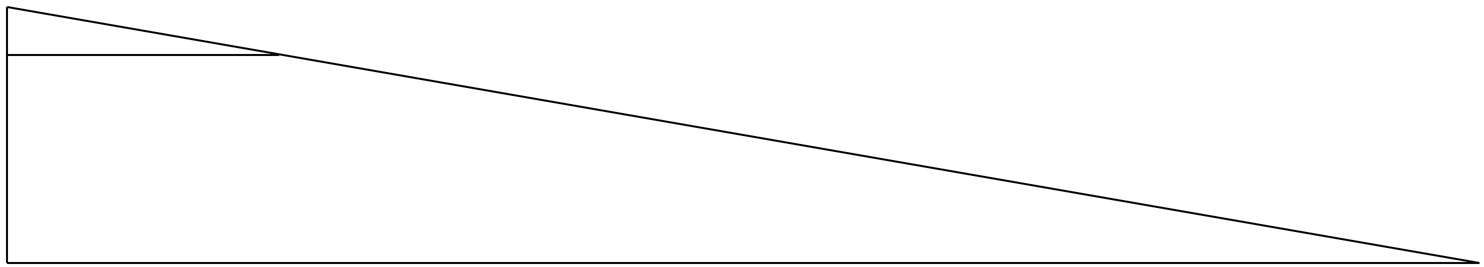
a

Which is evidence in favor of a sun-centered model of the solar system?

A) Retrograde motion of planets.
B) Venus is never more than 47 degrees from the Sun.
C) Venus is never seen in opposition.
D) Venus goes through the same set of phases as the Moon.

How can you measure the distance to an object you can’t reach?

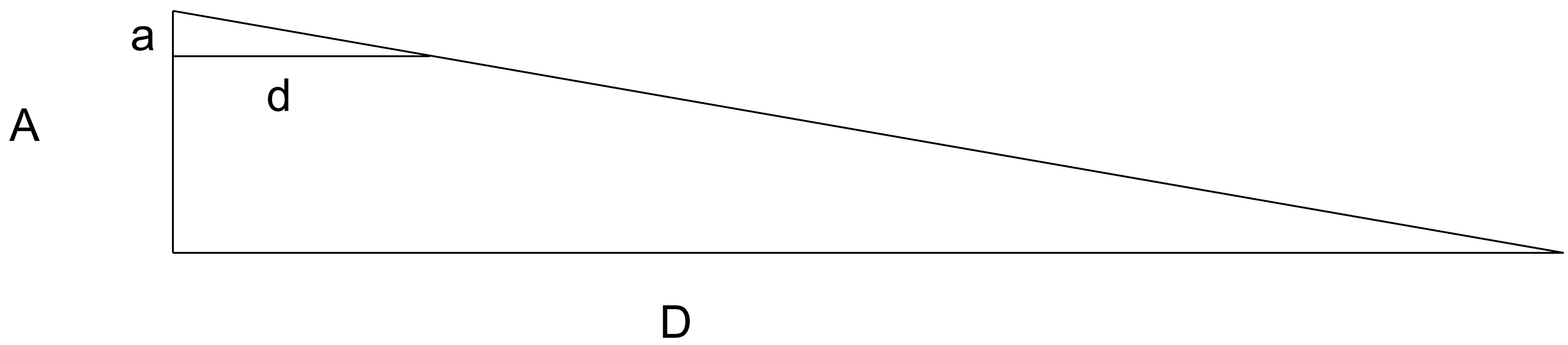
Triangles



The small triangle has the same shape as the large one.

By measuring the two sides of the small triangle and the short side of the big triangle, we can calculate the length of the long side of the big triangle.

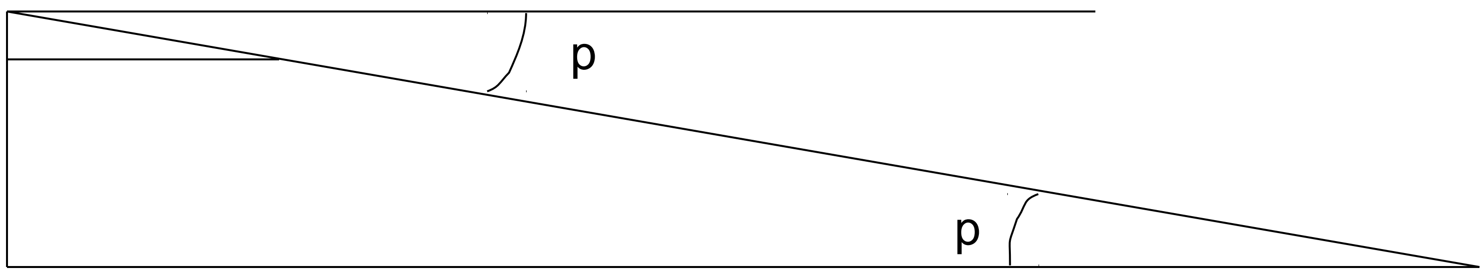
Measuring distance



$$\frac{D}{A} = \frac{d}{a}$$

$$D = A\frac{d}{a}$$

So, how can we measure the distance to stars?



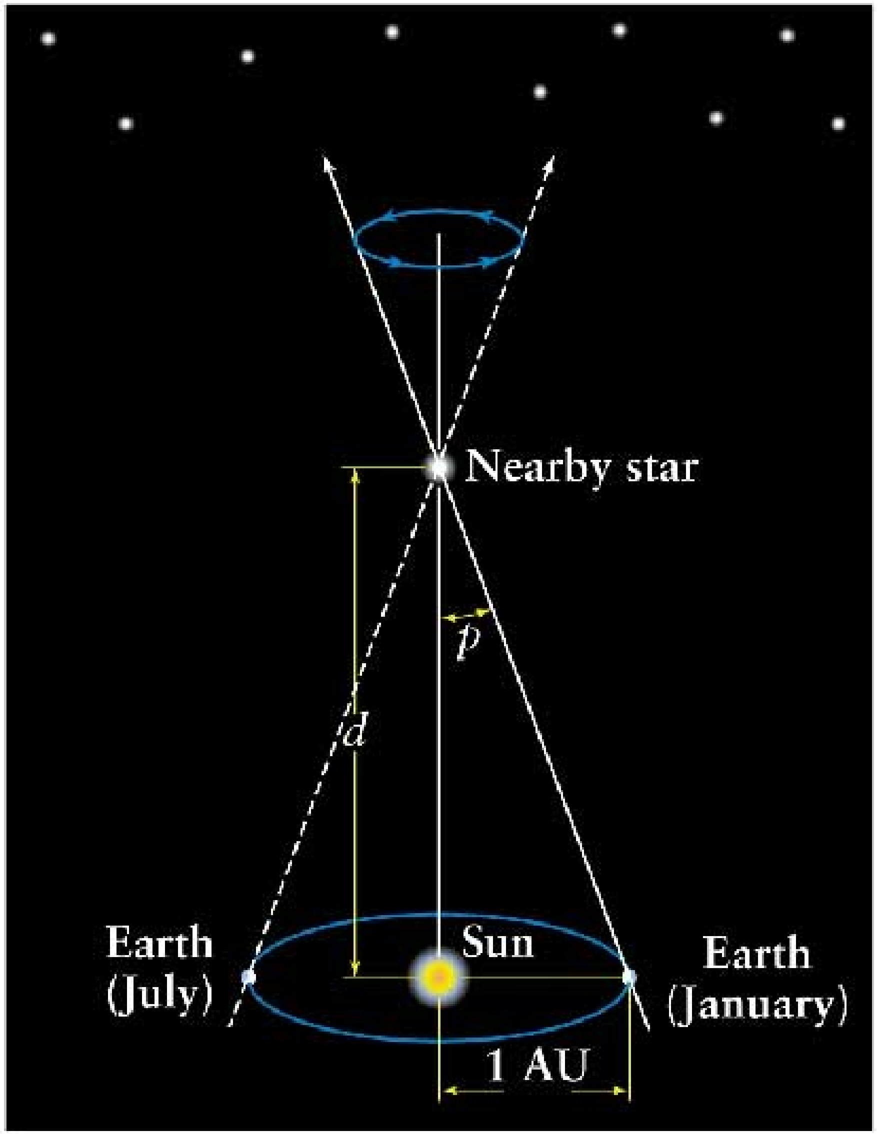
Take two telescopes some distance apart and observe the same star.
Measure the tilt between the two telescopes – this sets all the angles for the triangles.
Then we can find the distance to the star from the distance between the telescopes and the angle of the tilt.

So, how can we measure the distance to stars?

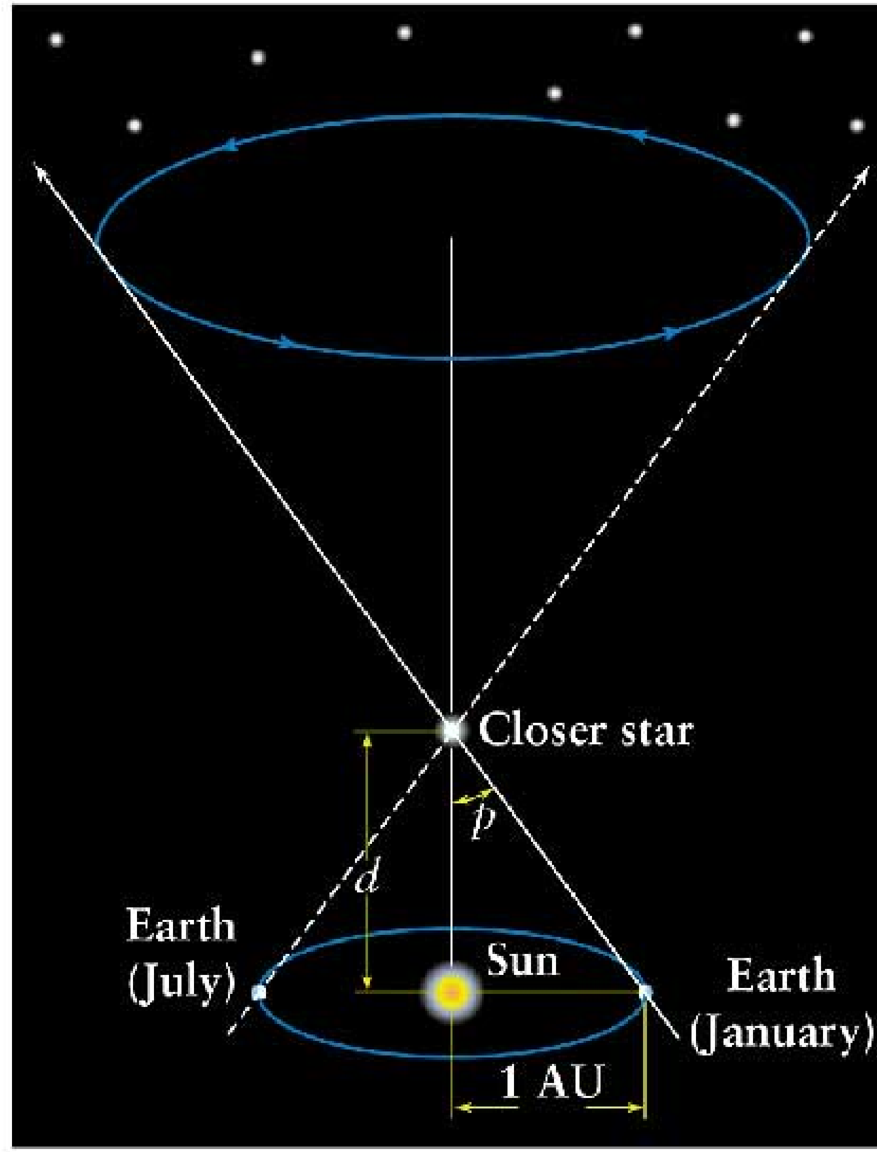
- We want to use the largest distance we can for the short side of the big triangle
- What is the largest distance we can get between the two telescopes (if both of them have to be on Earth – no spacecraft).

So, how can we measure the distance to stars?

- The largest distance is not by placing the two telescopes at opposite ends of the Earth.
- Instead, we can use one telescope and just let the earth move.



a



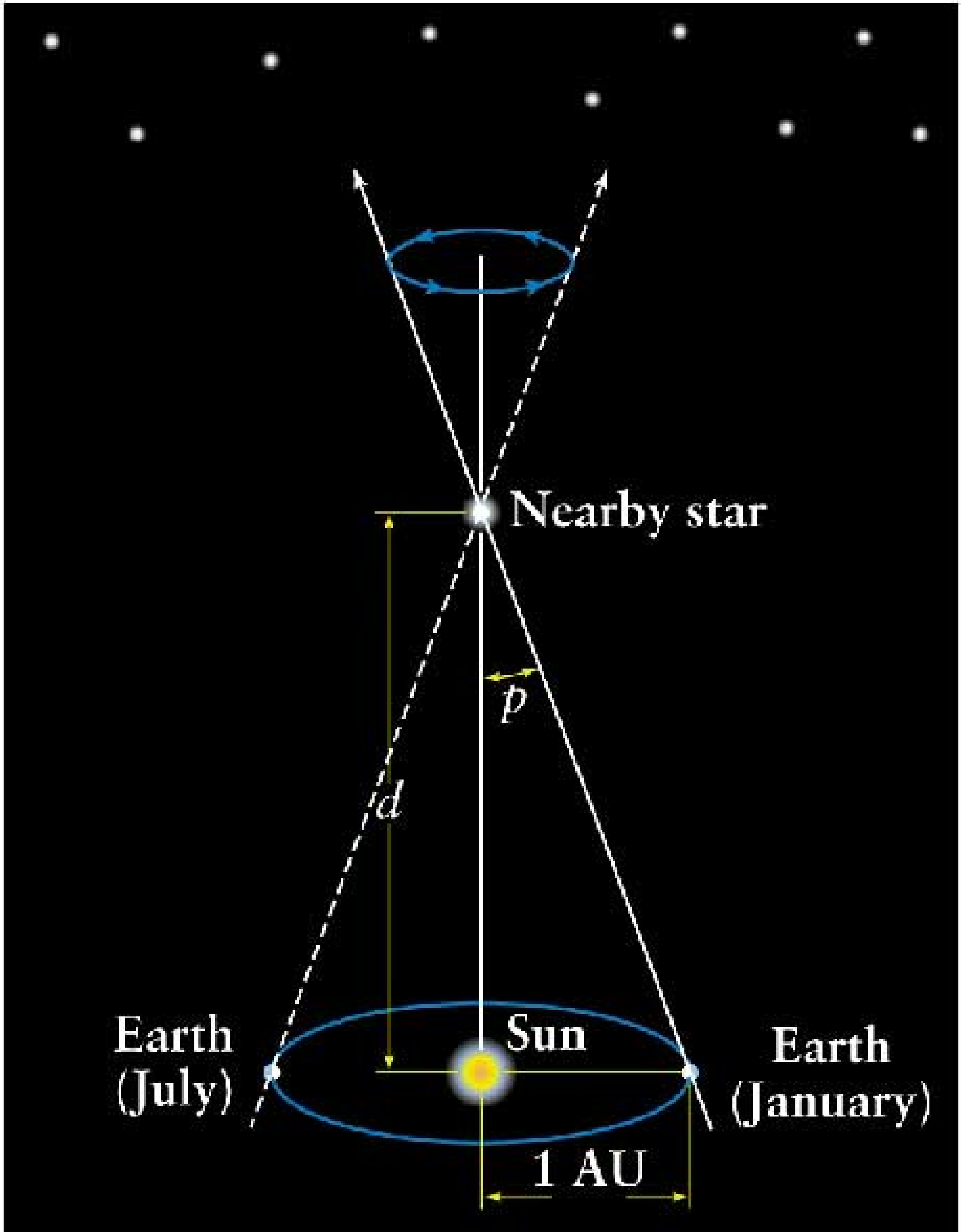
b

Farther star – smaller parallax

Closer star – larger parallax

Parallax of your thumb

- Look at the person sitting next to you or some nearby object.
- Look through your right eye and put your thumb 6 inches in front of your eye, then line up your thumb with the other person's nose.
- Now switch between your left and right eyes? Does your thumb stay lined up with the person's nose?
- Now repeat the procedure with your thumb 12 inches from your nose. Does your thumb appear to move more or less (relative to the person's face)?



a

Stellar Parallax

As Earth moves from one side of the Sun to the other, a nearby star will seem to change its position relative to the distant background stars.

$$d = 1 / p$$

d = distance to nearby star in parsecs

p = parallax angle of that star in arcseconds

Example: Using parallax to determine distance

The bright star Vega has a measured parallax of 0.1 arcsec ($p = 0.1''$)

This means that Vega appears to move from $+0.1''$ to $-0.1''$ with respect to distant stars over a year's observation

$$D(\text{pc}) = 1/p('') = 1/0.1 = 10 \text{ pc}$$

Vega is 10 pc (parsec) from Earth
(remember: 1 pc = 3.26 light years)

The parallax of the star Vega is 0.1 arcseconds. On which planet would the parallax be larger than 0.1 arcsec?

A) Venus

B) Mars

C) Parallax doesn't depend on planet

D) None of the other answers is correct

Sizes of Astronomical Objects

- How can we measure the sizes of astronomical objects?
- The same way that we measure distances – using triangles

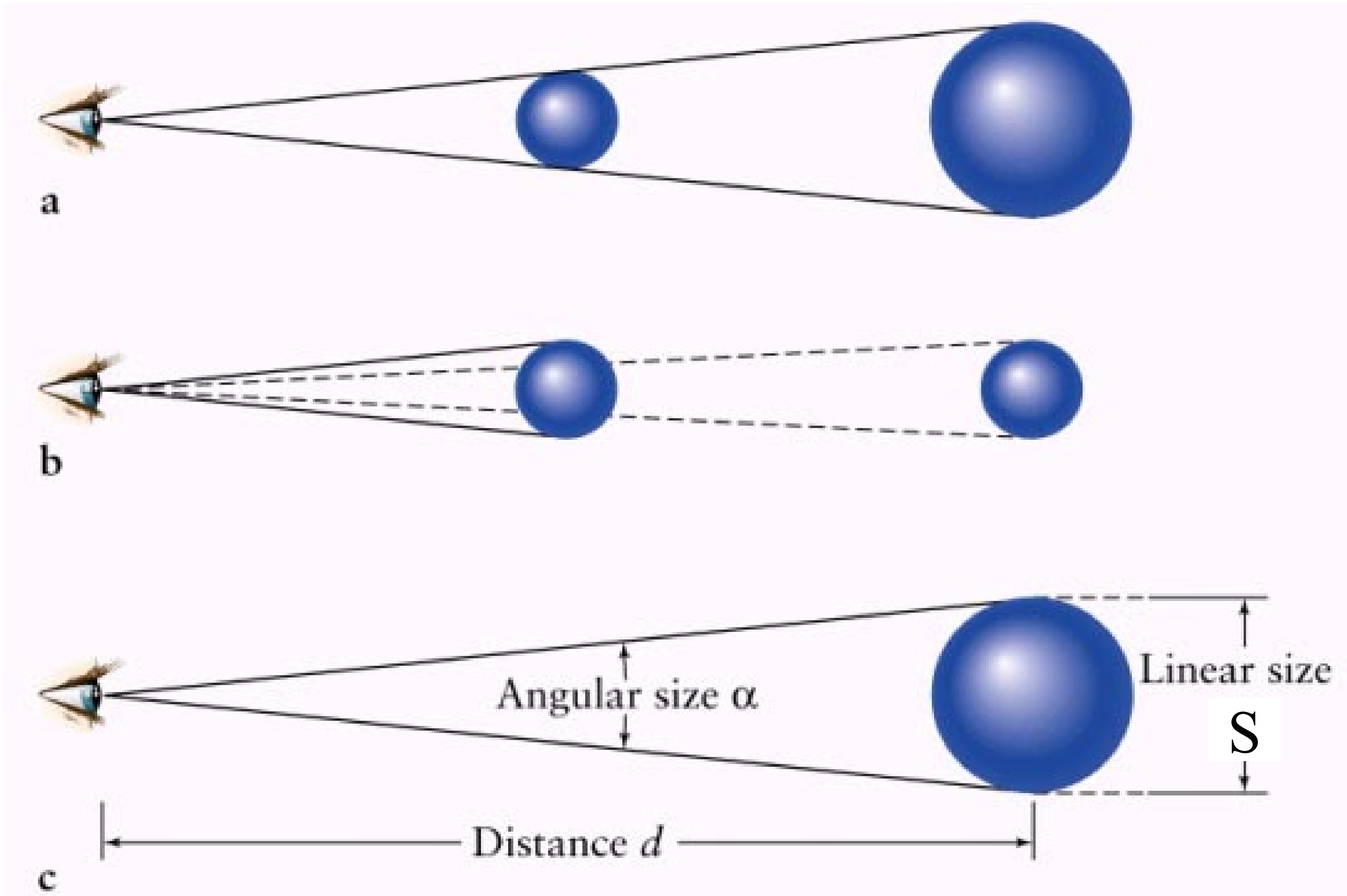
The Small-Angle Formula

$$S = \frac{\alpha \cdot d}{206265}$$

S = linear size of object

α = angular size of object (**in arcseconds**)

d = distance to the object



Example: On November 28, 2000, the planet Jupiter was 609 million kilometers from Earth and had an angular diameter of 48.6″. Using the small-angle formula, determine Jupiter's actual diameter.

S = 48.6″ x 609,000,000 km / 206265 = 143,000 km

The Small-Angle Formula

$$S = \frac{\alpha \cdot d}{206265}$$

S = linear size of object

α = angular size of object (in arcseconds)

d = distance to the object

An object is 2000 m away and has an angular size of 1”. How big is it?

A) Size of a grain of salt

B) Size of the finger nail on your pinky

C) Height of a person

D) Length of the Titanic

E) No clue

$$S = \frac{\alpha \cdot d}{206265}$$

How big is the Universe?

- Greeks (up about 100 B.C.)
  - Earth at Center (except for Aristarchus)
  - Universe extends to ‘sphere of Saturn’, largest measured distance is from Earth to Sun at several million miles
- Renaissance (1500-1650)
  - Sun at Center
  - Universe extends to `distant stars’ with inferred distance of about 100 billion miles, largest measured distance is from Sun to Saturn at about 1 billion miles

How big is the Universe?

- Parallax to stars
  - First parallax measured in 1838 to star 61 Cygni of 0.3 arcseconds for a distance of 11 ly = 7×10^{13} miles.
- Distance to center of Milky Way
  - from globular clusters 50,000 ly (1915)
- Distance to Andromeda nebula
  - from Cepheids 2,000,000 ly (1923)
  - (really 2,500,000 ly)

How big is the Universe?

- Distance to first discovered quasar 3C 273 (supermassive black hole)
  - from redshift 2×10^9 light years (1960)
- Distance to early Universe
  - from cosmic background radiation 1.4×10^{10} light years (1965)

Review Questions

- What is an epicycle?
- What was the flaw in Copernicus's heliocentric model of the solar system?
- What did Galileo observe about Venus and why is it important?
- Does Pluto orbit faster or slower than Mercury. How did Newton explain this?
- How is parallax related to the distance to an object?
- Over history, how did the size of the Universe change?