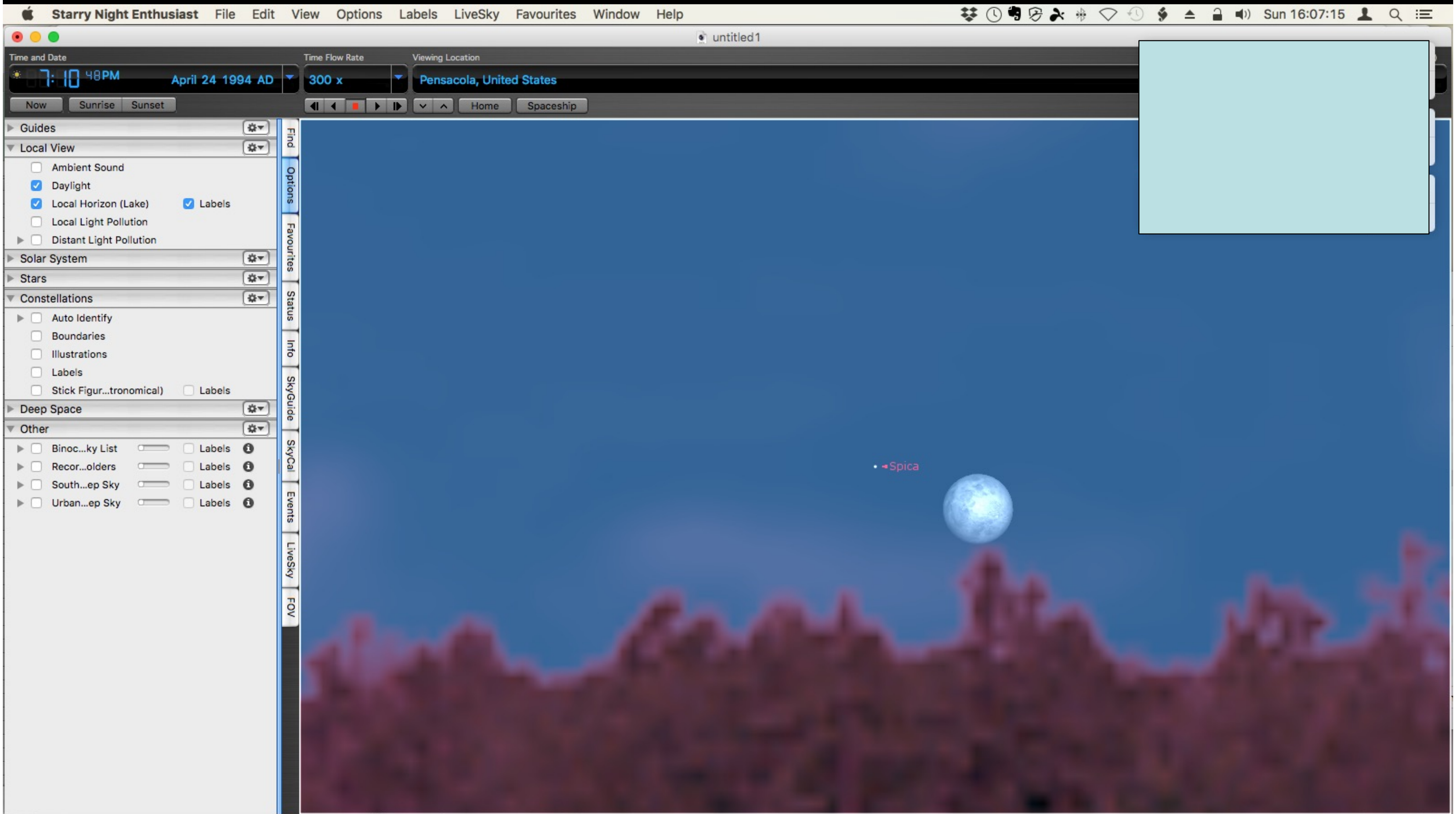
Charting the Heavens

- Since antiquity, astronomers have sought methods for predicting how bodies move on the celestial sphere
- Stars are in fixed locations, just rotate around Earth daily
- The motions of the Sun and Moon move are relatively simple
- The motions of the planets are not


Starry Night Enthusiast
File
Edit
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Labels
LiveSky
Favourites
Window
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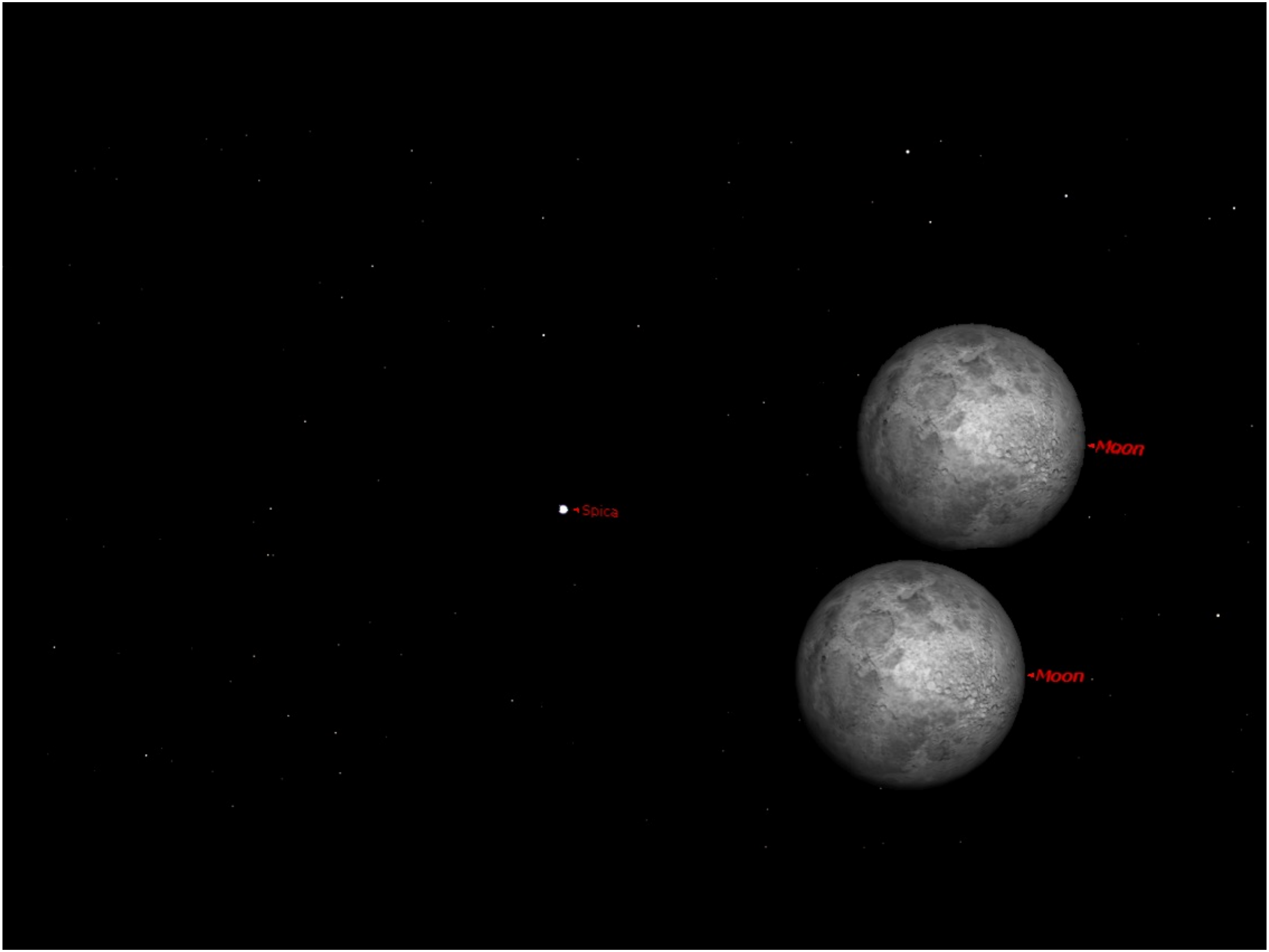
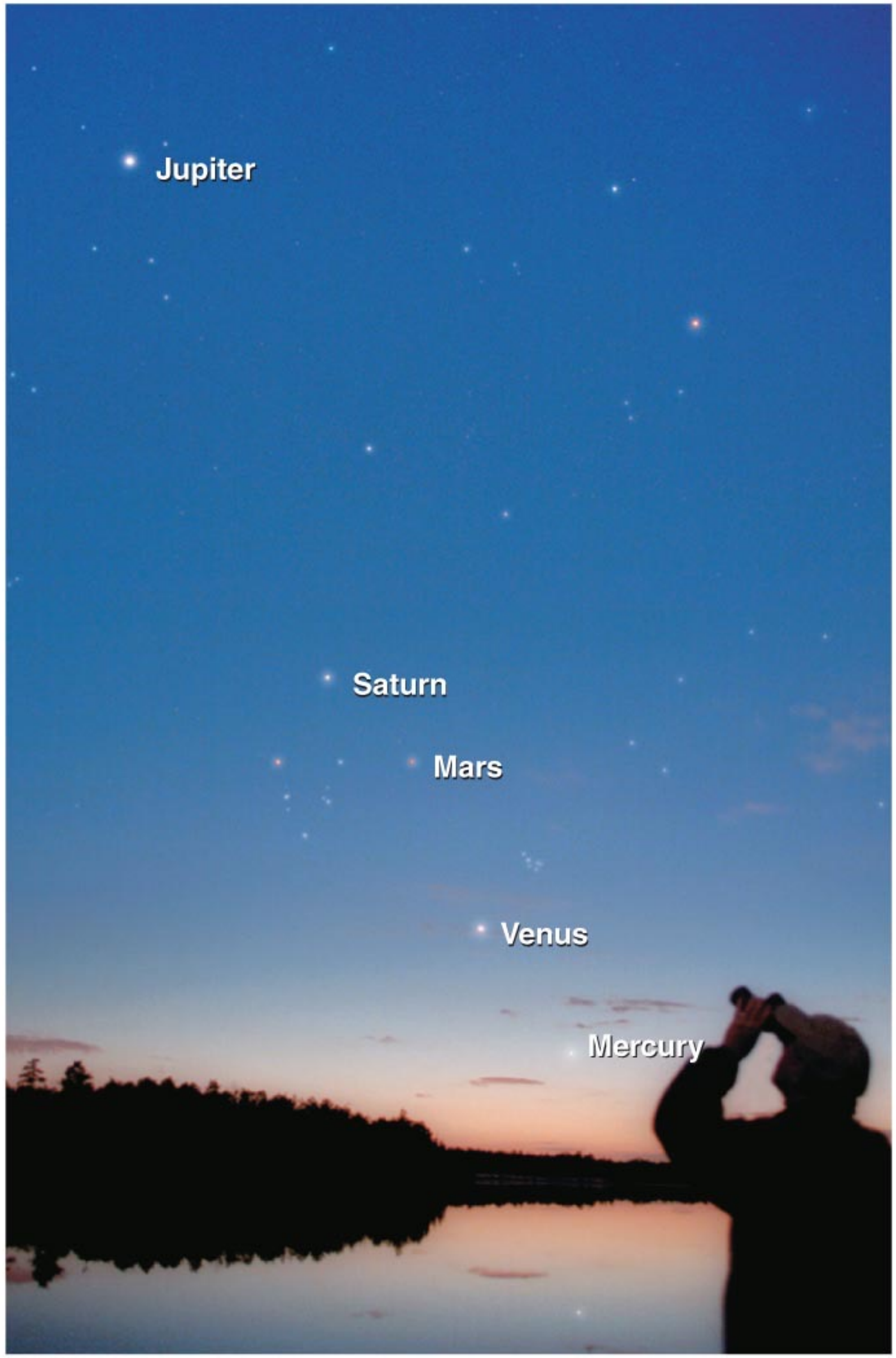
Sun 16:07:15
untitled1
Time and Date
7:10 48PM
April 24 1994 AD
Time Flow Rate
300 x
Viewing Location
Pensacola, United States
Now
Sunrise
Sunset
Home
Spaceship
Guides
Local View
Ambient Sound
Daylight
Local Horizon (Lake)
Labels
Local Light Pollution
Distant Light Pollution
Solar System
Stars
Constellations
Auto Identify
Boundaries
Illustrations
Labels
Stick Figur...tronomical)
Labels
Deep Space
Other
Binoc...ky List
Labels
Recor...olders
Labels
South...ep Sky
Labels
Urban...ep Sky
Labels
Find
Options
Favourites
Status
Info
SkyGuide
SkyCal
Events
LiveSky
FOV
Spica


Spica
Moon
Moon


Jupiter
Saturn
Mars
Venus
Mercury

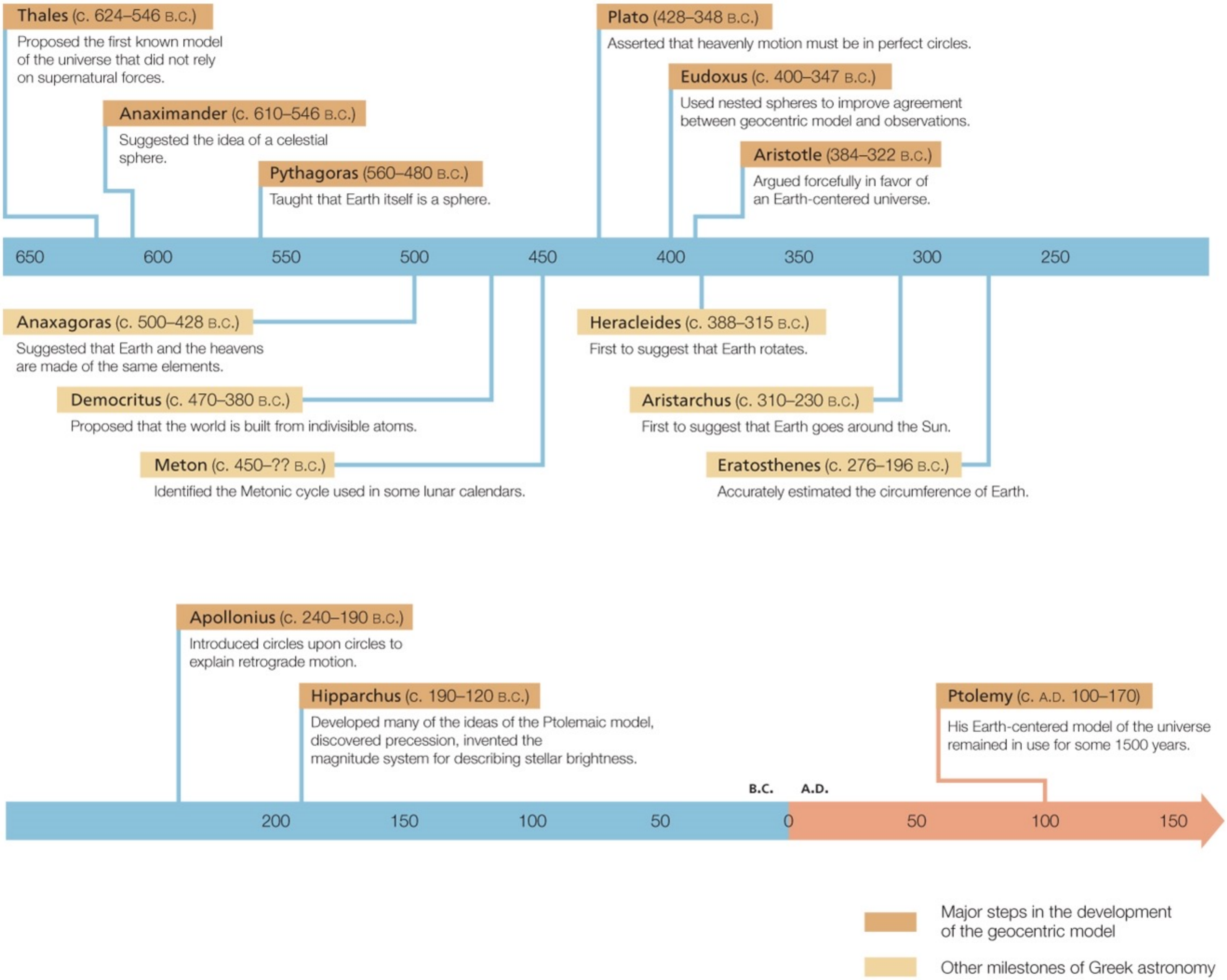
The reason the planets always appear to be near the ecliptic is that

1. The ecliptic is only 23.5° from the celestial equator
2. The planets orbit around the Sun in nearly the same plane
3. Compared to the stars, the planets are nearer to the Sun
4. The planets come much nearer to us than the Sun does

The reason the planets always appear to be near the ecliptic is that

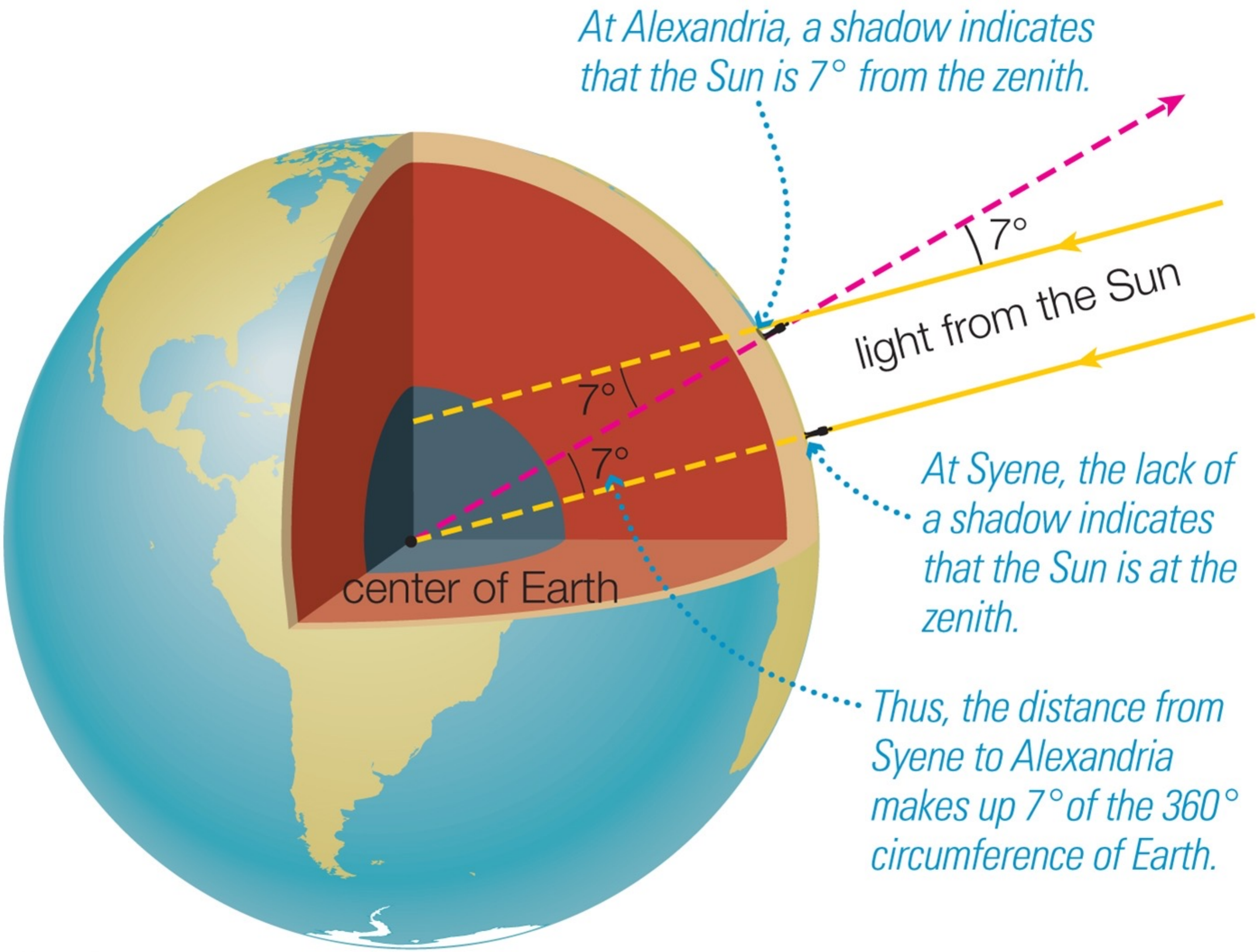
1. The ecliptic is only 23.5° from the celestial equator
2. **The planets orbit around the Sun in nearly the same plane**
3. Compared to the stars, the planets are nearer to the Sun
4. The planets come much nearer to us than the Sun does

Figure 3.12

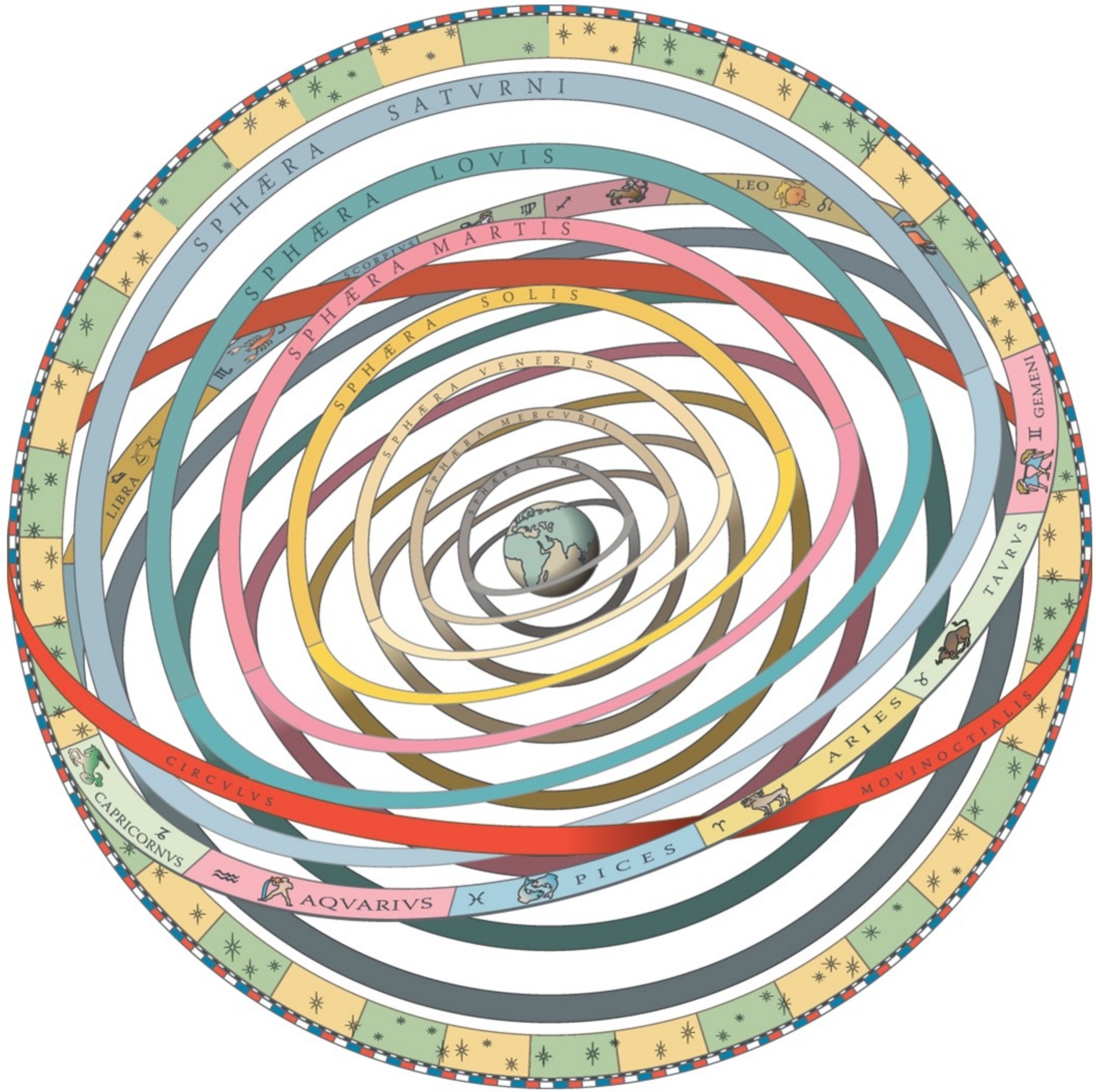


Thales (c. 624–546 B.C.)
Proposed the first known model of the universe that did not rely on supernatural forces.
Anaximander (c. 610–546 B.C.)
Suggested the idea of a celestial sphere.
Pythagoras (560–480 B.C.)
Taught that Earth itself is a sphere.
Plato (428–348 B.C.)
Asserted that heavenly motion must be in perfect circles.
Eudoxus (c. 400–347 B.C.)
Used nested spheres to improve agreement between geocentric model and observations.
Aristotle (384–322 B.C.)
Argued forcefully in favor of an Earth-centered universe.
650
600
550
500
450
400
350
300
250
Anaxagoras (c. 500–428 B.C.)
Suggested that Earth and the heavens are made of the same elements.
Democritus (c. 470–380 B.C.)
Proposed that the world is built from indivisible atoms.
Meton (c. 450–?? B.C.)
Identified the Metonic cycle used in some lunar calendars.
Heracleides (c. 388–315 B.C.)
First to suggest that Earth rotates.
Aristarchus (c. 310–230 B.C.)
First to suggest that Earth goes around the Sun.
Eratosthenes (c. 276–196 B.C.)
Accurately estimated the circumference of Earth.
Apollonius (c. 240–190 B.C.)
Introduced circles upon circles to explain retrograde motion.
Hipparchus (c. 190–120 B.C.)
Developed many of the ideas of the Ptolemaic model, discovered precession, invented the magnitude system for describing stellar brightness.
Ptolemy (c. A.D. 100–170)
His Earth-centered model of the universe remained in use for some 1500 years.
B.C.
A.D.
200
150
100
50
0
50
100
150
Major steps in the development of the geocentric model
Other milestones of Greek astronomy

The Greeks knew the Shape of the Earth



Greek Model of the Universe



Problem: Retrograde Motion

Ptolemy's Geocentric Model

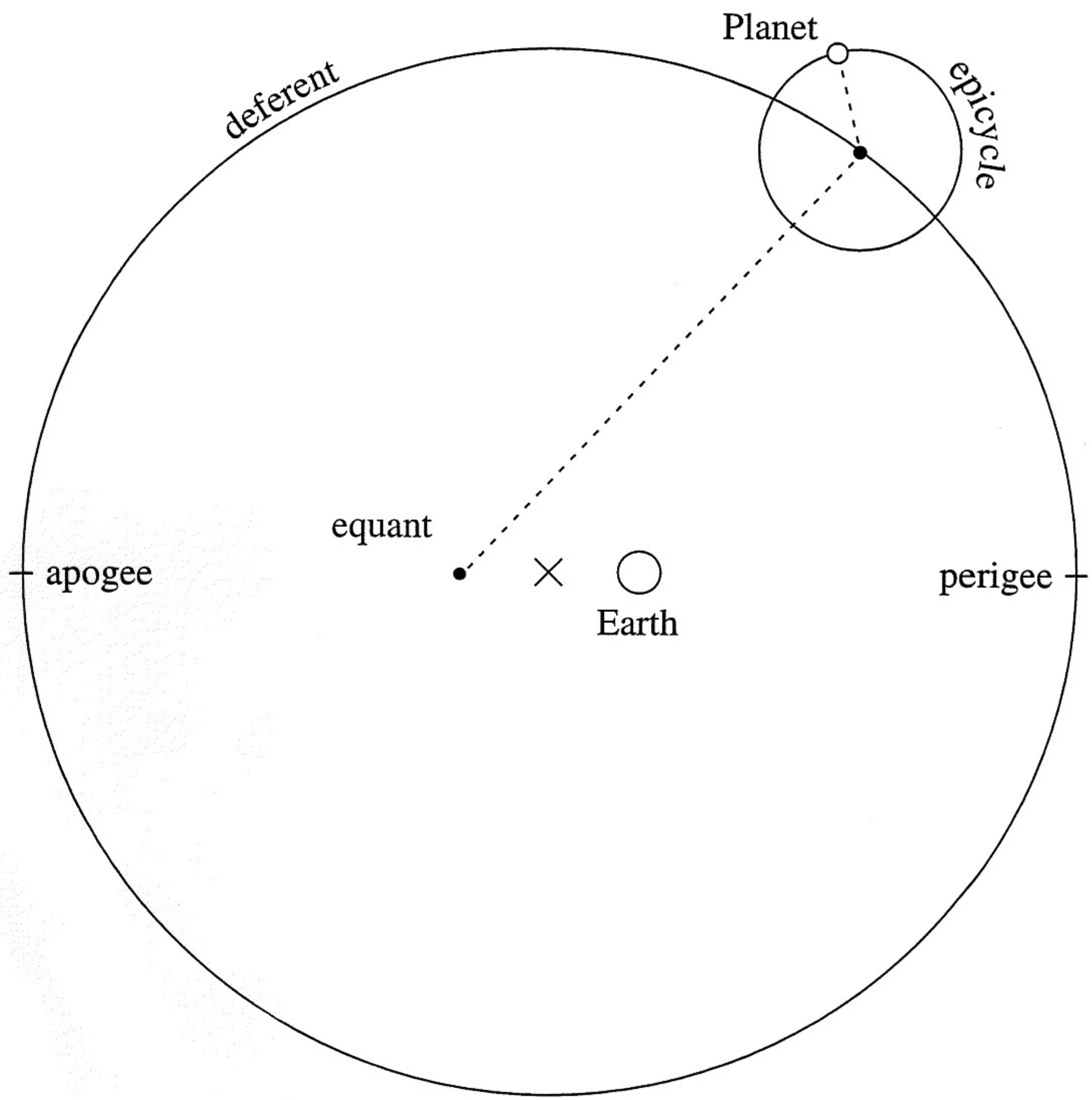
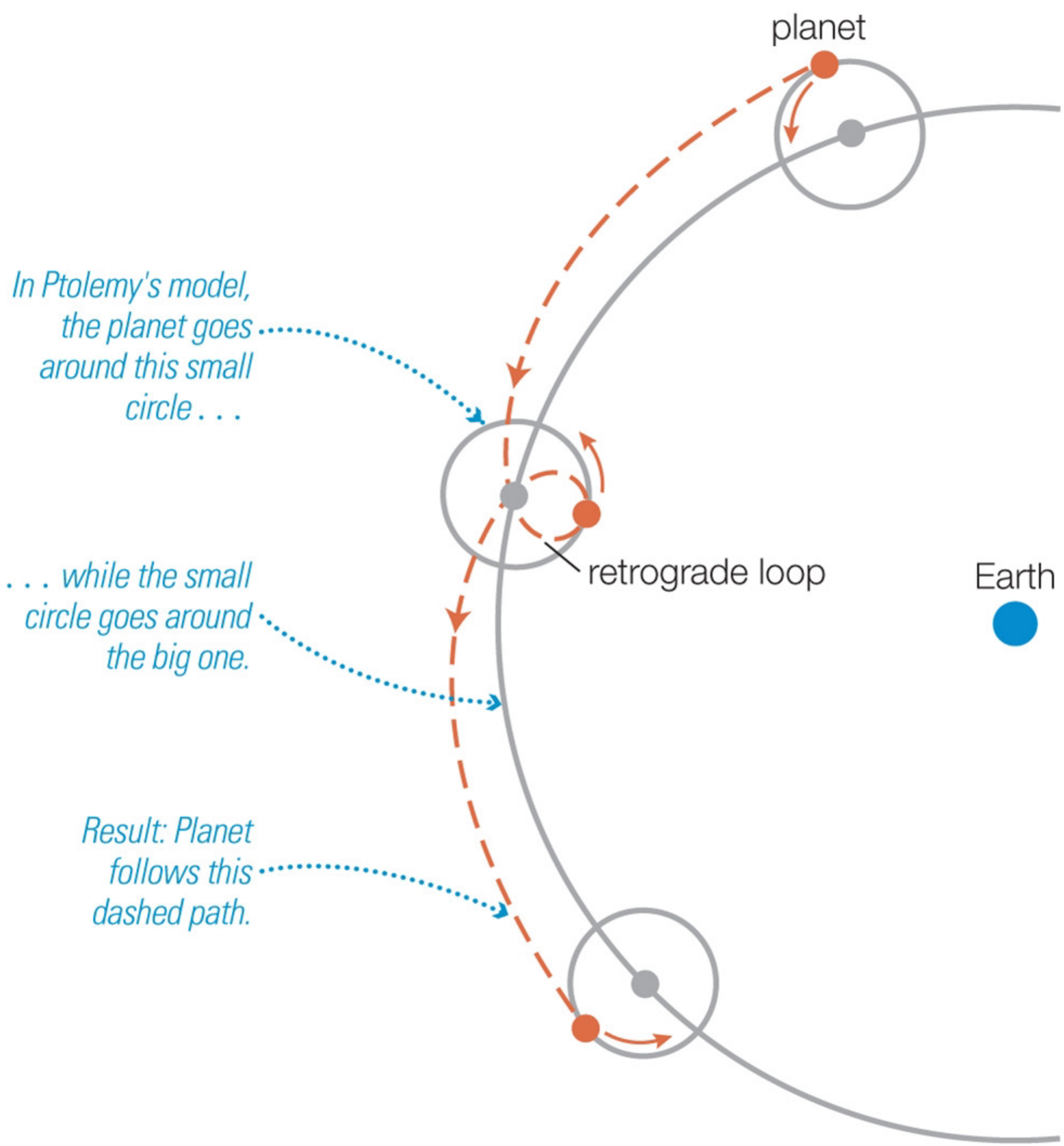
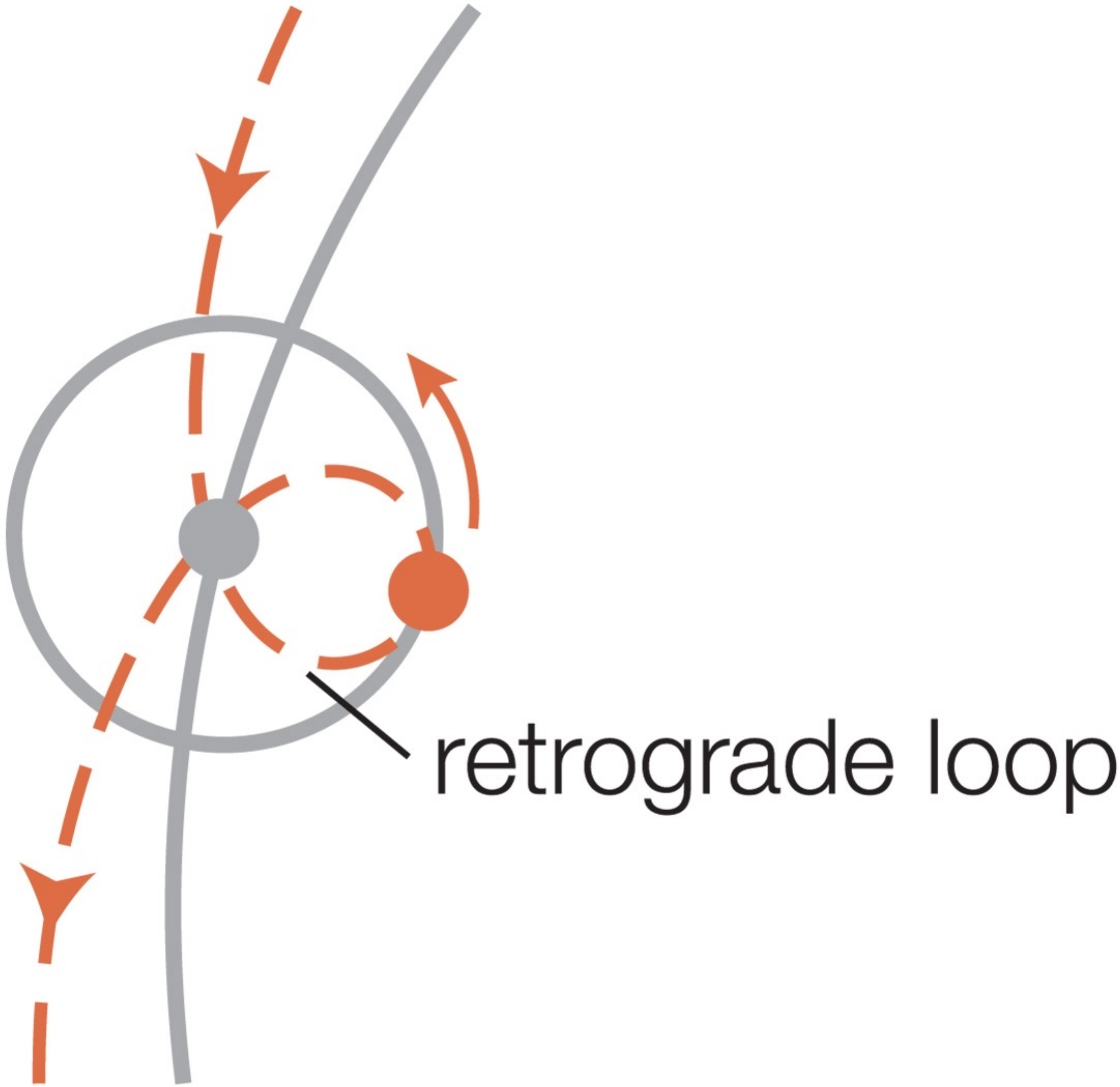


Figure 3.14

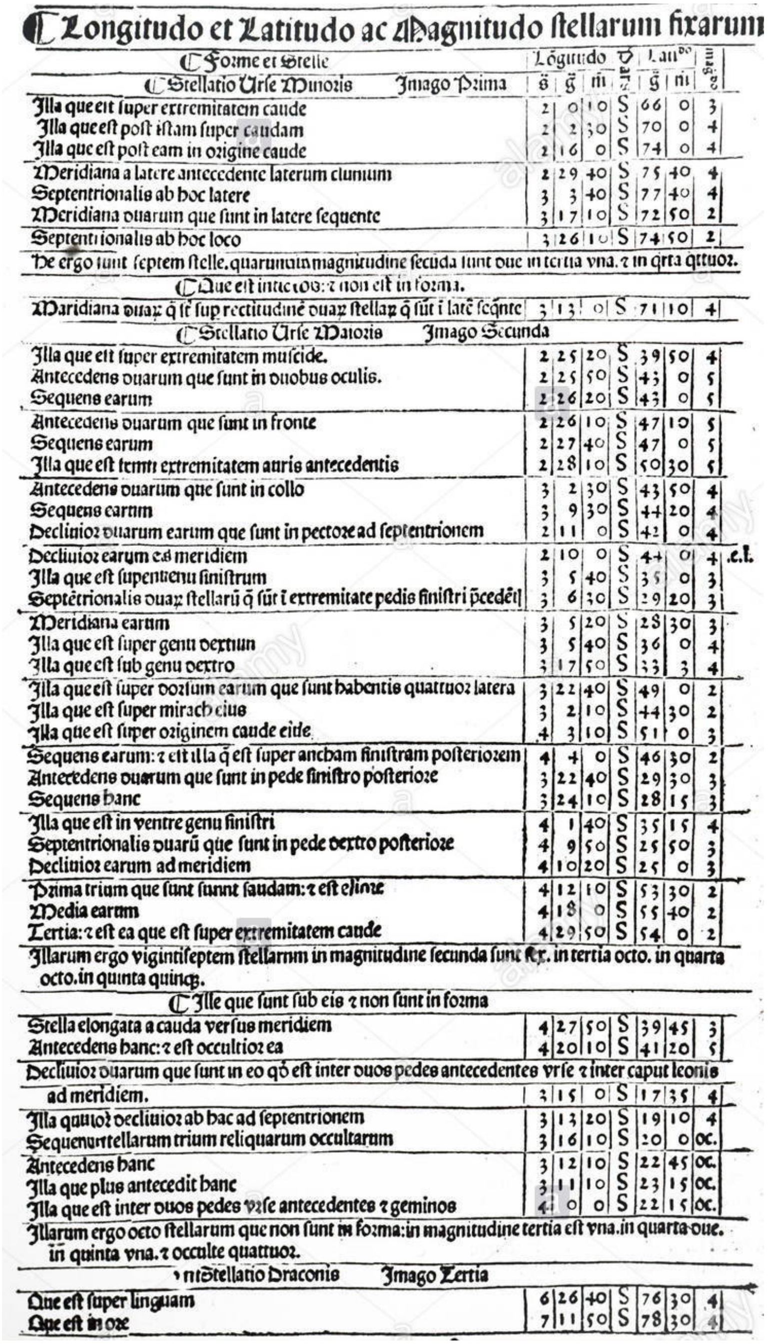


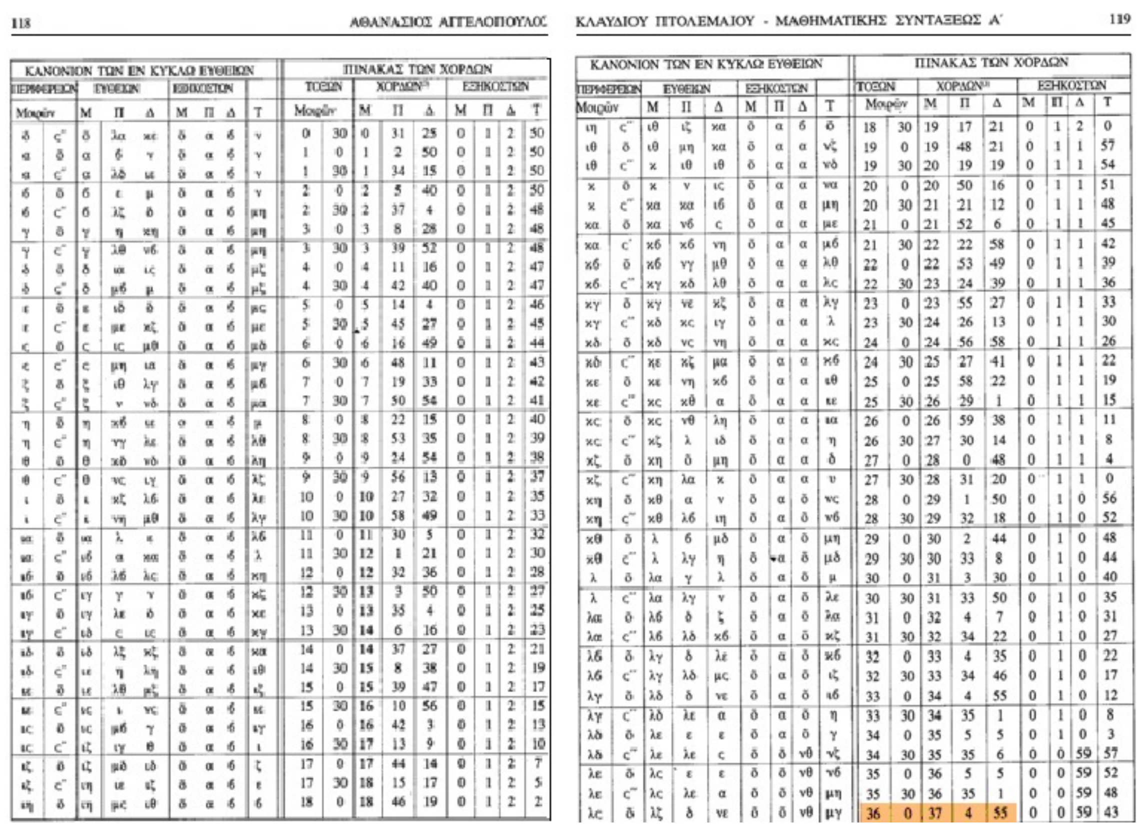
planet
In Ptolemy's model, the planet goes around this small circle . . .
. . . while the small circle goes around the big one.
retrograde loop
Earth
Result: Planet follows this dashed path.


retrograde loop

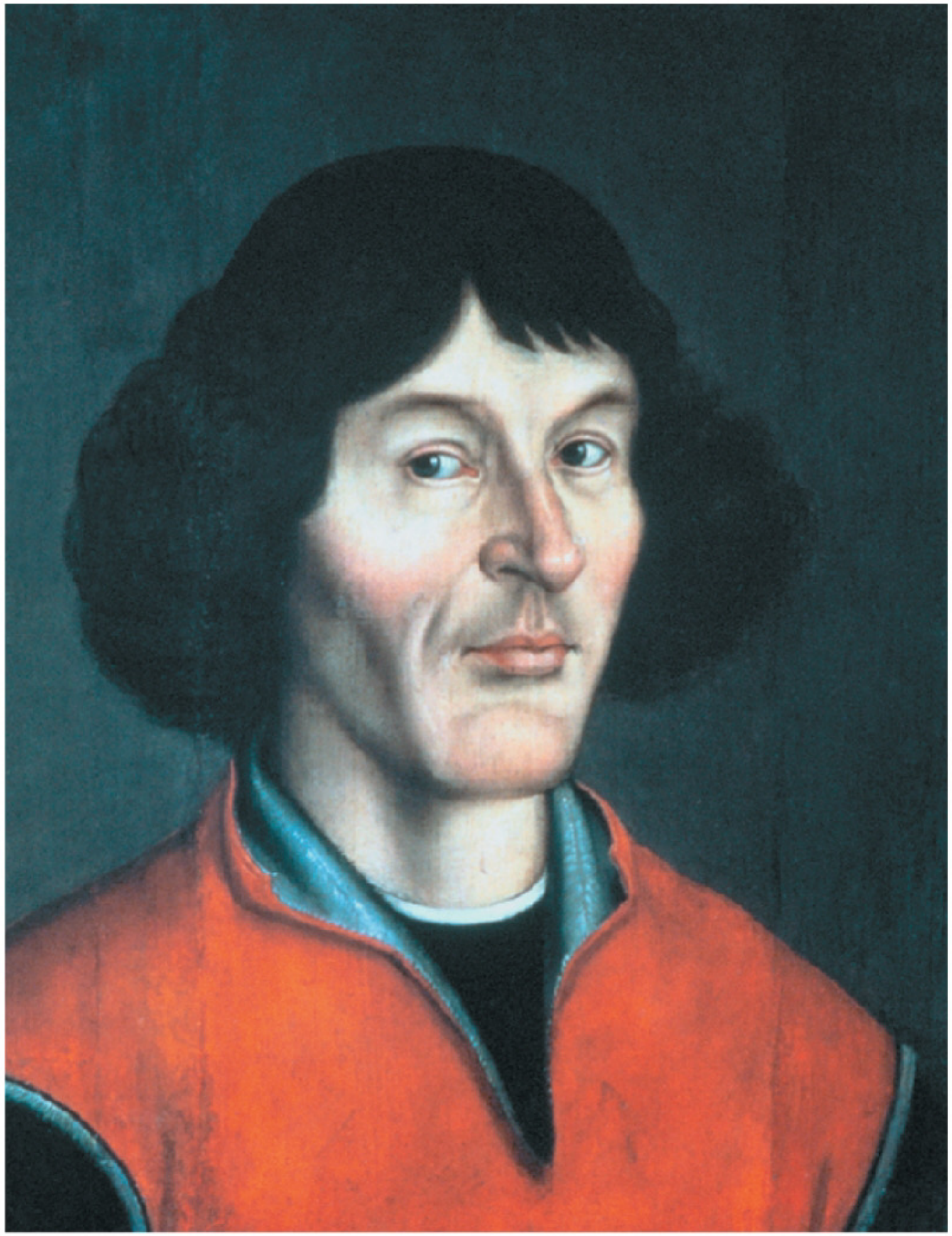
Problem: Retrograde Motion

Data for Ptolemy's Model

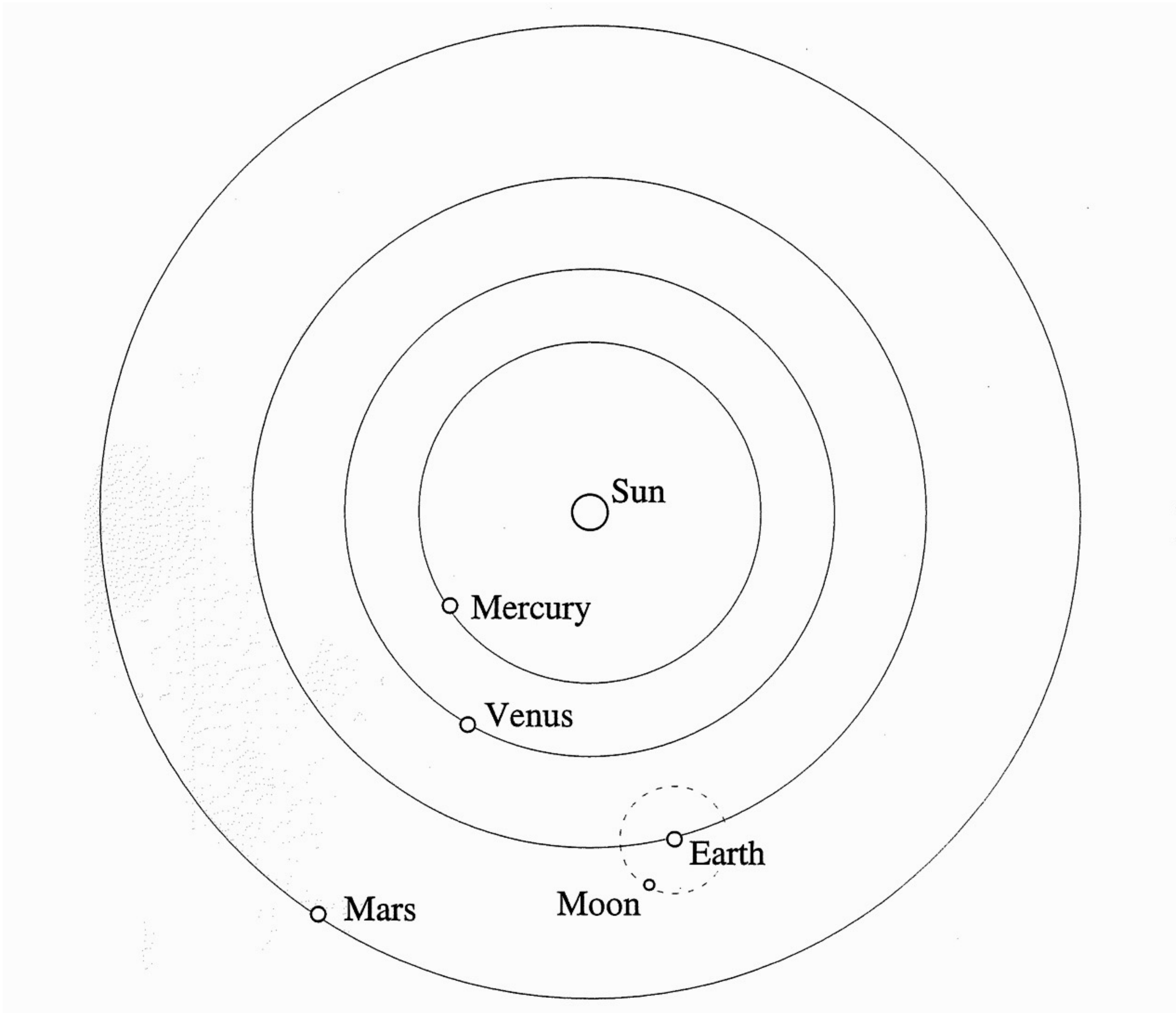


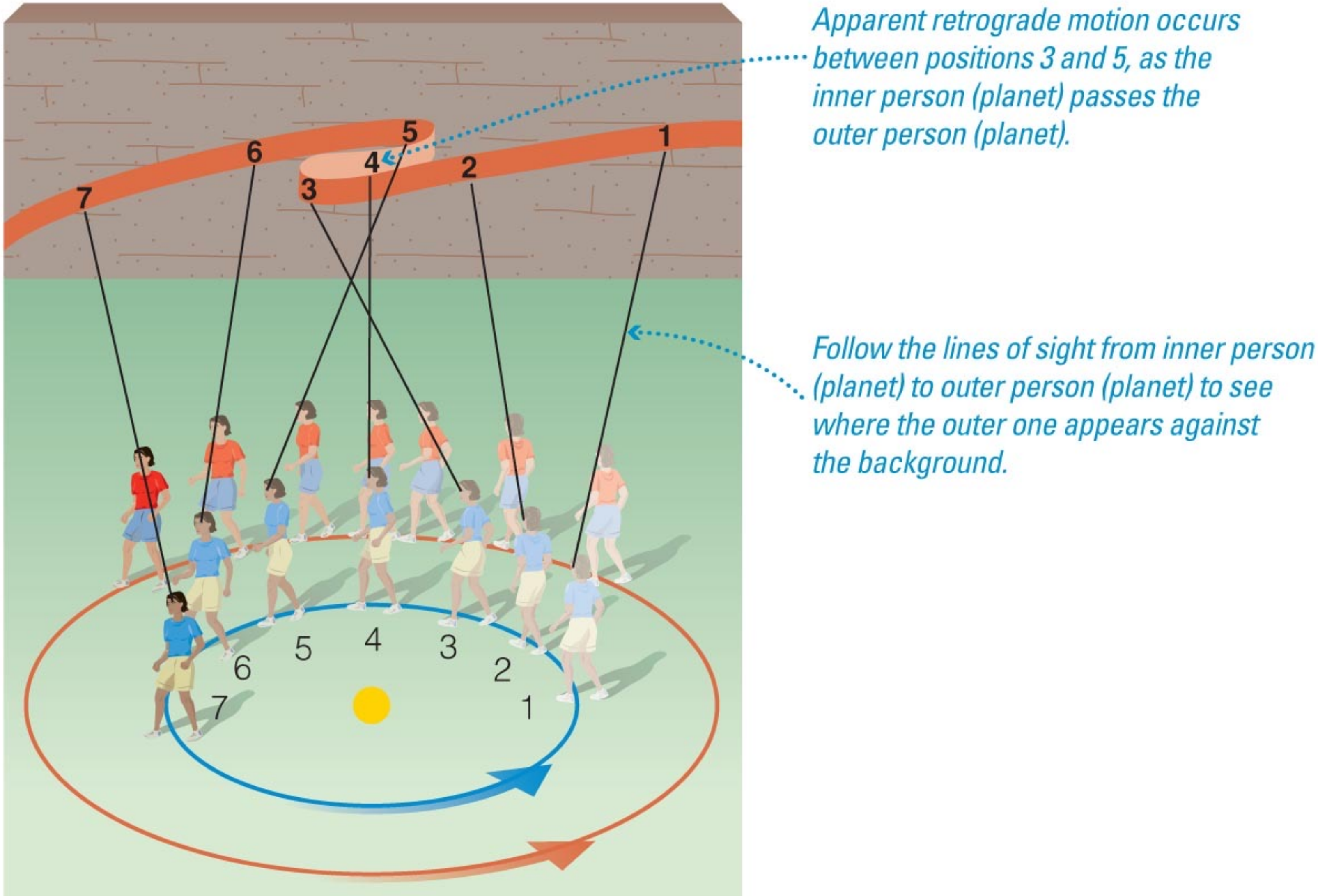


Nicolaus Copernicus (1473 - 1543)



Copernicus' Heliocentric Model





a The retrograde motion demonstration: Watch how your friend (in red) usually appears to move forward against the background of the building in the distance but appears to move backward as you (in blue) catch up to and pass her in your "orbit."

Ptolemy (~AD 127–145)

- Geocentric
- Orbits combine multiple perfect circles with uniform motion
- Good predictions
- Complicated
- No apparent path for expansion for new planets
- 1500 years of popularity and success!

Copernicus (1473–1543)

- Heliocentric
- Orbits are single, concentric perfect circles with uniform motion
- Fairly poor predictions
- Simple
- No apparent path for expansion for new planets
- Fairly new, hasn't passed the test of time

Which key assumption(s) made Ptolemy's model very complicated but allowed it to adequately describe planetary motions?

1. The Sun is at the center of the Universe.
2. All heavenly bodies move in combinations of perfect circles.
3. The Earth is at the center of the Universe.
4. The stars never move.
5. 1 & 2
6. 2 & 3
7. 1 & 4
8. other (and be ready to specify!)

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2. All heavenly bodies move in combinations of perfect circles.
3. The Earth is at the center of the Universe.
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6. **2 & 3**
7. 1 & 4
8. other (and be ready to specify!)

Which key assumption(s) made Copernicus' model very simple but prevented it from adequately describing planetary motions?

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5. **1 & 2**
6. 2 & 3
7. 1 & 4
8. other (and be ready to specify!)

The best test of a scientific hypothesis or model is that it

a. agrees with previously known theories
b. explains all known observations
c. explains the observations in a particularly simple fashion
d. correctly predicts new observations
e. is easily transcribed into mathematical notation

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a. agrees with previously known theories

b. explains all known observations

c. explains the observations in a particularly simple fashion

d. correctly predicts new observations

e. is easily transcribed into mathematical notation

Important Claims of the Aristotelian View

- The universe is geocentric: All heavenly bodies orbit the Earth
- Heavenly bodies are perfect, unblemished
- The heavens are eternal, unchanging


Galileus Galileus
Florentinus
Superioꝝ
licentia
16
24.
Eques Octauius Leonus
Roman' pictor feci

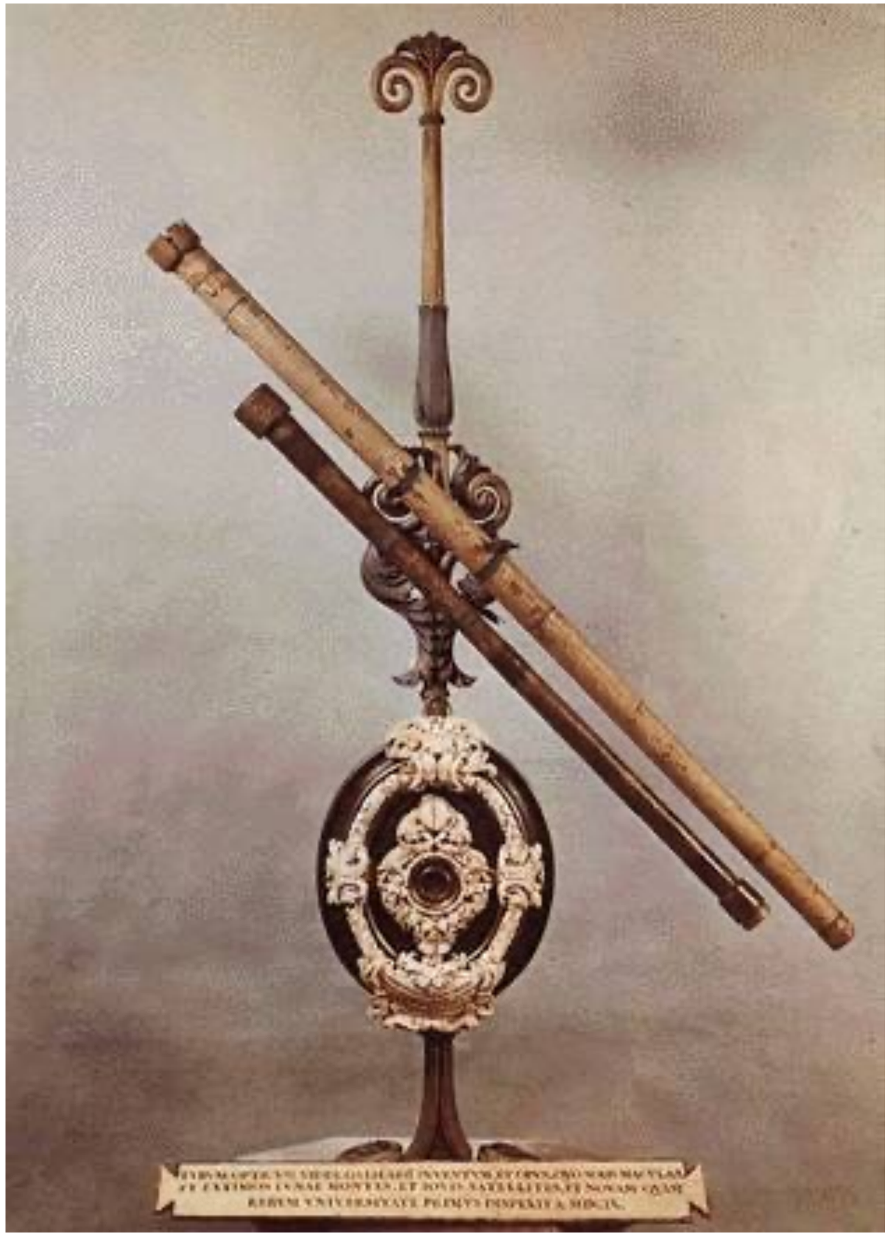
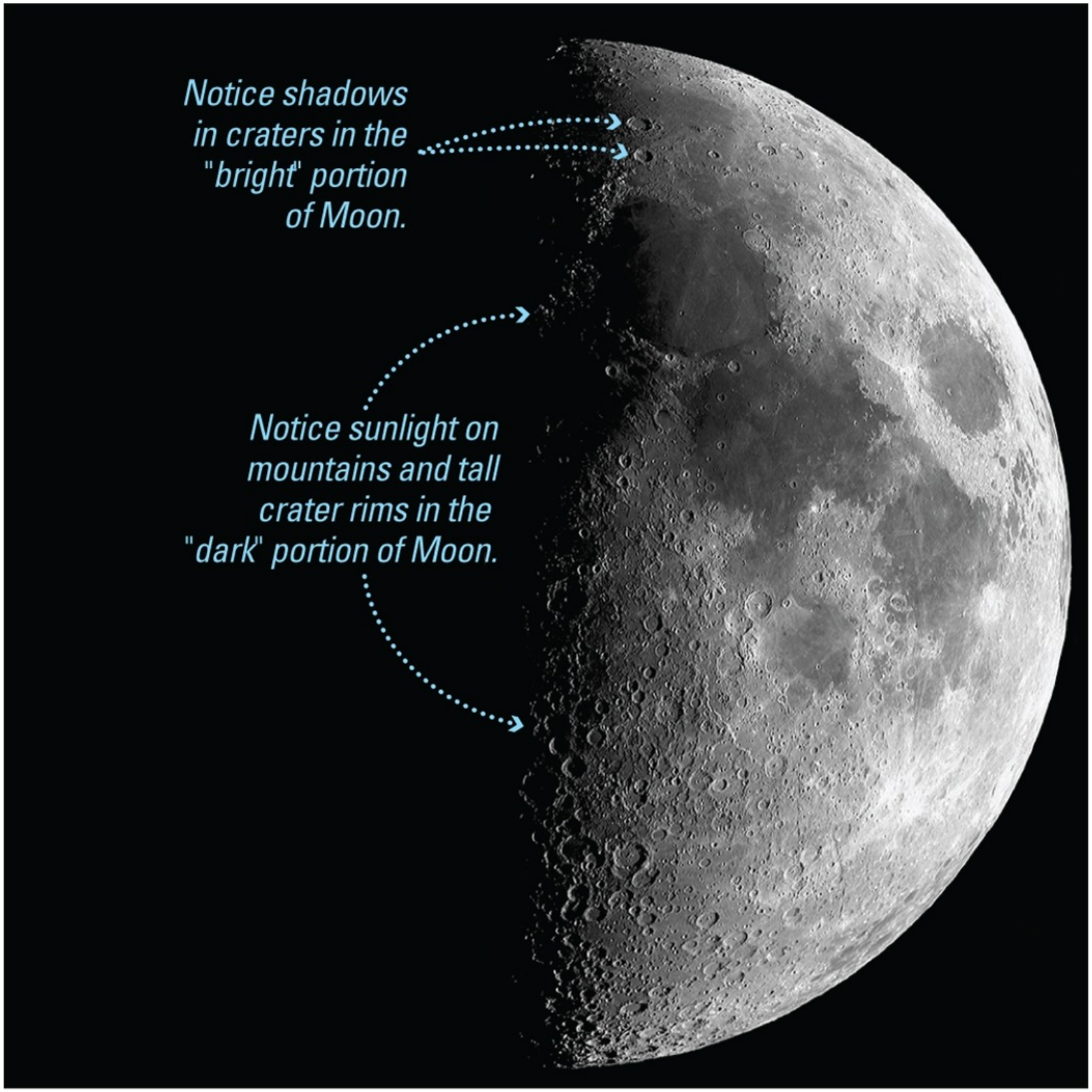
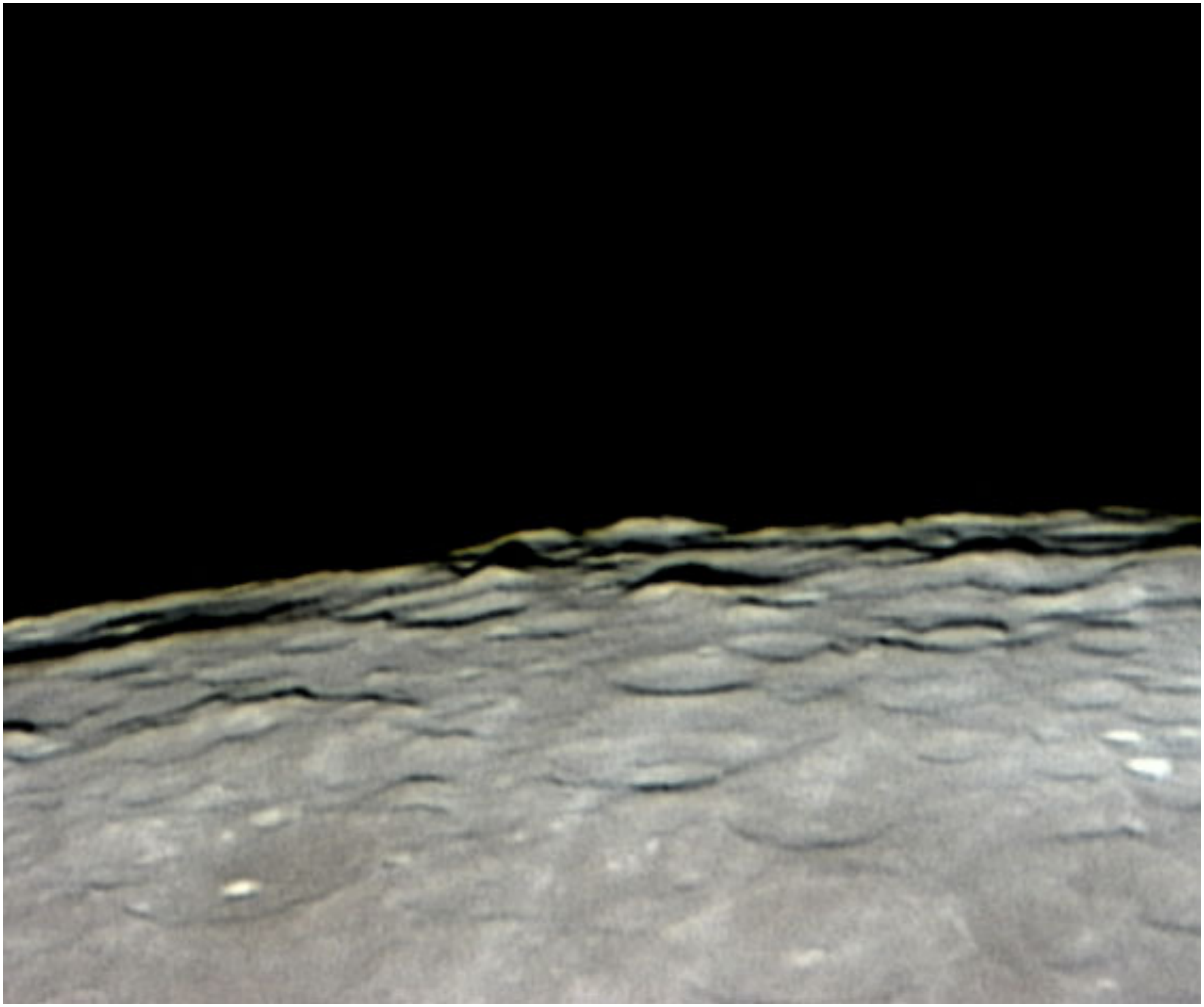
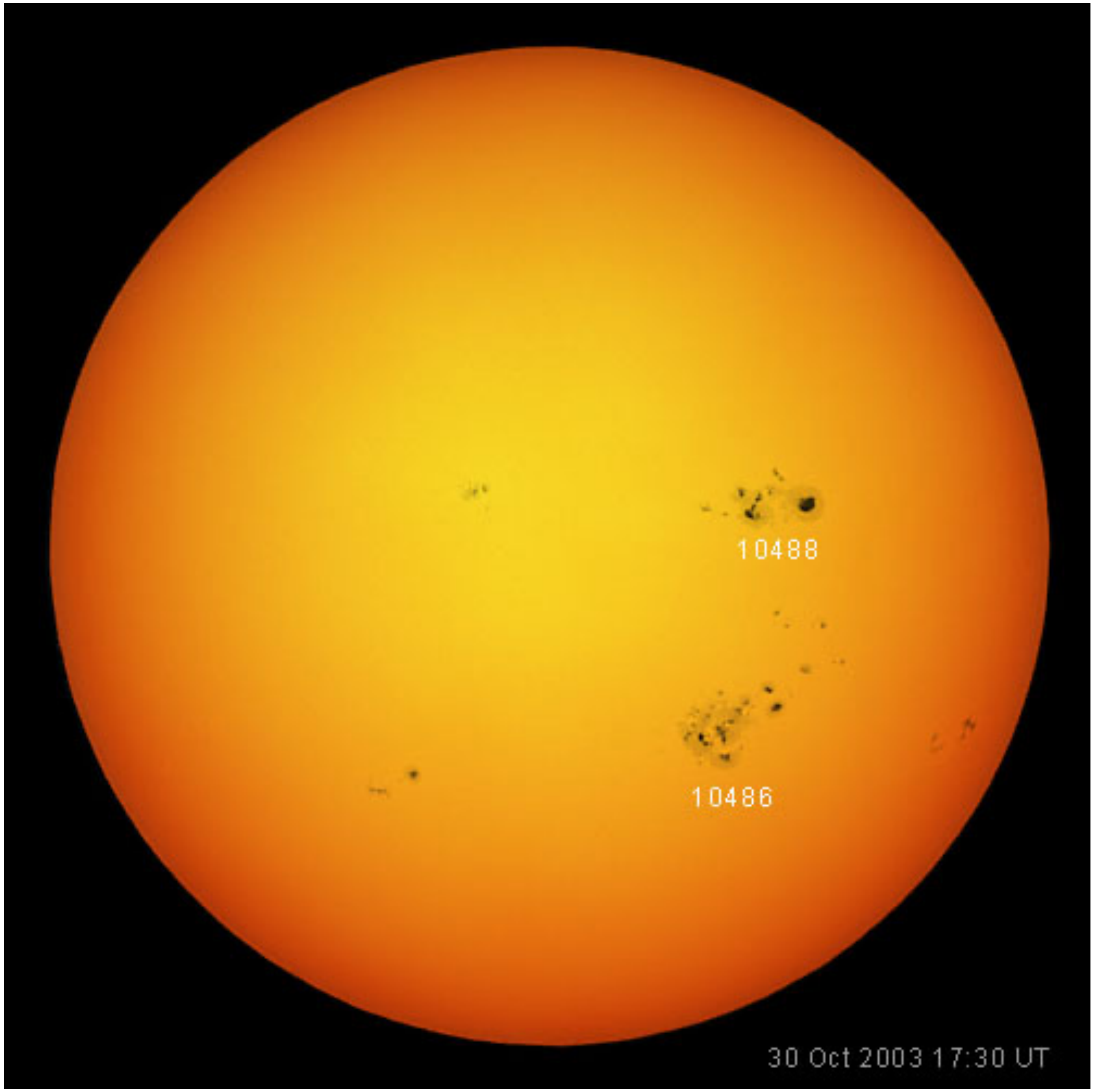


Figure 3.20



Notice shadows in craters in the "bright" portion of Moon.
Notice sunlight on mountains and tall crater rims in the "dark" portion of Moon.




10488
10486
30 Oct 2003 17:30 UT

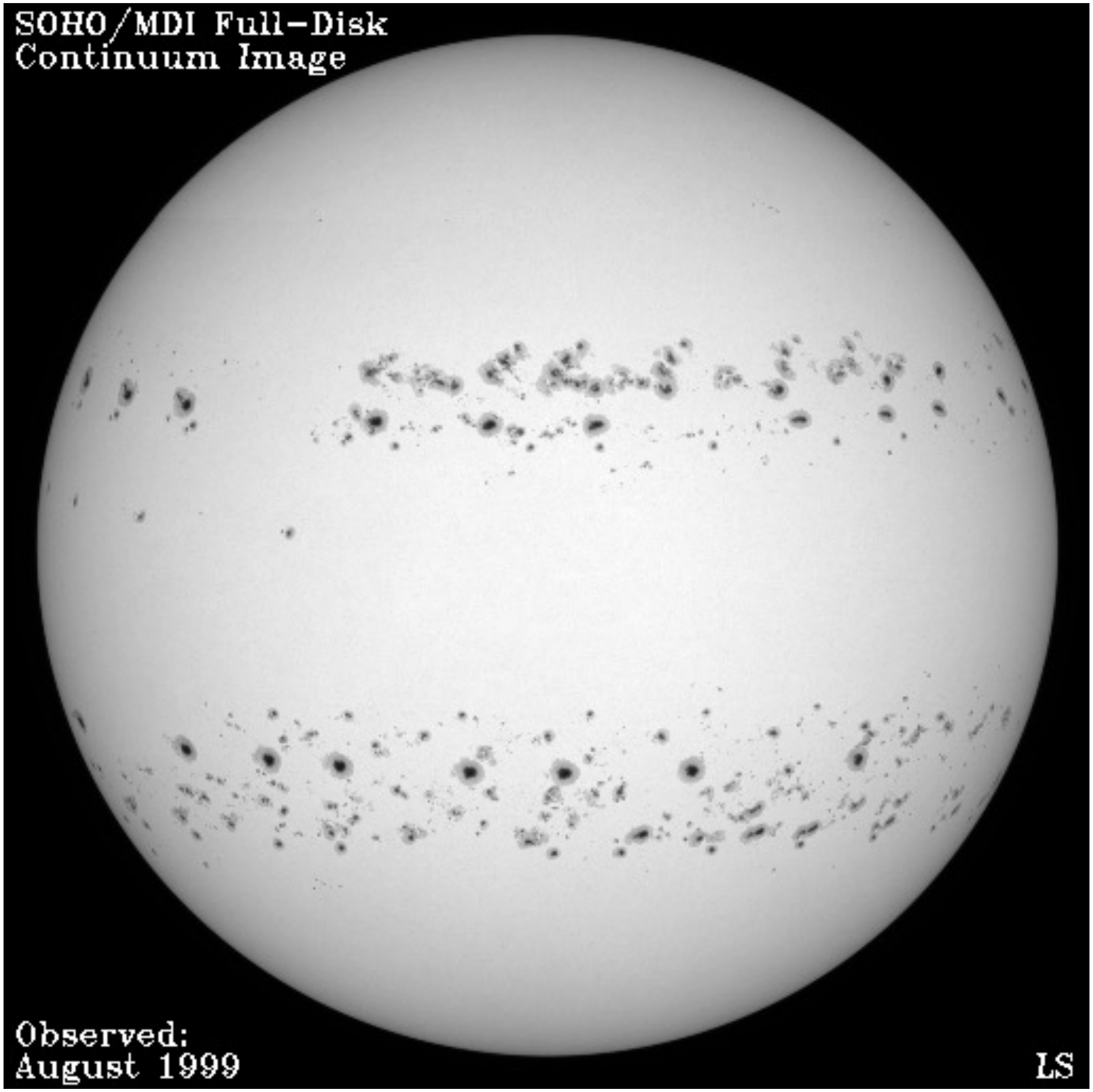
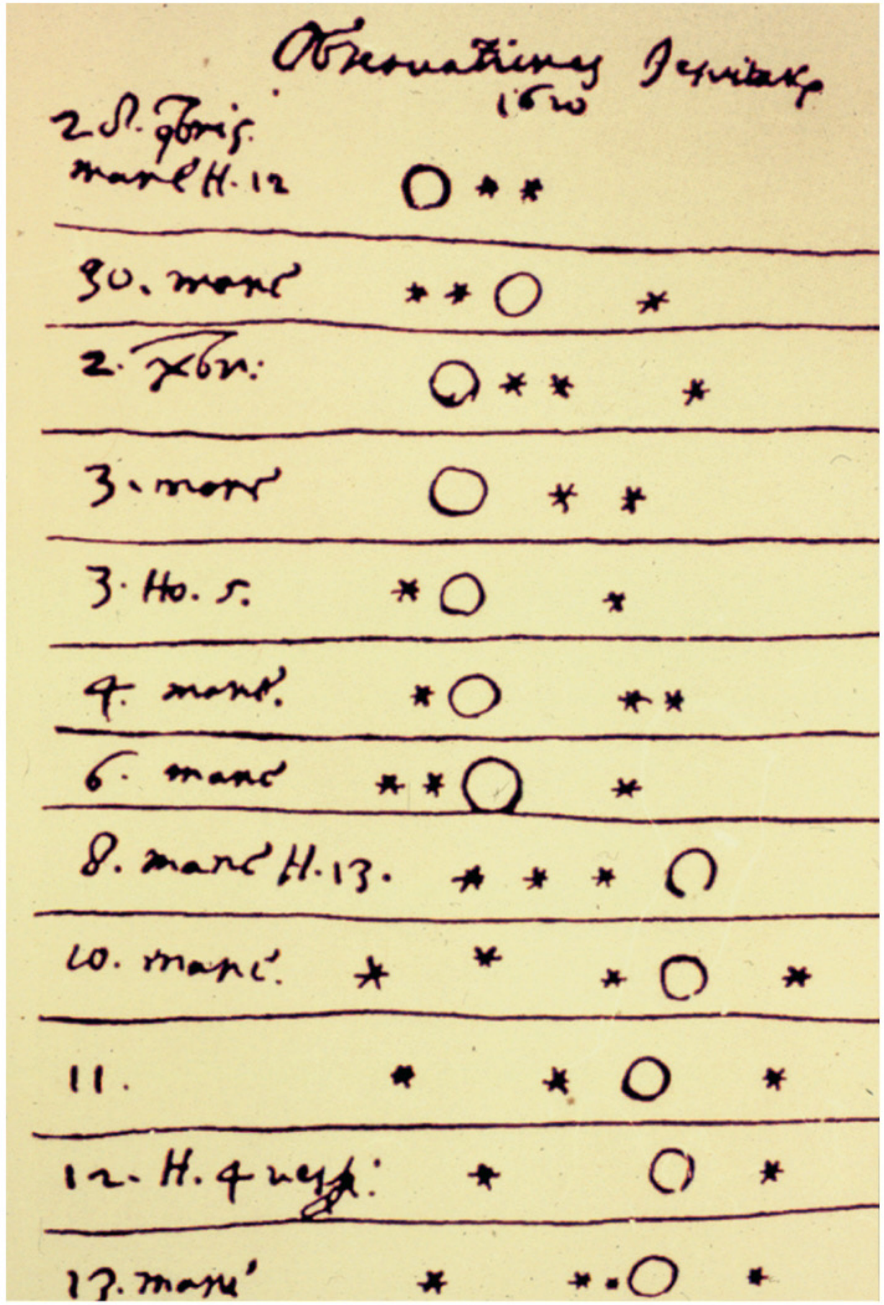
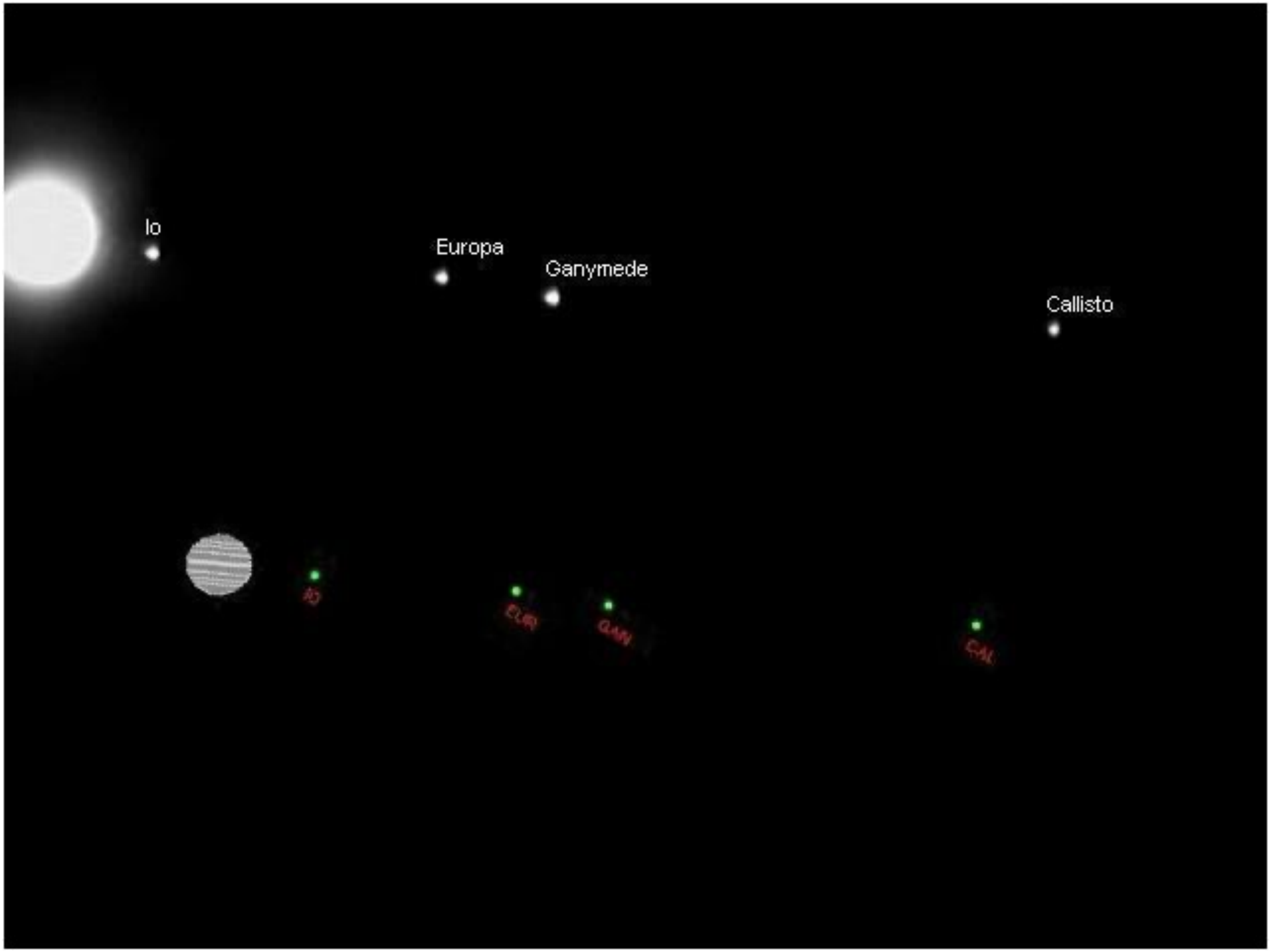

SOHO/MDI Full-Disk
Continuum Image
Observed:
August 1999
LS

Figure 3.21


30. mane
3. Ho. 5.
4. mane.
6. mane
8. mane H.13.
10. mane.
11.
12. H. 4 vesp:
13. mane


Io
Europa
Ganymede
Callisto
IO
EUR
GAN
CAL

You see Venus in the evening sky close to the horizon. How long will it be before Venus is near the zenith at midnight?

a. six hours (a quarter of one day)
b. one day
c. one week
d. one month
e. a quarter of a Venusian year (about two months)
f. half a Venusian year (about four months)
g. none of the above

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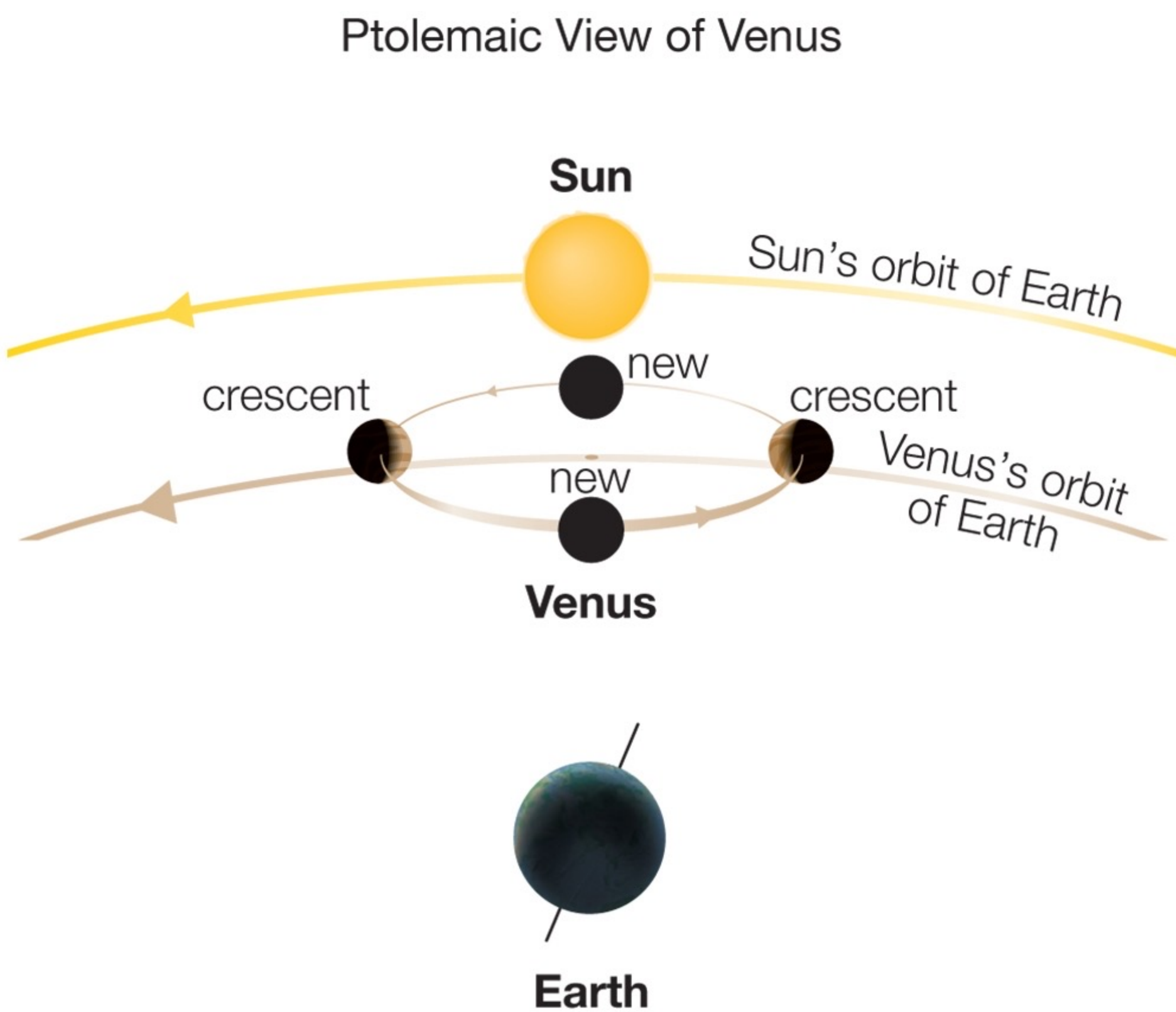
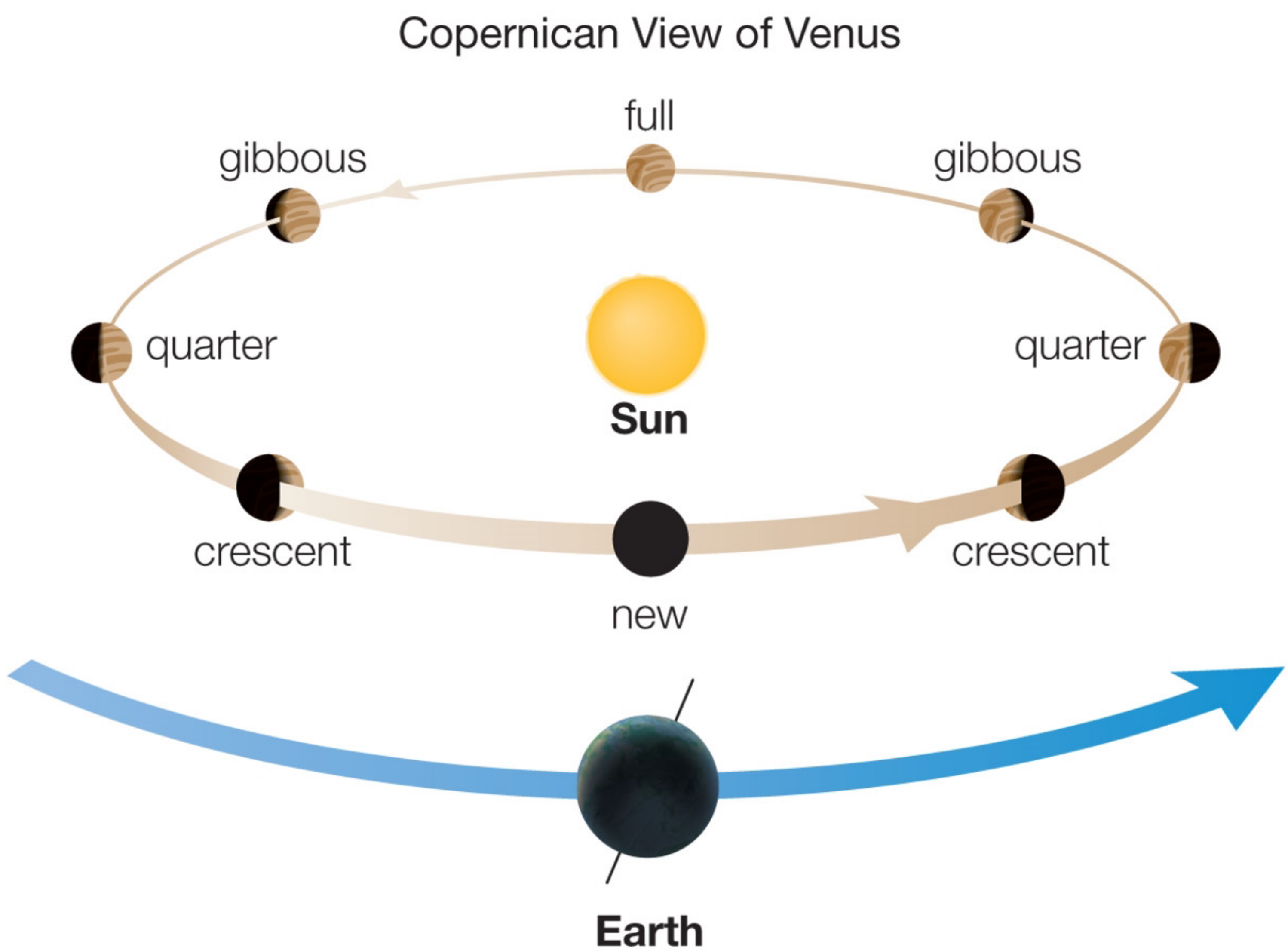
a. six hours (a quarter of one day)
b. one day
c. one week
d. one month
e. a quarter of a Venusian year (about two months)
f. half a Venusian year (about four months)
g. none of the above – it can never happen!

Figure 3.22a



a In the Ptolemaic system, Venus orbits Earth, moving around a smaller circle on its larger orbital circle; the center of the smaller circle lies on the Earth-Sun line. If this view were correct, Venus's phases would range only from new to crescent.

Figure 3.22b



b In reality, Venus orbits the Sun, so from Earth we can see it in many different phases. This is just what Galileo observed, telling him that Venus orbits the Sun.


April 1
May 1
April 10
May 9
April 19
April 25
May 15


1241 UT
23/10/02
1342 UT
12/10/02
1352 UT
5/10/02
1352 UT
23/9/02
1519 UT
16/9/02
1541 UT
10/9/02
1548 UT
31/8/02
1350 UT
12/8/02
1803 UT
1/8/02
1630 UT
20/7/02
1940 UT
3/7/02
1525 UT
19/6/02
1902 UT
1/6/02
1810 UT
3/5/02
VENUS 2002
Photographed at the TBGS Observatory
by Chris Proctor

Tycho Brahe (1546-1601)

Figure 3.15

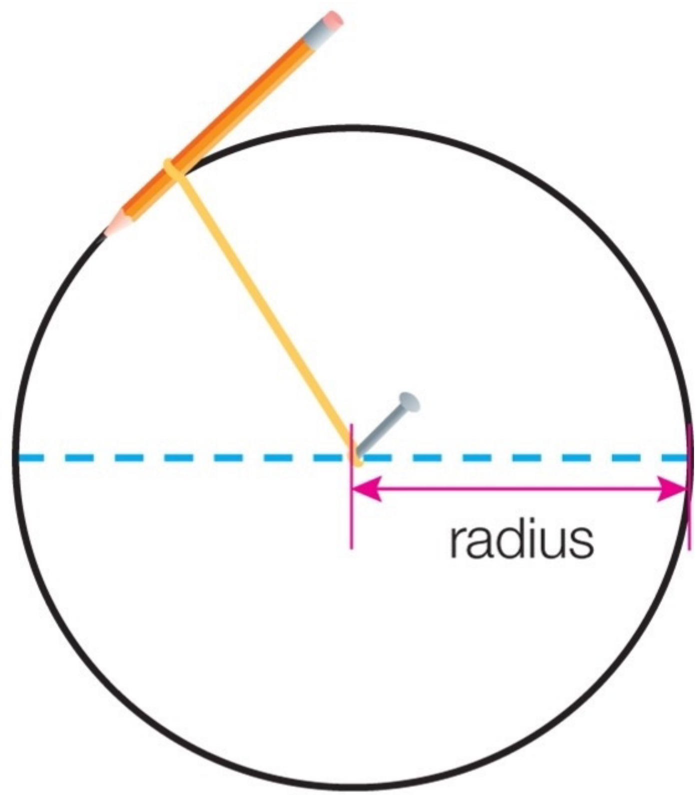

EFFIGIES TYCHONIS BRAHE O.F.
ÆDIFICII ET INSTRUMENTORUM
ASTRONOMICORUM STRUCTORIS.
A°. DOMINI 1587, ÆTATIS SUÆ 40.

Johannes Kepler (1571-1630)

Johannes Kepler (1571-1630)

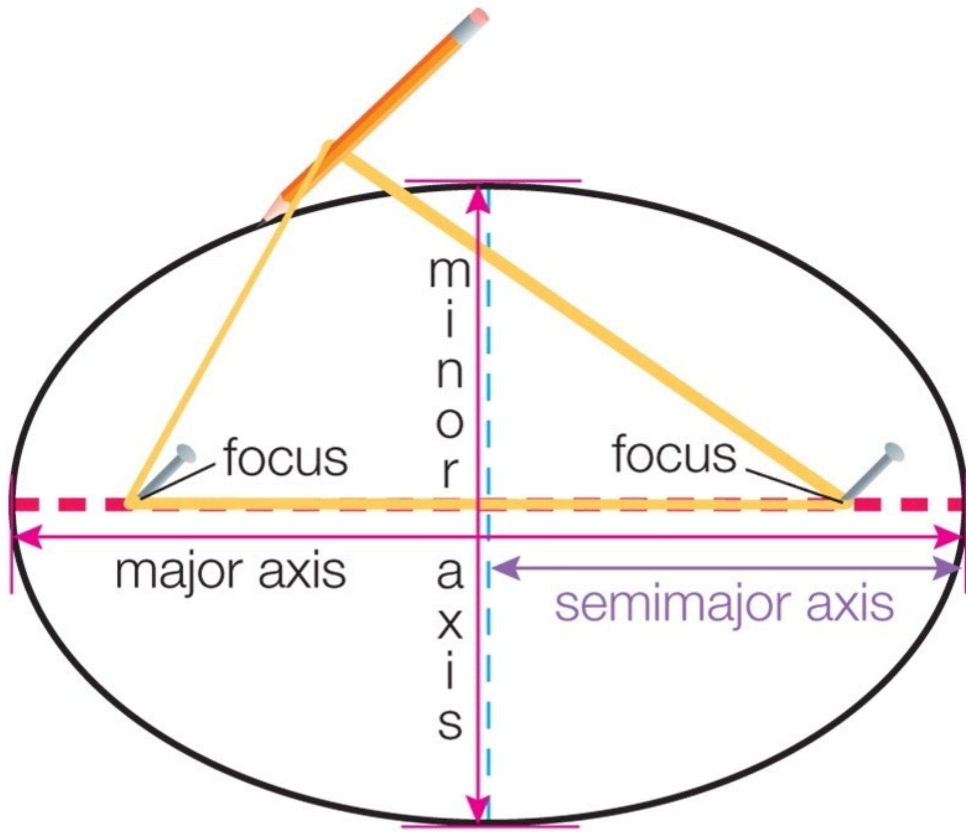
- Orbits are ellipses, not circles
- Sun at one focus, not center: Helio-focal, not heliocentric (though casually called “heliocentric”)
- Excellent predictions! Modern astronomy computer programs use them
- Slightly more complicated than Copernican, but ellipses are elegant, classically recognized shapes
- Predicts the orbital characteristics of future planets!

What's an ellipse? First, all points on a circle are the same distance from the center

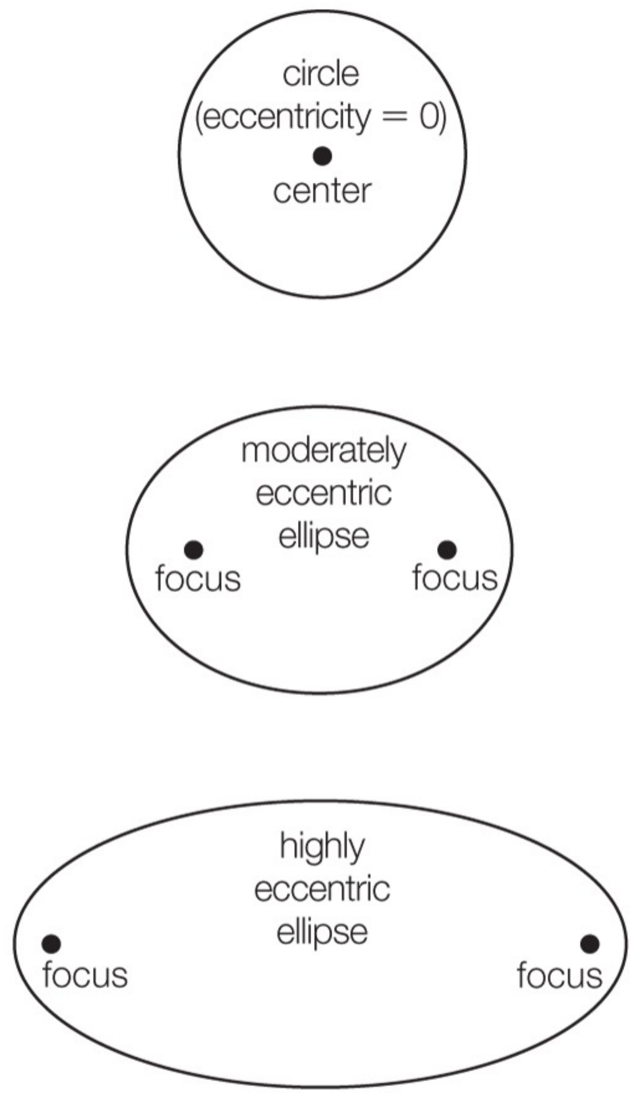


a Drawing a circle with a string of fixed length.

An ellipse has two focus points instead of one center, and the sum of distances from them remains constant

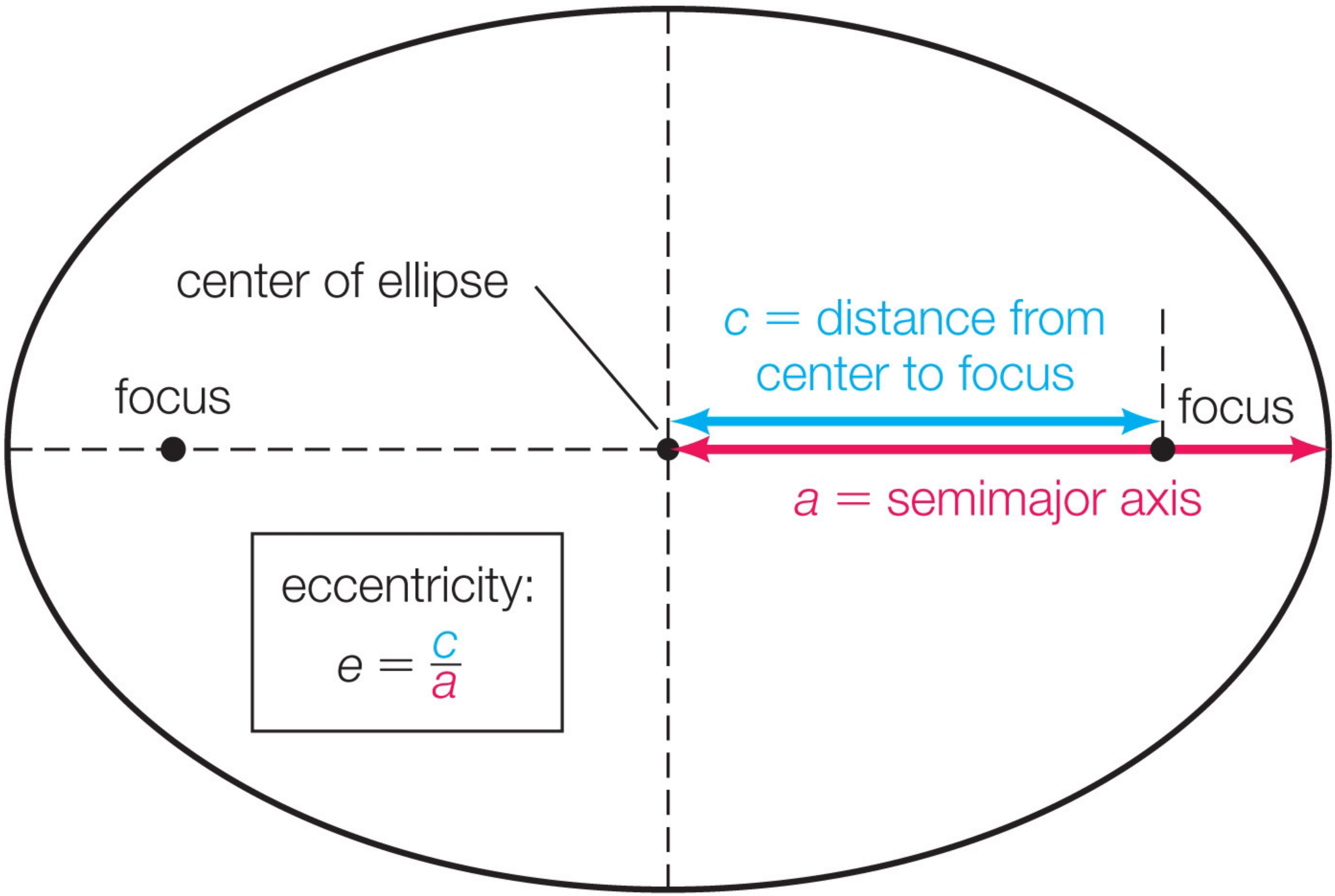


b Drawing an ellipse with a string of fixed length.

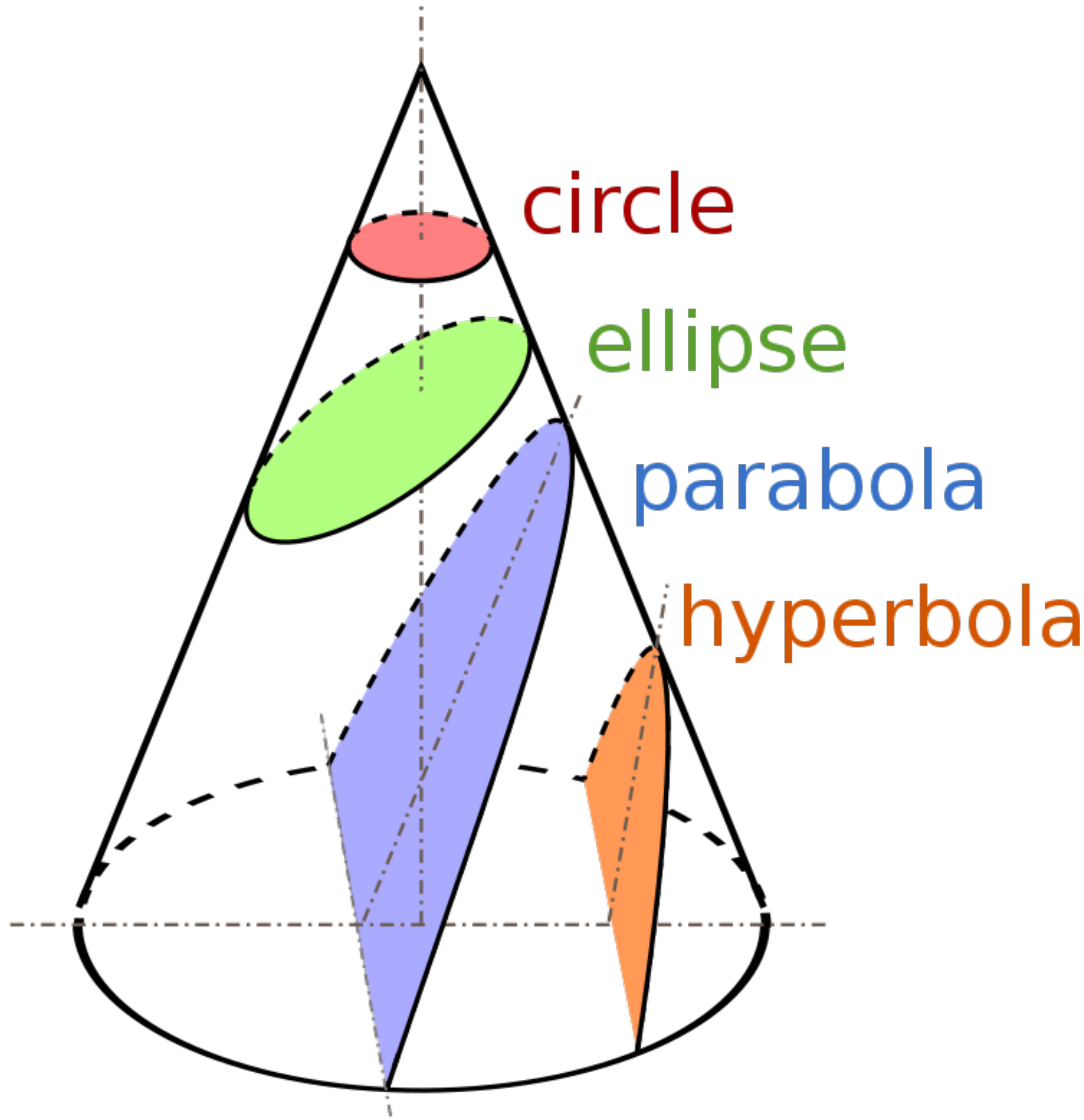


c Eccentricity describes how much an ellipse deviates from a perfect circle.

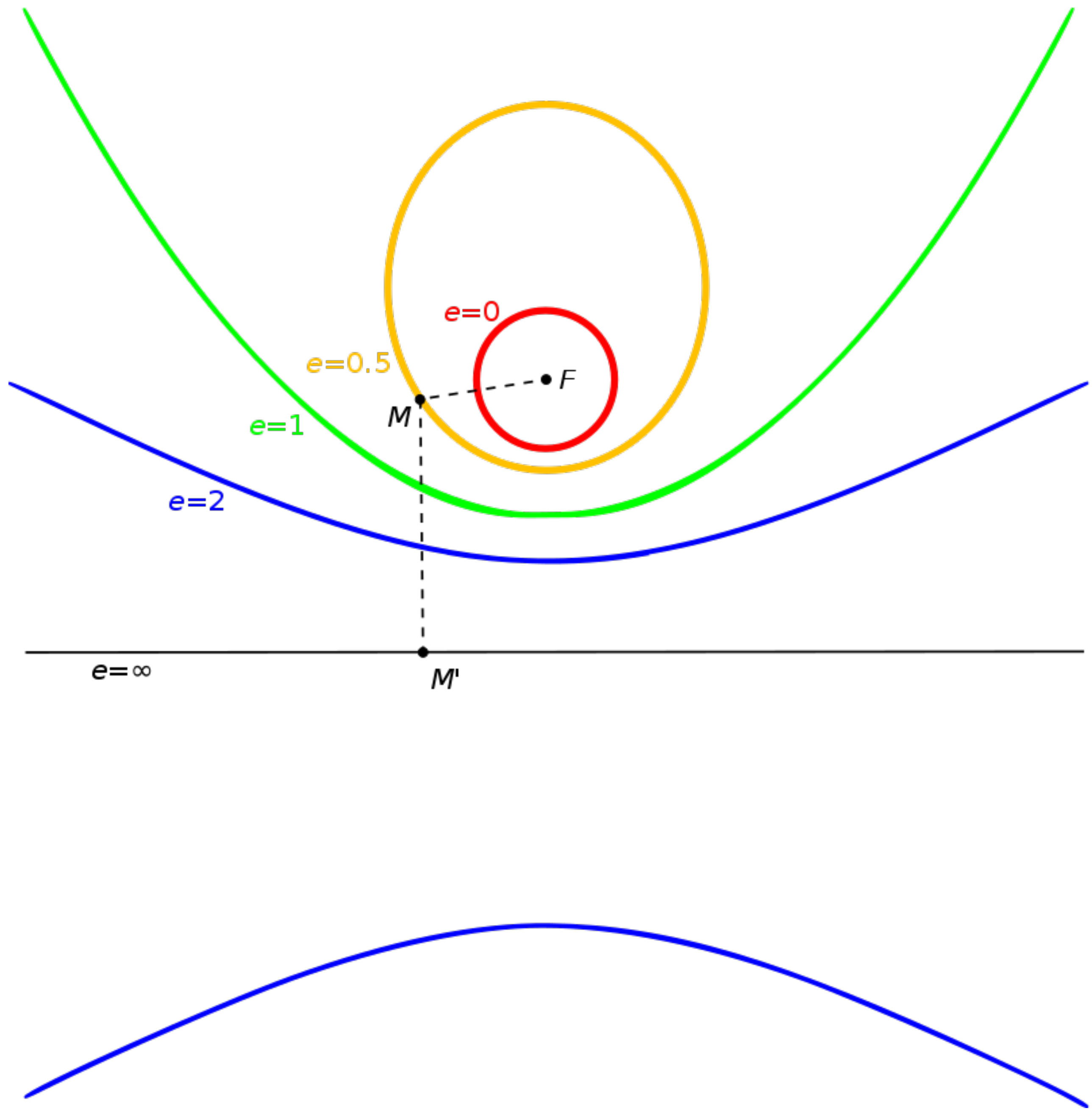
Unnumbered Figure 1 Page 68



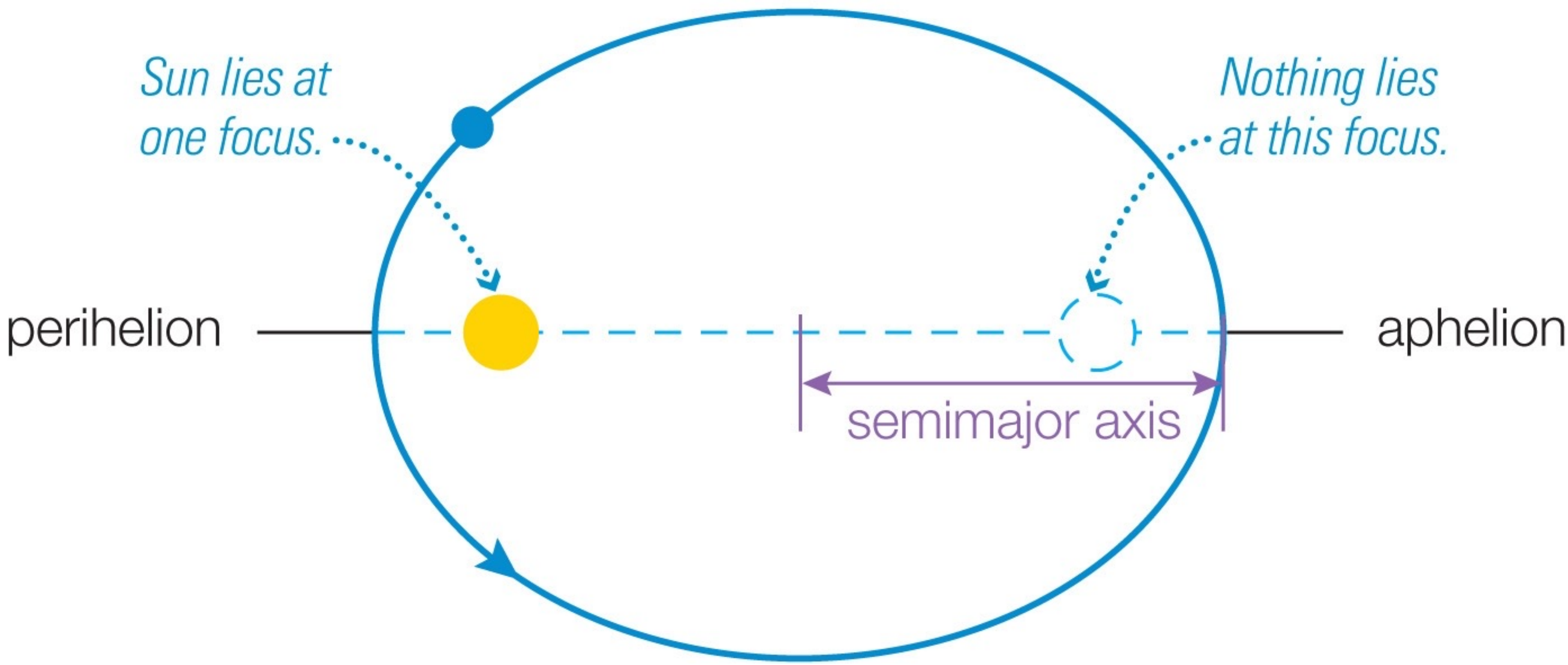
Conic Sections – Perspective

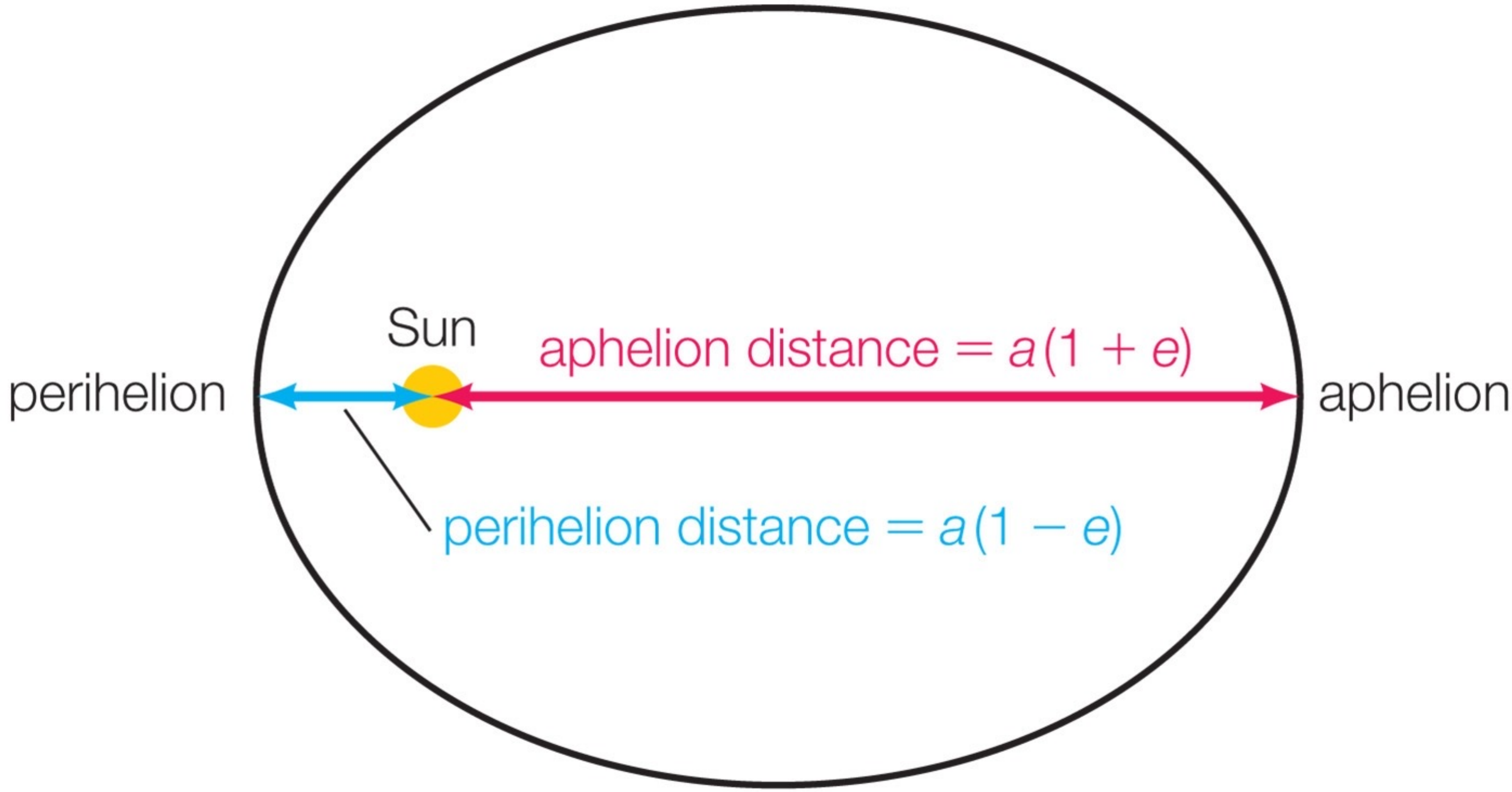


Conic sections in a plane



First law: Planetary orbits are ellipses with the Sun at one focus




Sun
aphelion distance = a(1 + e)
perihelion
aphelion
perihelion distance = a(1 − e)

A spacecraft in orbit around the Sun has its aphelion at Earth's orbit (1 A.U.), then moves inward and just reaches its perihelion at Mercury's orbit (about 0.4 A.U.). What is the semi-major axis of this spacecraft's orbit?

a. 0.4 A.U.
b. 0.7 A.U.
c. 1.0 A.U.
d. 1.4 A.U.
e. other

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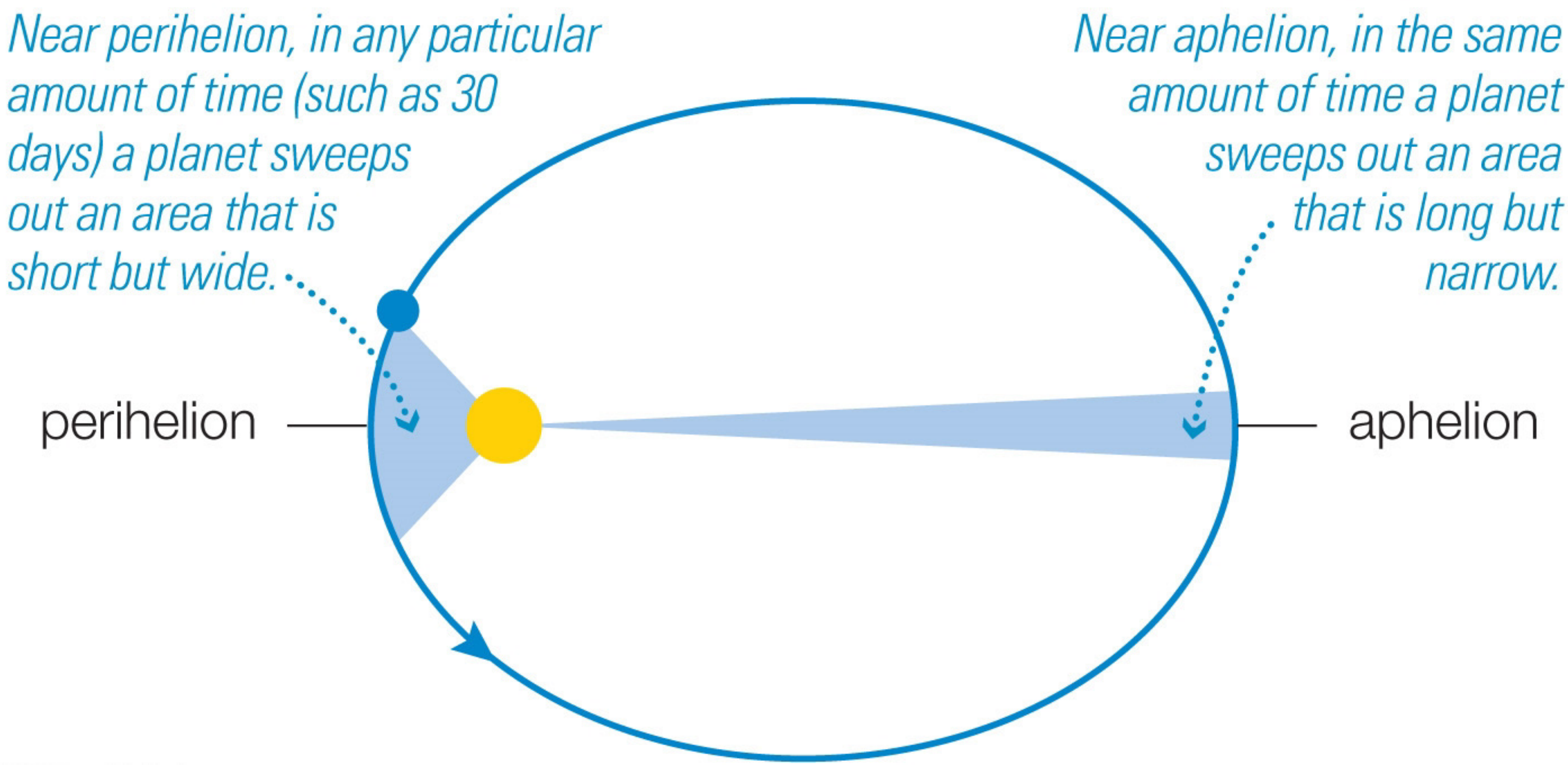
a. 0.4 A.U.
b. 0.7 A.U.
c. 1.0 A.U.
d. 1.4 A.U.
e. other

Second law: a line from the Sun to a planet sweeps out equal areas in equal times



Recall: the spacecraft has aphelion at 1 A.U. and perihelion at 0.4 A.U. How does its speed at perihelion compare with its speed at aphelion?

a. $0.16 = 0.4^2$ times as fast
b. 0.4 times as fast
c. The two speeds are exactly the same
d. $2.5 = 1/0.4$ times as fast
e. $6.25 = (1/0.4)^2$ times as fast

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e. $6.25 = (1/0.4)^2$ times as fast

A spacecraft in orbit around the Sun has its perihelion at Earth's orbit (1 A.U.), where its speed is 40 km/s. Its aphelion is at Jupiter's orbit (about 5 A.U.). What is its speed at that point?

a. 200 km/s
b. 40 km/s
c. 20 km/s
d. 8 km/s
e. 4 km/s
f. none of the above

A spacecraft in orbit around the Sun has its perihelion at Earth's orbit (1 A.U.), where its speed is 40 km/s. Its aphelion is at Jupiter’s orbit (about 5 A.U.). What is its speed at that point?

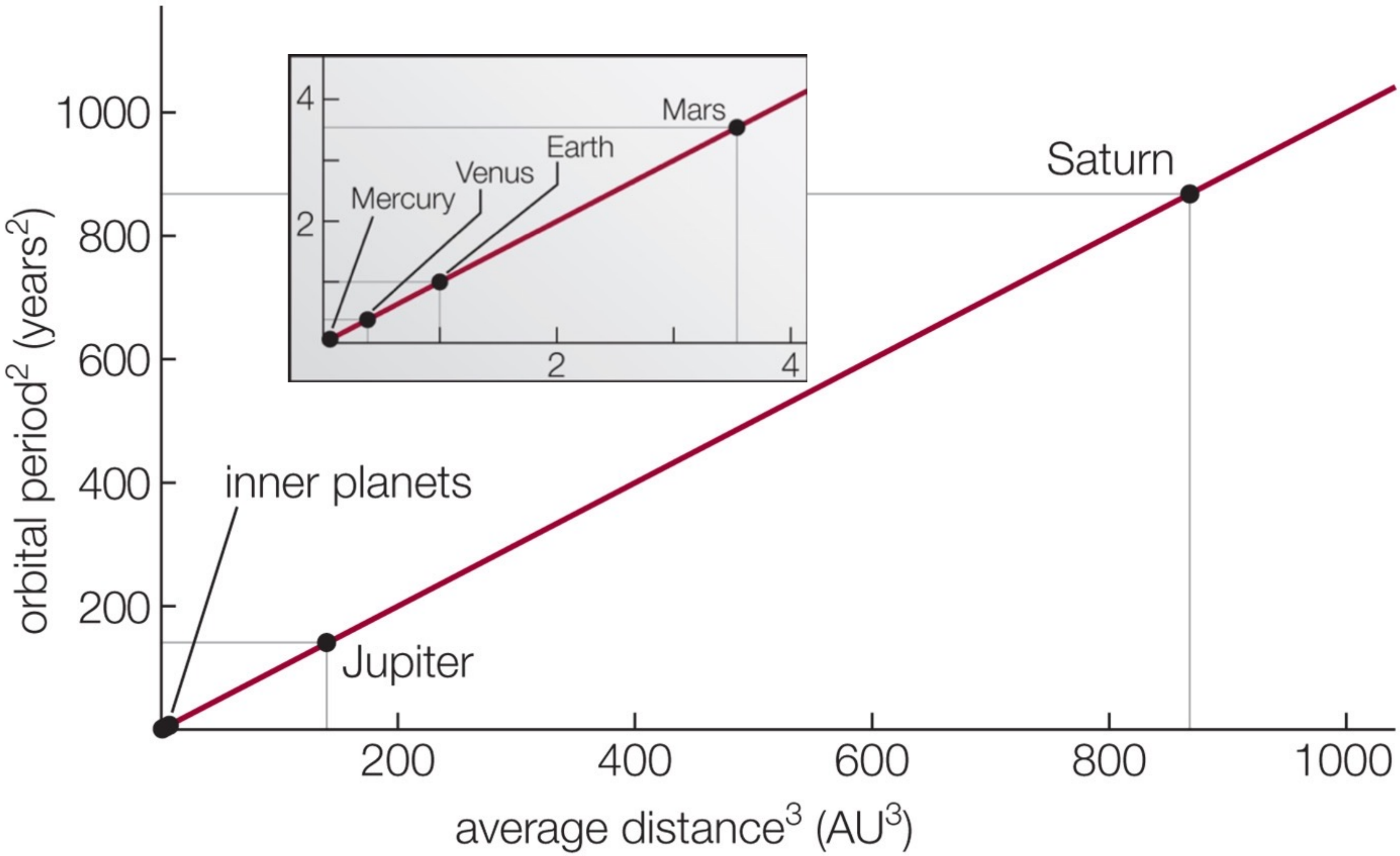
a. 200 km/s
b. 40 km/s
c. 20 km/s
d. 8 km/s
e. 4 km/s
f. none of the above

Third law: the cube of the semi-major axis is proportional to the square of the orbital period

- The proportionality can be related to Earth's values of 1 AU and 1 year
- If a planet's semi-major axis is in AUs, its calculated period will be in years
- Unlike the others, this law makes predictions for newly discovered planets

Planetary Data

	semi-major axis (10^6 km)	semi-major axis (AU)	Eccentricity -	Perihelion (10^6 km)	Aphelion (10^6 km)	Orbital Period (days)	Orbital Period (years)
MERCURY	57.9	0.39	0.205	46	69.8	88	0.24
VENUS	108.2	0.72	0.007	107.5	108.9	224.7	0.62
EARTH	149.6	1.00	0.017	147.1	152.1	365.2	1.00
MARS	227.9	1.52	0.094	206.6	249.2	687	1.88
JUPITER	778.6	5.20	0.049	740.5	816.6	4331	11.86
SATURN	1433.5	9.58	0.057	1352.6	1514.5	10747	29.43
URANUS	2872.5	19.20	0.046	2741.3	3003.6	30589	83.76
NEPTUNE	4495.1	30.05	0.011	4444.5	4545.7	59800	163.75
PLUTO	5906.4	39.48	0.244	4436.8	7375.9	90560	247.97



orbital period² (years²)
1000
800
600
400
200
average distance³ (AU³)
200
400
600
800
1000
inner planets
Jupiter
Saturn
Mercury
Venus
Earth
Mars
4
2
2
4

a

Suppose a comet had a very eccentric orbit that brought it quite close to the Sun at closest approach (perihelion) and beyond Mars when furthest from the Sun (aphelion), but with an average distance of 1 AU. How long would it take to complete an orbit?

a. less than one year

b. exactly one year

c. more than one year

d. It depends on the exact value of the eccentricity.

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a. less than one year

b. **exactly one year**

c. more than one year

d. It depends on the exact value of the eccentricity.

For the same comet with an average distance of 1 AU, where would it spend most of its time?

a. Farther from the Sun than Earth

b. Closer to the Sun than Earth

c. On average, it would be the same as Earth’s orbit

d. It depends on the exact value of the eccentricity.

For the same comet with an average distance of 1 AU, where would it spend most of its time?

a. **Farther from the Sun than Earth**

b. Closer to the Sun than Earth

c. On average, it would be the same as Earth’s orbit

d. It depends on the exact value of the eccentricity.

You discover a new planet in orbit around the Sun! On average, it is 4 times farther from the Sun than the Earth. What is its orbital period?

a. 4 years
b. 8 years
c. 16 years
d. 32 years
e. 64 years
f. other

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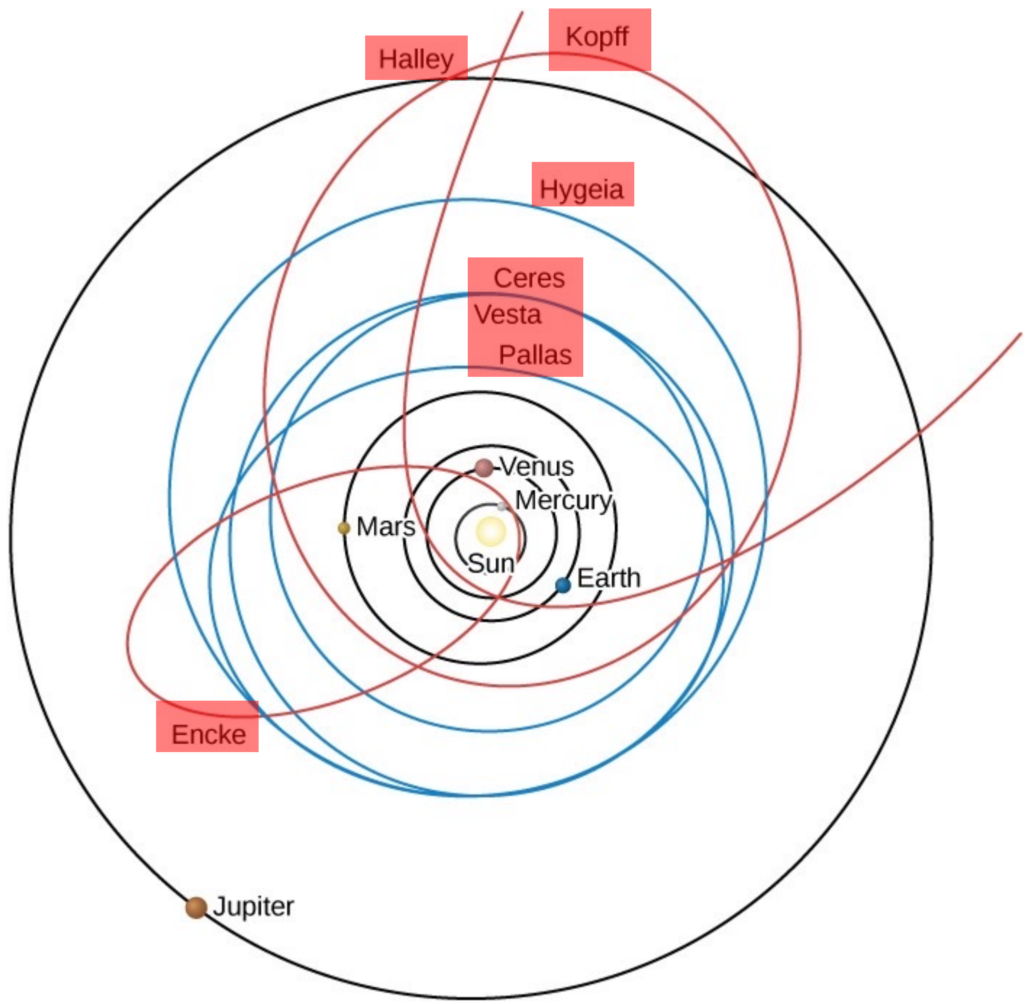
JOHANNES KEPLER'S UPHILL BATTLE
...SO, YOU SEE, THE ORBIT OF A PLANET IS ELLIPTICAL.
WHAT'S AN ORBIT?
WHAT'S A PLANET?
WHAT'S 'ELLIPTICAL'?
S. harris

Kepler's Laws work for new bodies!



Consider two bodies with circular orbits around the same star. According to Kepler's third law, the closer one has a shorter period, but why is that true?

1. It moves at a higher speed
2. It has a shorter distance to travel
3. Both of the above
4. None of the above

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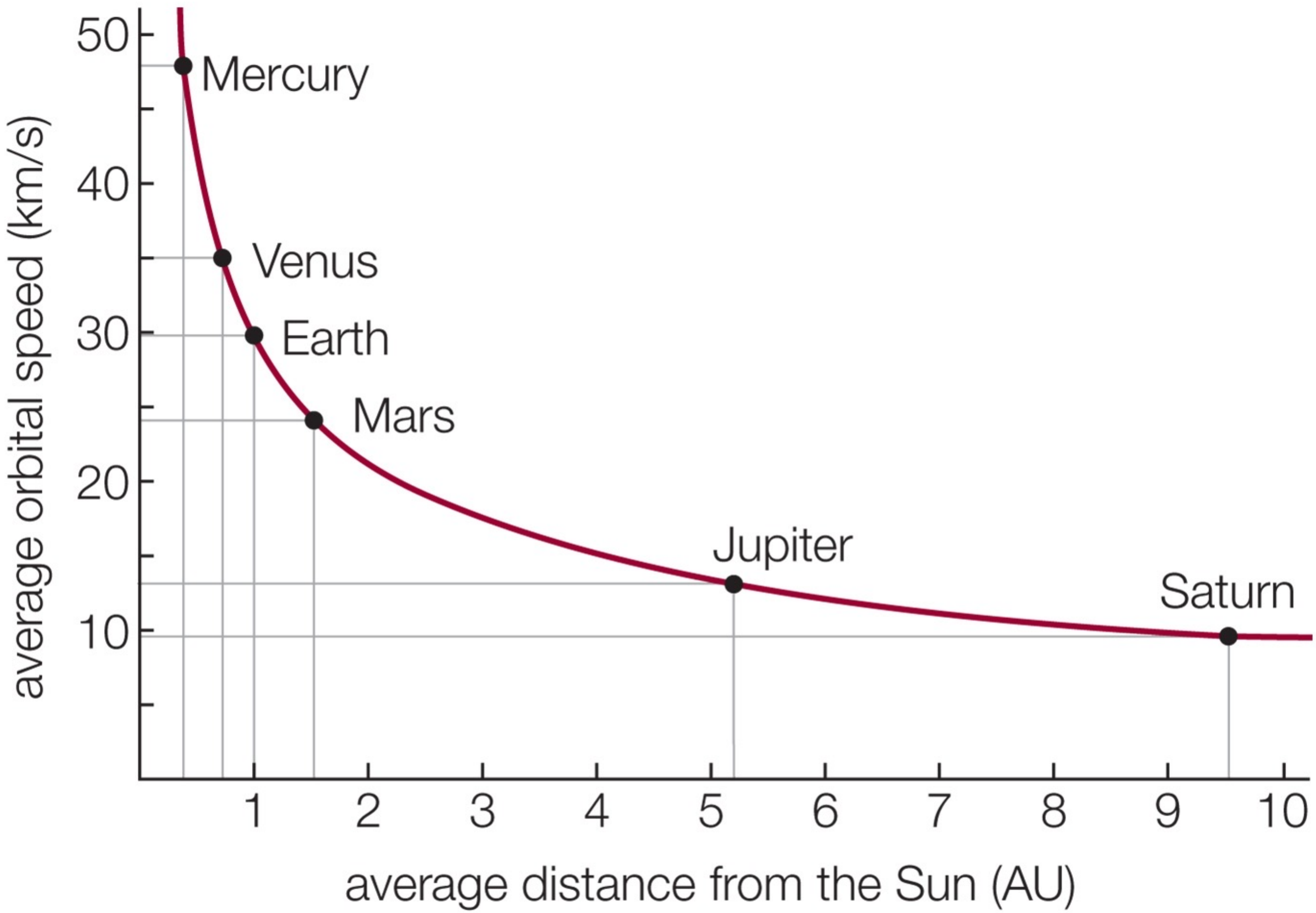

average orbital speed (km/s)
50
40
30
20
10
Mercury
Venus
Earth
Mars
Jupiter
Saturn
1
2
3
4
5
6
7
8
9
10
average distance from the Sun (AU)

b

How much time (in Earth years) does it take a satellite whose semi-major axis is 0.7 A.U. to complete a full orbit around the Sun?

a. 0.343 years = 0.7^3 years
b. 0.490 years = 0.7^2 years
c. 0.586 years = $0.7^{3/2}$ years
d. 0.7 years
e. 0.788 years = $0.7^{2/3}$ years
f. 0.837 years = $0.7^{1/2}$ years
g. 1 year

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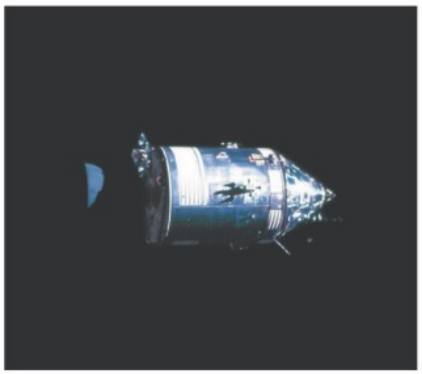
g. 1 year

Sir Isaac Newton

Figure 4.6

Newton's first law of motion: An object moves at constant velocity unless a net force acts to change its speed or direction.



Example: *A spaceship needs no fuel to keep moving in space.*

Newton's second law of motion: Force = mass × acceleration

Example: *A baseball accelerates as the pitcher applies a force by moving his arm. (Once the ball is released, the force from the pitcher's arm ceases, and the ball's path changes only because of the forces of gravity and air resistance.)*

Newton's third law of motion: 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.*

Newton’s laws of motion

I. An object moves in a straight line at a constant speed unless influenced by a force external to itself
II. When an object is acted upon by one or more forces, it experiences acceleration in the direction of their net sum with a magnitude inversely proportional to its mass
III. All forces appear in reciprocal pairs. If object A exerts a force on object B, then a simultaneous force of the same physical mechanism with equal magnitude and opposite direction is exerted by object B on object A

Figure 4.1

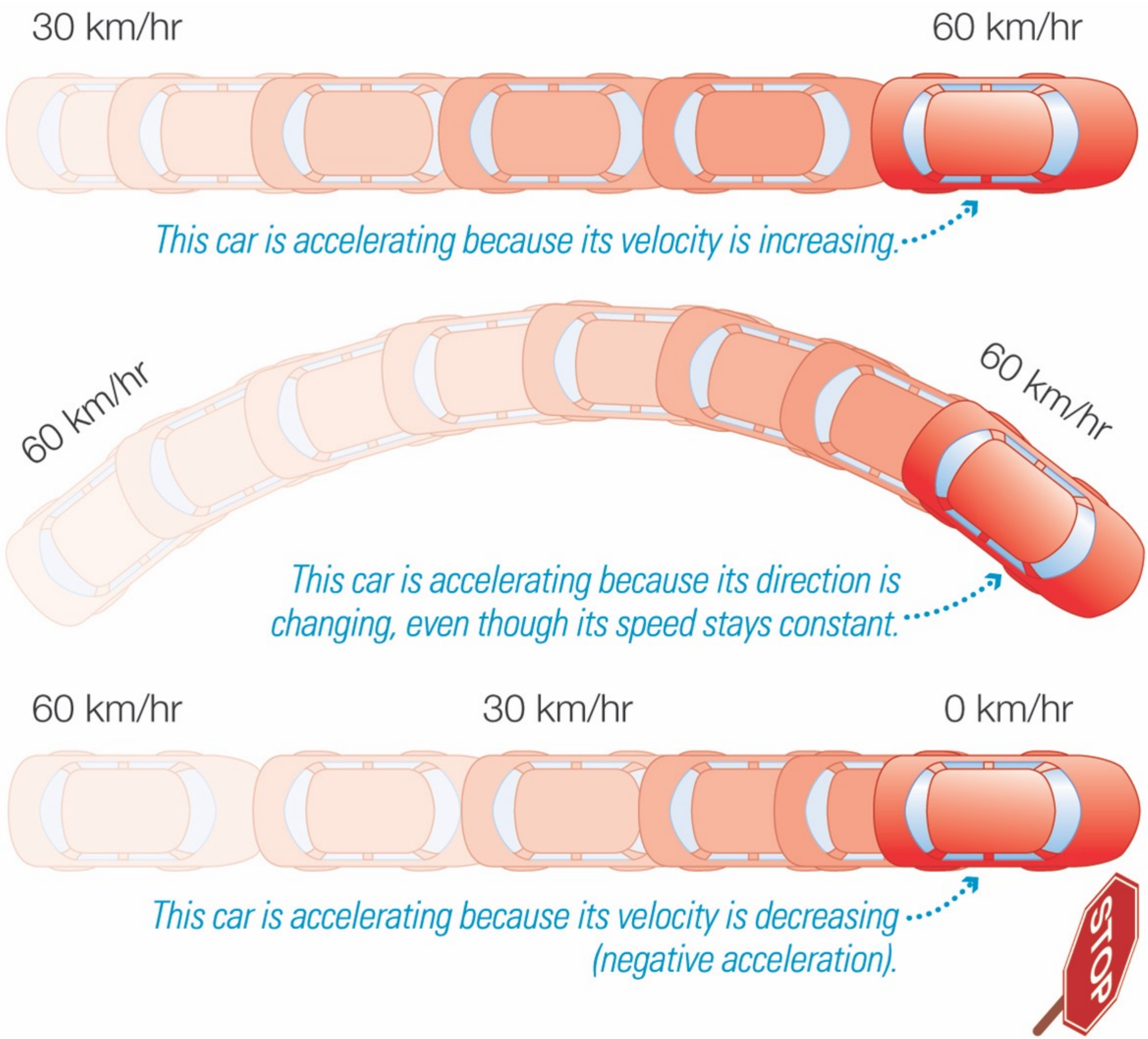
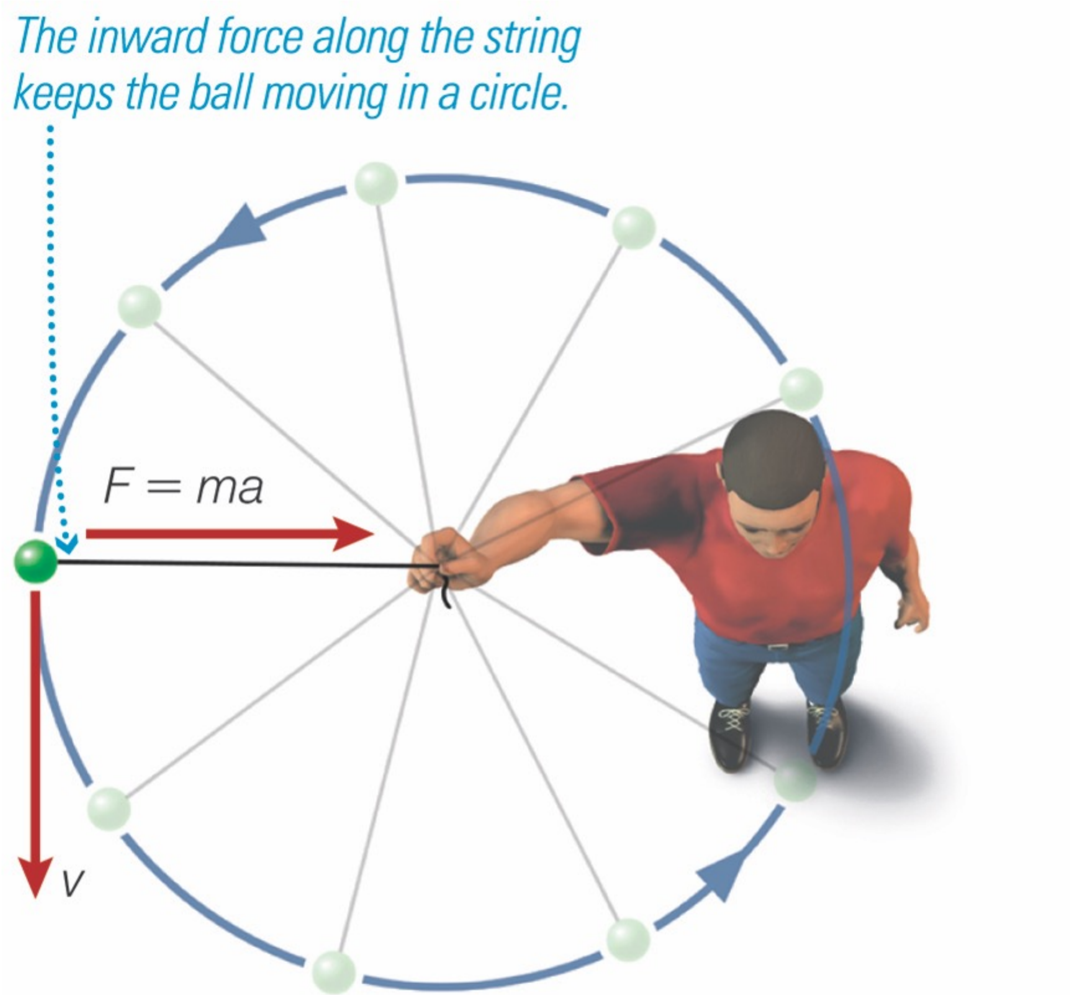
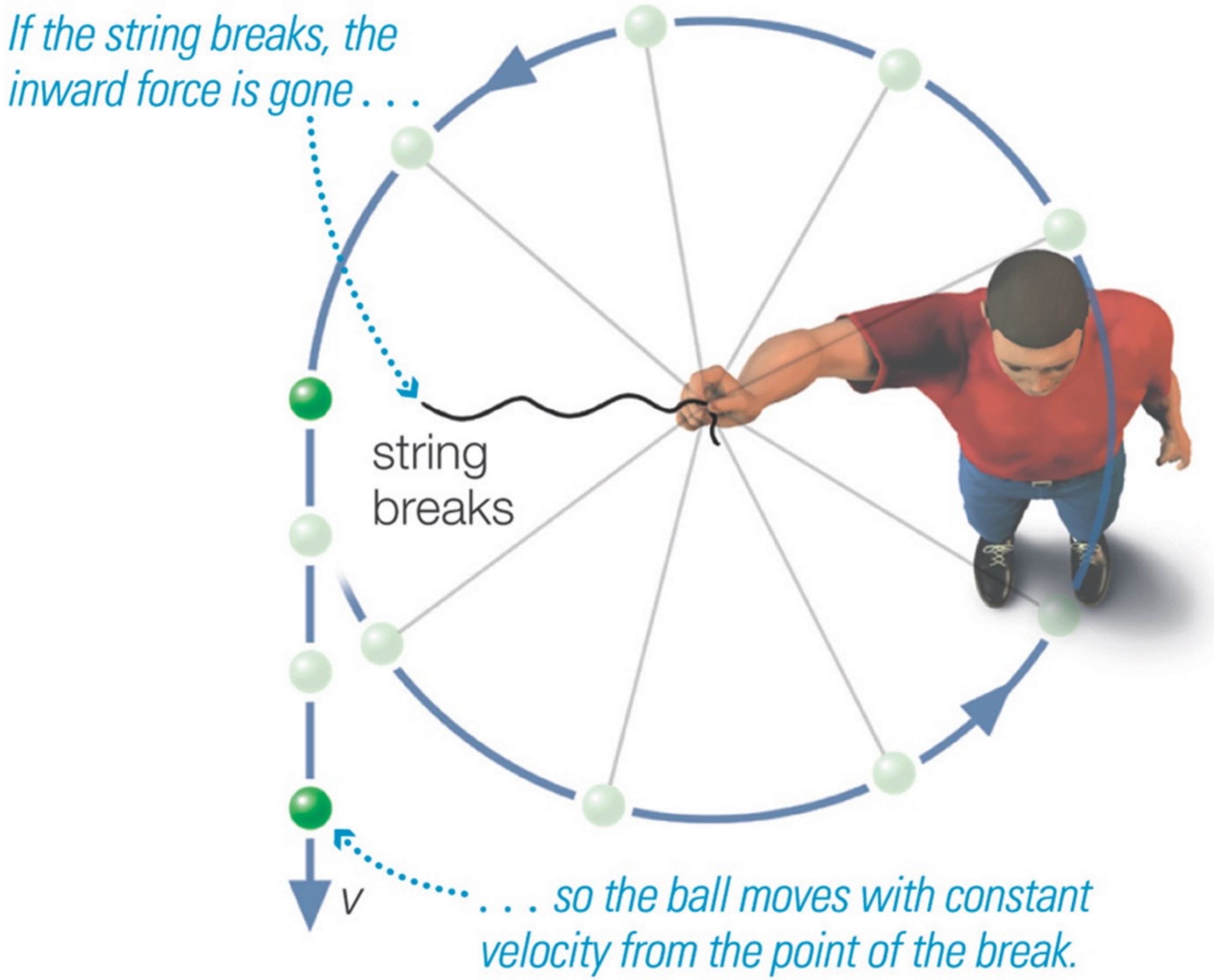

30 km/hr
60 km/hr
This car is accelerating because its velocity is increasing.
60 km/hr
60 km/hr
This car is accelerating because its direction is changing, even though its speed stays constant.
60 km/hr
30 km/hr
0 km/hr
This car is accelerating because its velocity is decreasing (negative acceleration).
STOP

Figure 4.7a



a When you swing a ball on a string, the string exerts a force that pulls the ball inward.

Figure 4.7b



b If the string breaks, the ball flies off in a straight line at constant velocity.

The Moon does not fall to Earth because

a. The net force on it is zero.
b. It is beyond the main pull of Earth’s gravity.
c. It is being pulled by the Sun and planets as well as by Earth.
d. all of the above
e. none of the above

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The Moon is falling toward Earth, it just never gets there (fortunately!)

Figure 4.17

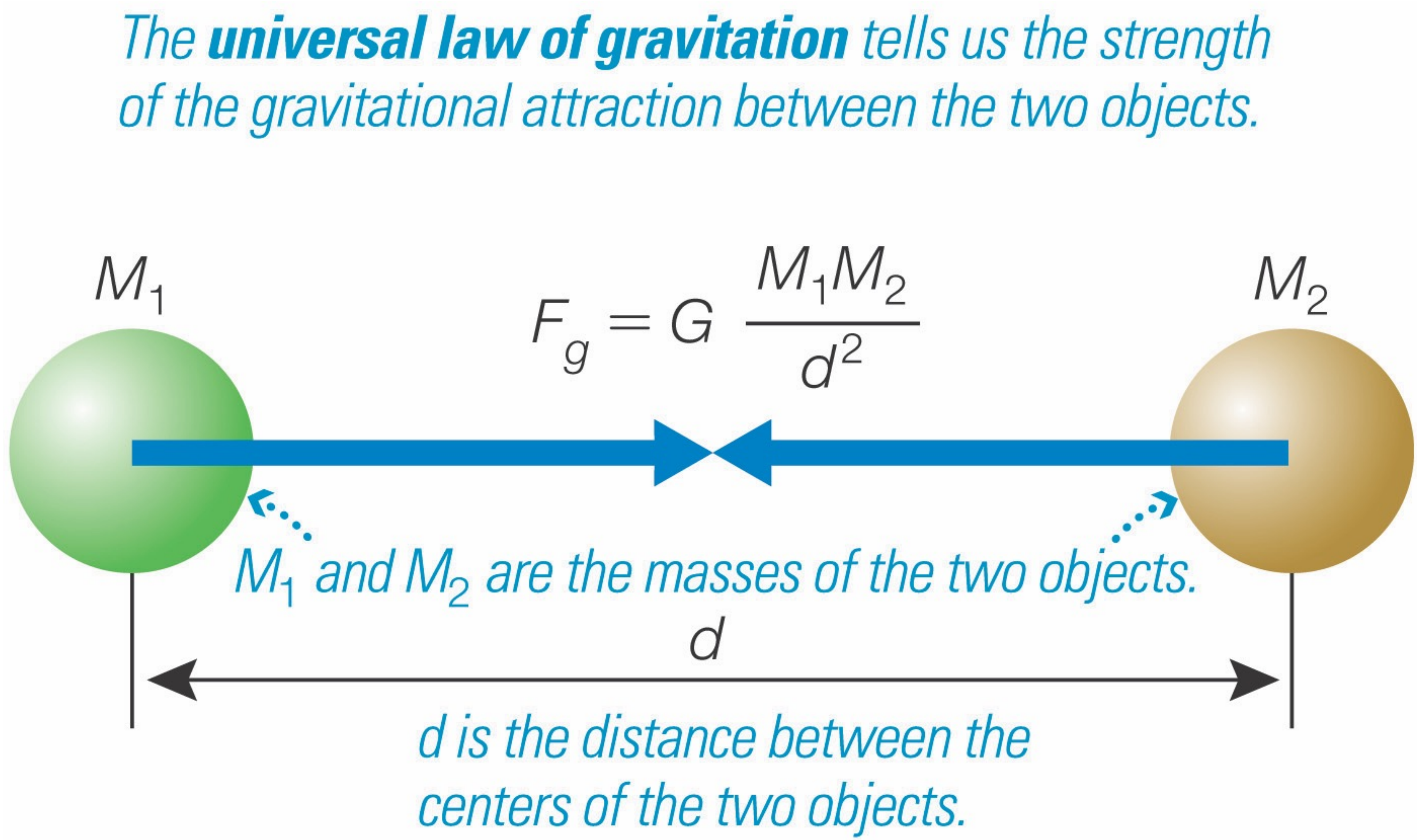
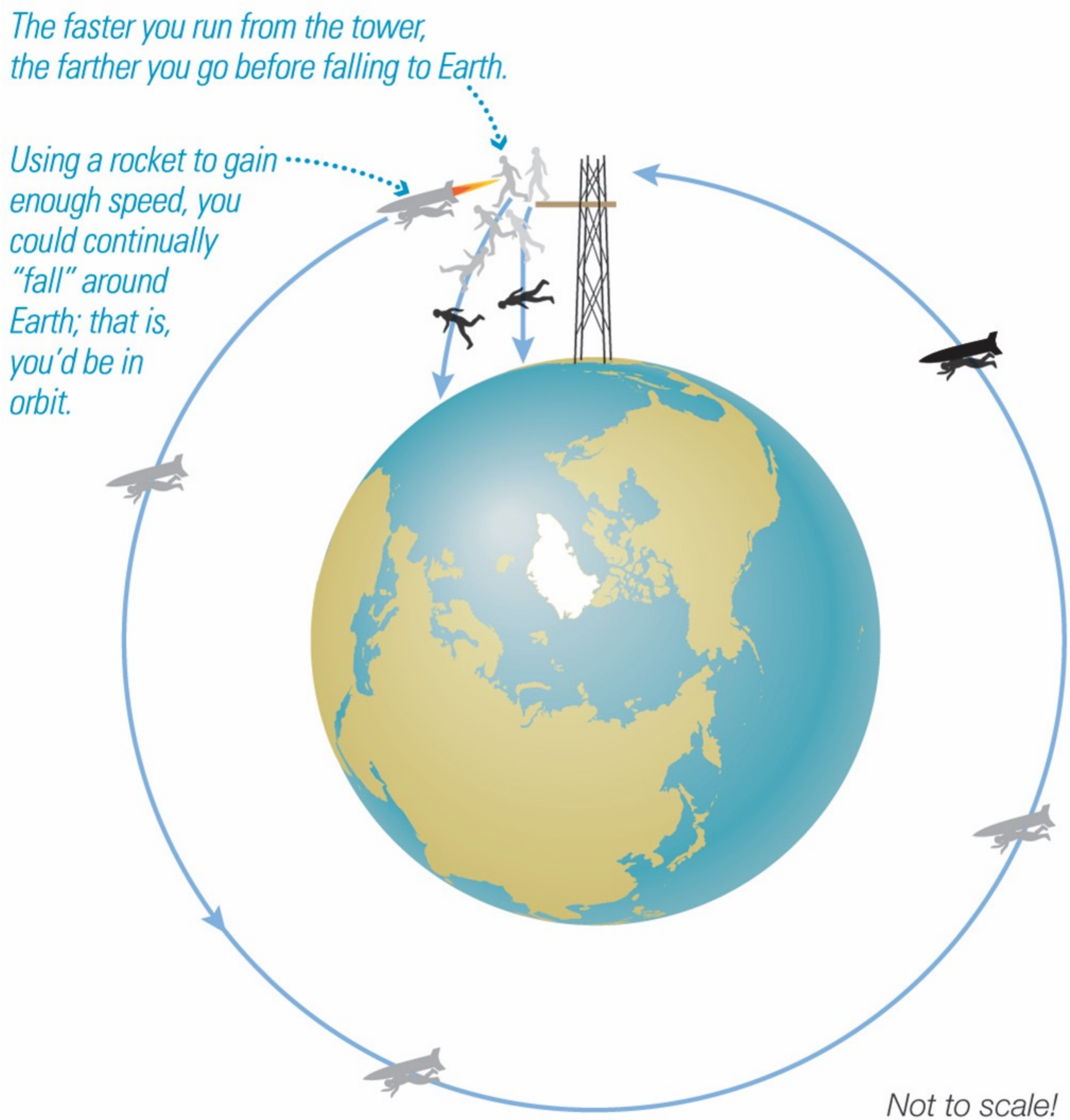

The universal law of gravitation tells us the strength of the gravitational attraction between the two objects.
M_1
$F_g = G\frac{M_1 M_2}{d^2}$
M_2
M_1 and M_2 are the masses of the two objects.
d
d is the distance between the centers of the two objects.

Figure 4.5

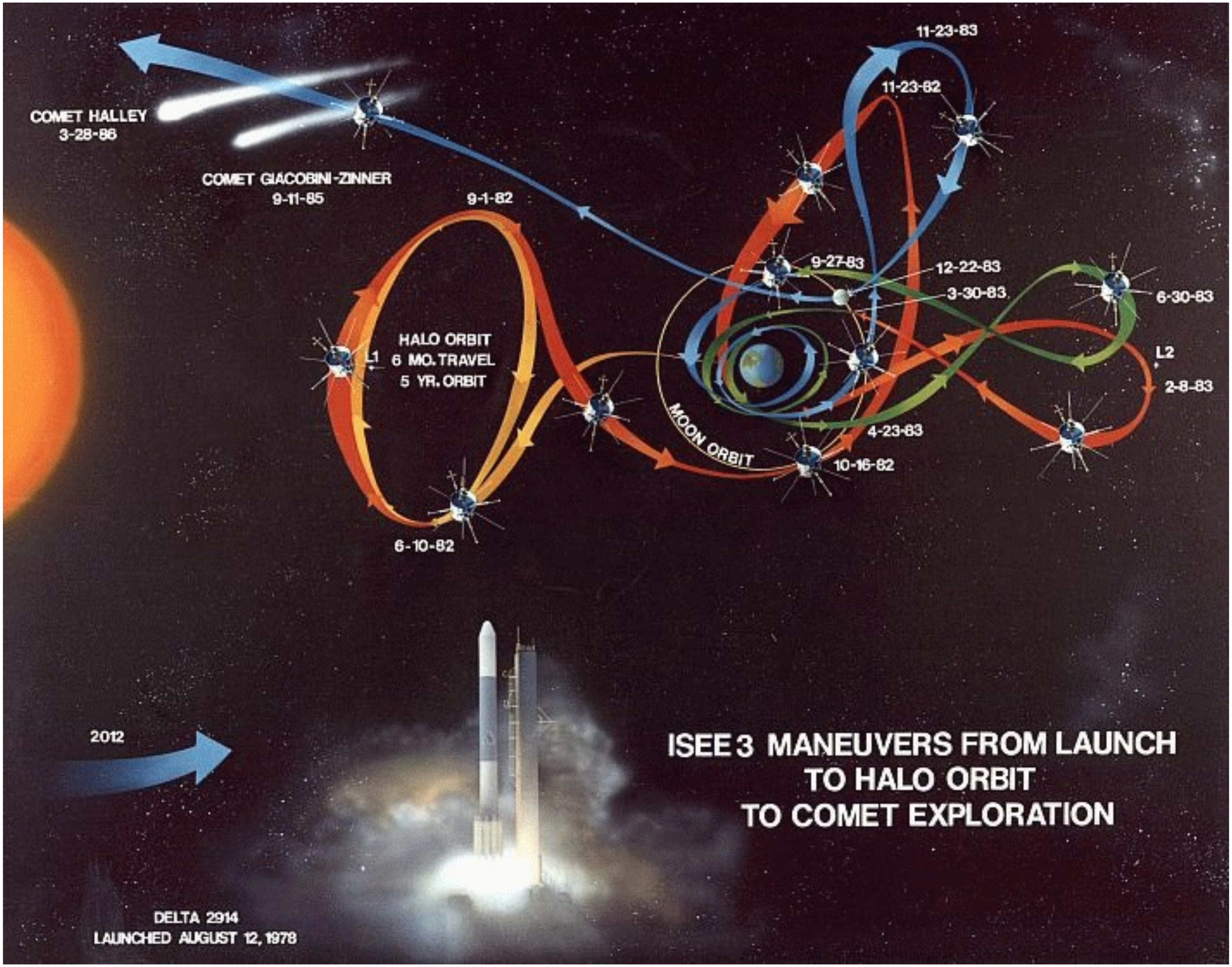


The faster you run from the tower,
the farther you go before falling to Earth.
Using a rocket to gain enough speed, you could continually "fall" around Earth; that is, you'd be in orbit.
Not to scale!

Consequences of Newton’s laws

- Kepler’s laws are a special case of planetary orbits involving just two perfectly uniform spheres
- For more than two bodies, it is impossible to derive simple equations for their exact paths, though useful approximations can be found
- In general, orbits governed by gravity are chaotic and unpredictable, though computers can calculate them for practical use

ICE (International Cometary Explorer) and Comet Giacobini-Zinner



More Consequences of Newton's laws

- Kepler's laws actually only apply for spherically symmetric distributions of mass, like uniform balls
- Most planets are slightly squished or "oblate" which cause further deviations from perfect ellipses
- Newton's laws predict that a planet's rotation axis shifts in time: precession

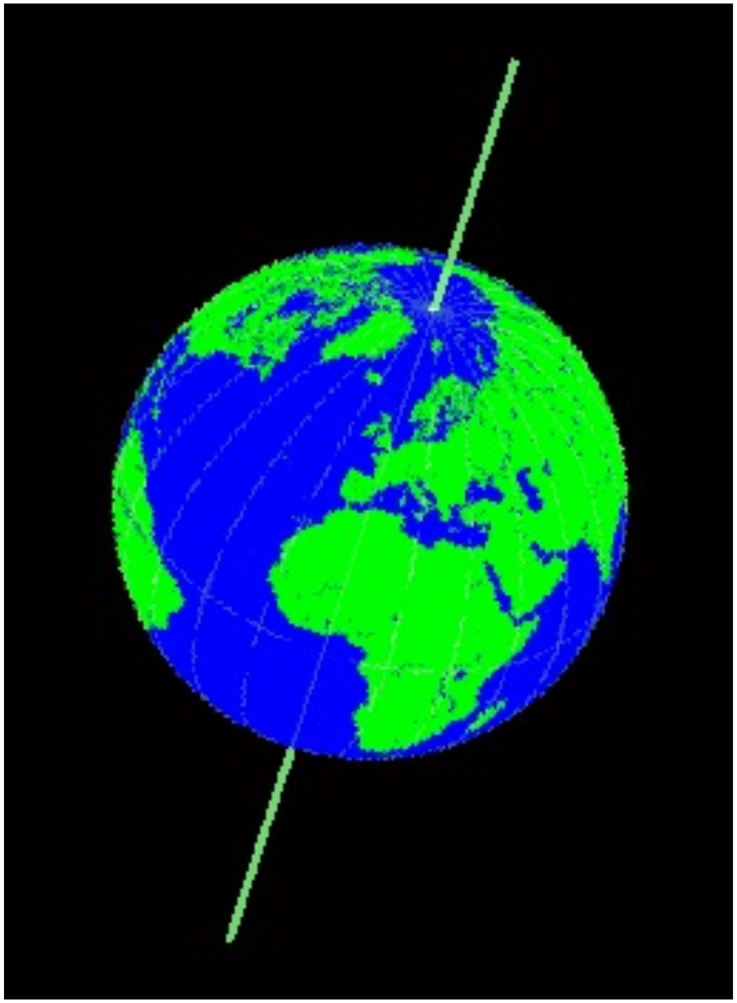
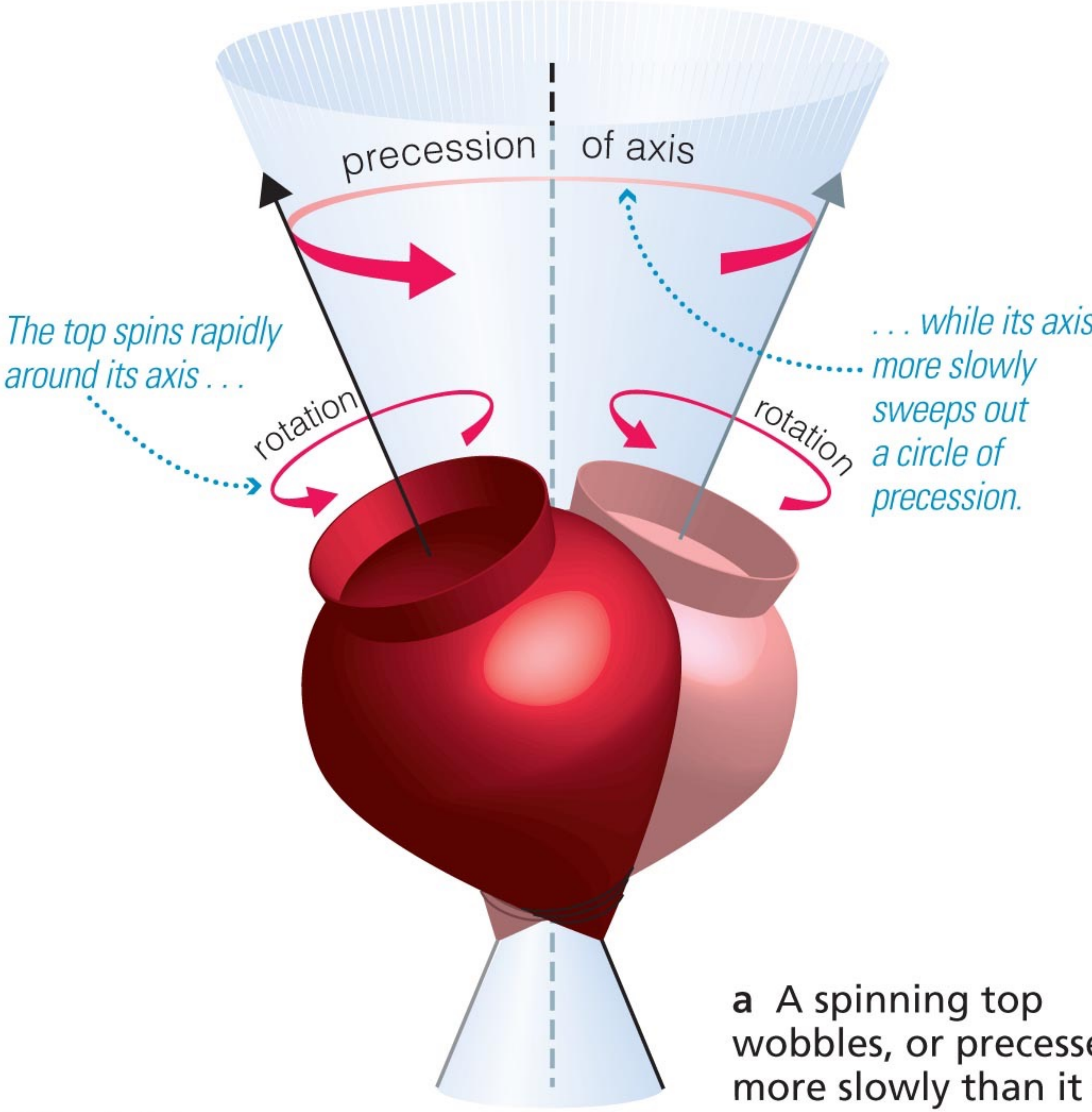
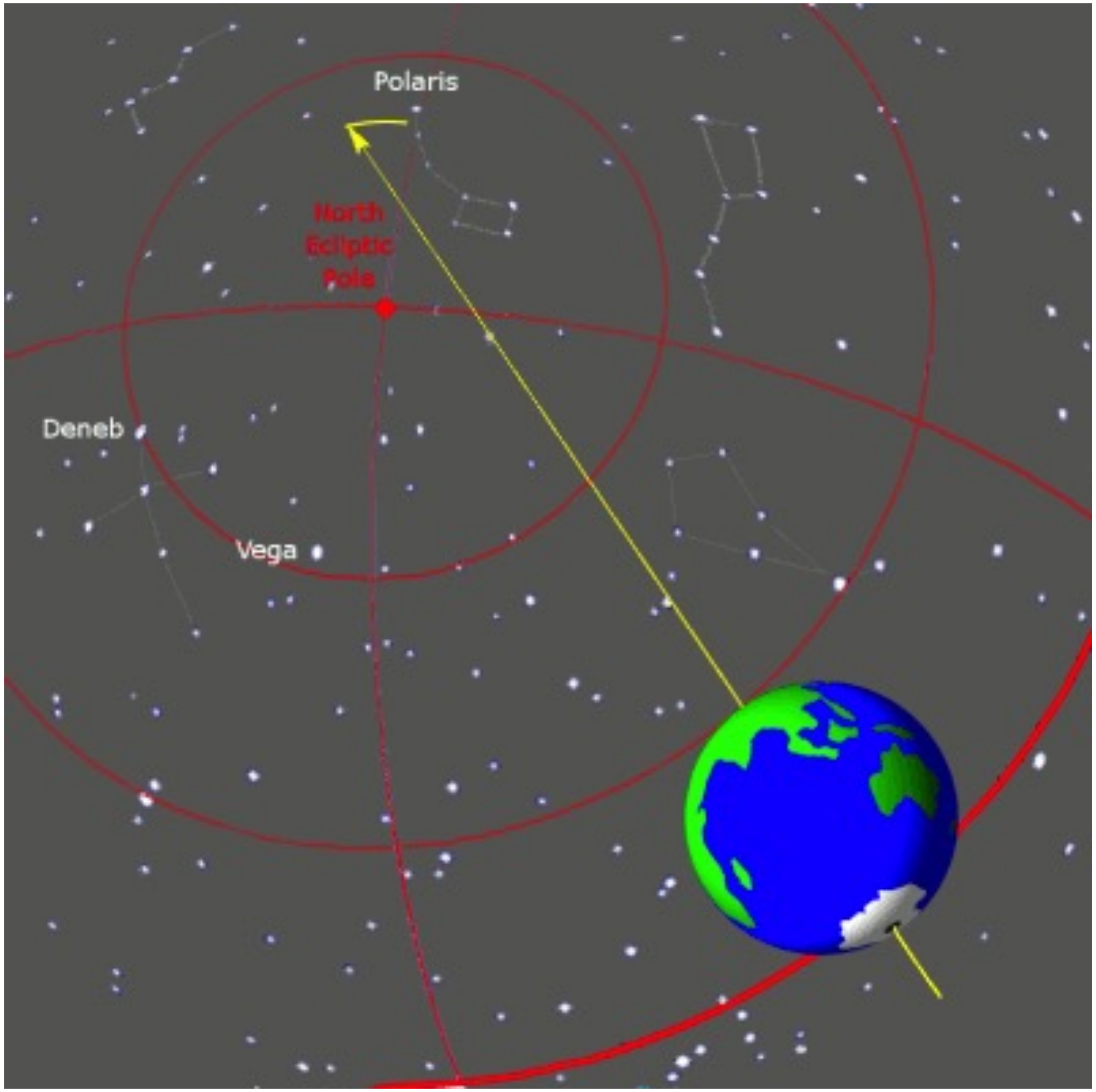


Figure 2.20a

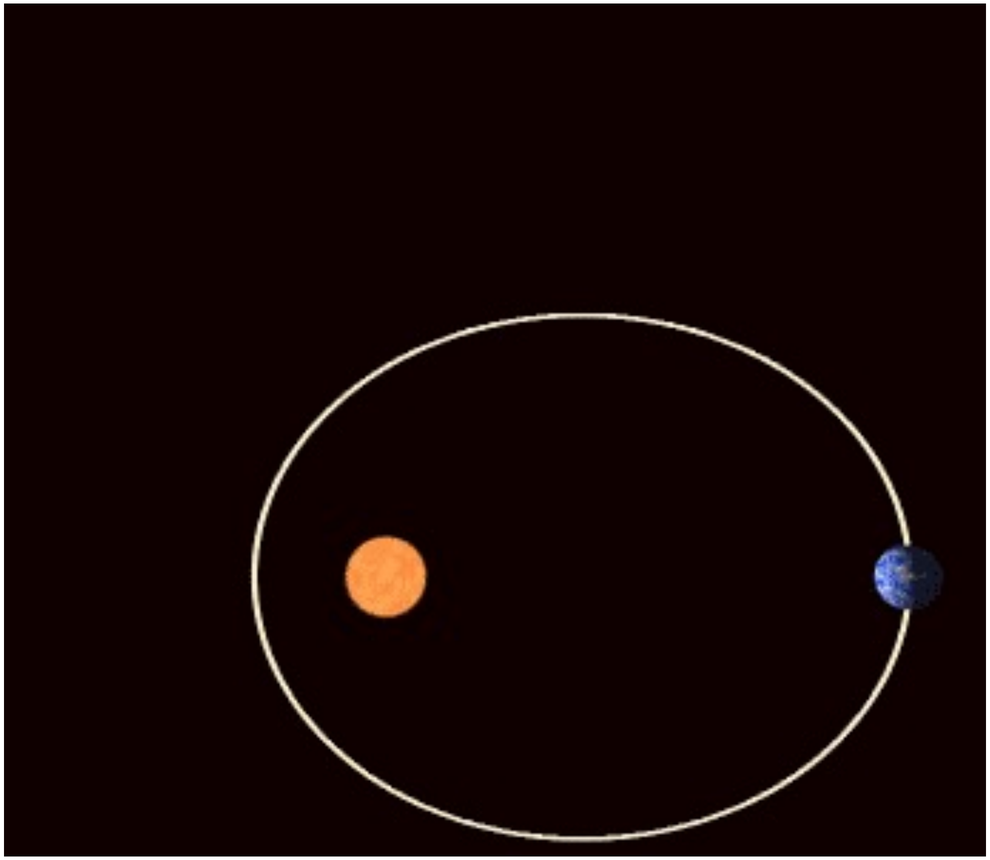


a A spinning top wobbles, or precesses, more slowly than it spins.

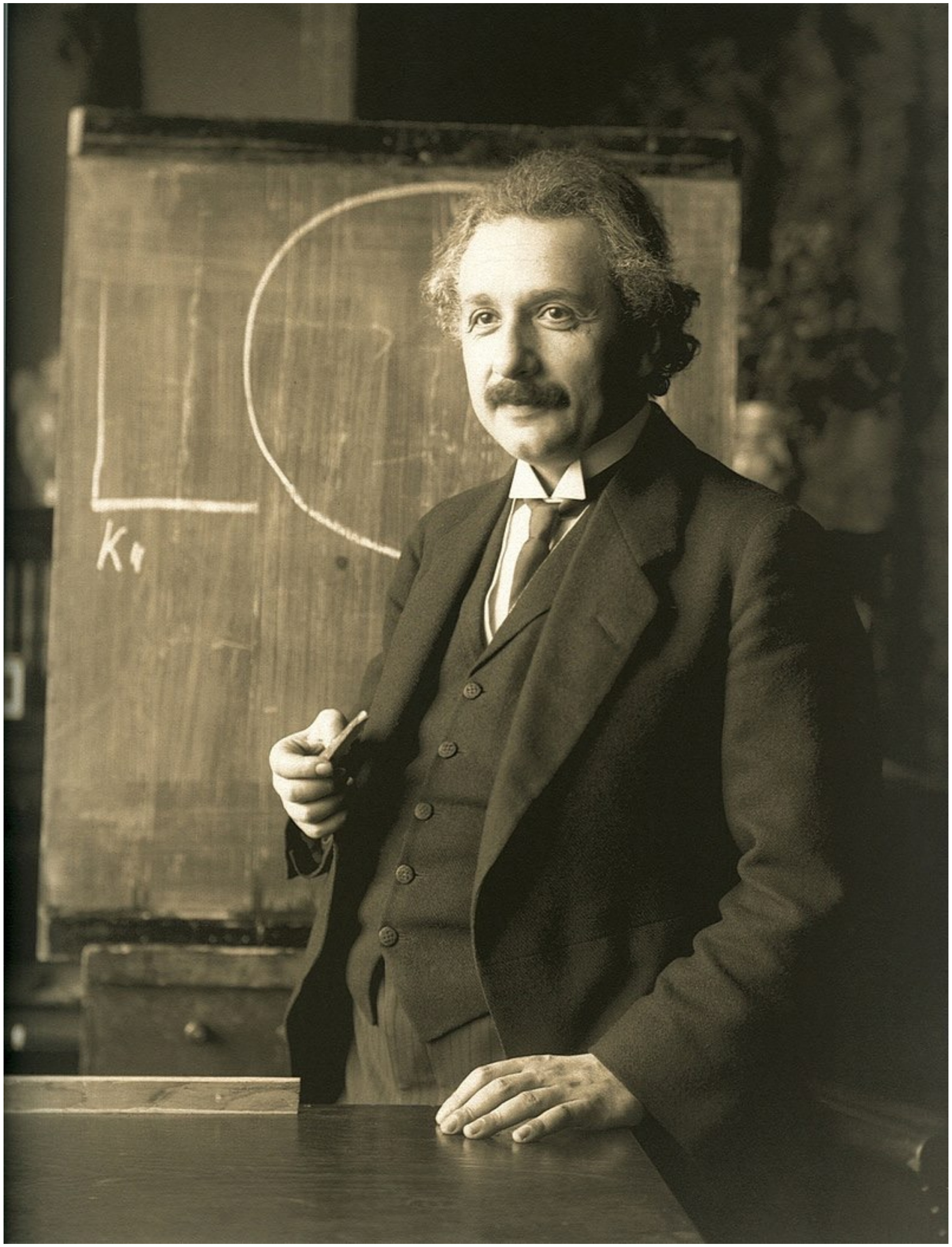

Polaris
North
Ecliptic
Pole
Deneb
Vega

More Consequences of Newton’s laws

- Newton’s laws also predict that the orbits will slightly advance, i.e. that perihelion will precess with time
- Mercury observed precession is 574.10" or about 10' ~ 1/6° per century
- 93% due to other bodies and Sun’s oblateness
- Remaining 7% (43" of arc or about 2.5 Mercury widths) is unexplained by Newton



Albert Einstein (1879 – 1955)



Summary of theory progression

- Ptolemy's model was complicated and made pretty good predictions about planets already observed
- Copernius' model was simple and made pretty poor predictions about planets already observed, but…
- Galileo showed that Copernicus was qualitatively better
- Kepler's model was of intermediate complexity but made excellent predictions even for planets not yet discovered!
- Newton's used his laws of motion, gravitation, and calculus to calculate Kepler's laws from scratch
- Einstein's showed that Newton's laws arise from his General Theory of Relativity for small speeds and masses

Scientists evaluate theories based on:

- Accuracy – how good are the predictions
- Okham's razor – simplicity, a scarcity of contrivances and artifices – assumptions should not be multiplied beyond necessity
- Time – Proponents of the loser die out

"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

Max Planck, 1949