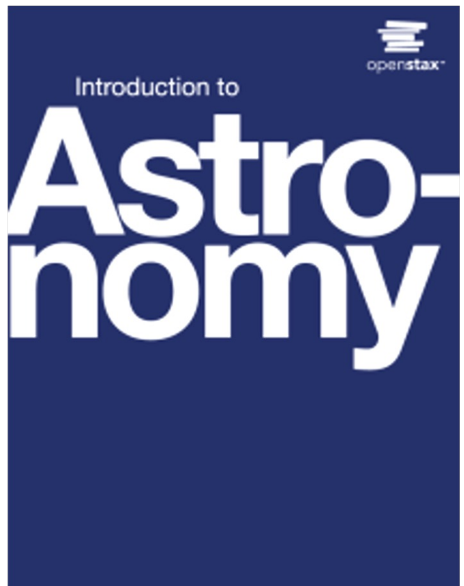
ASTRONOMY

Chapter 3 ORBITS AND GRAVITY
MODELS OF THE UNIVERSE



THE GREEK MODEL (~400 BC) OF THE HEAVENLY SPHERES

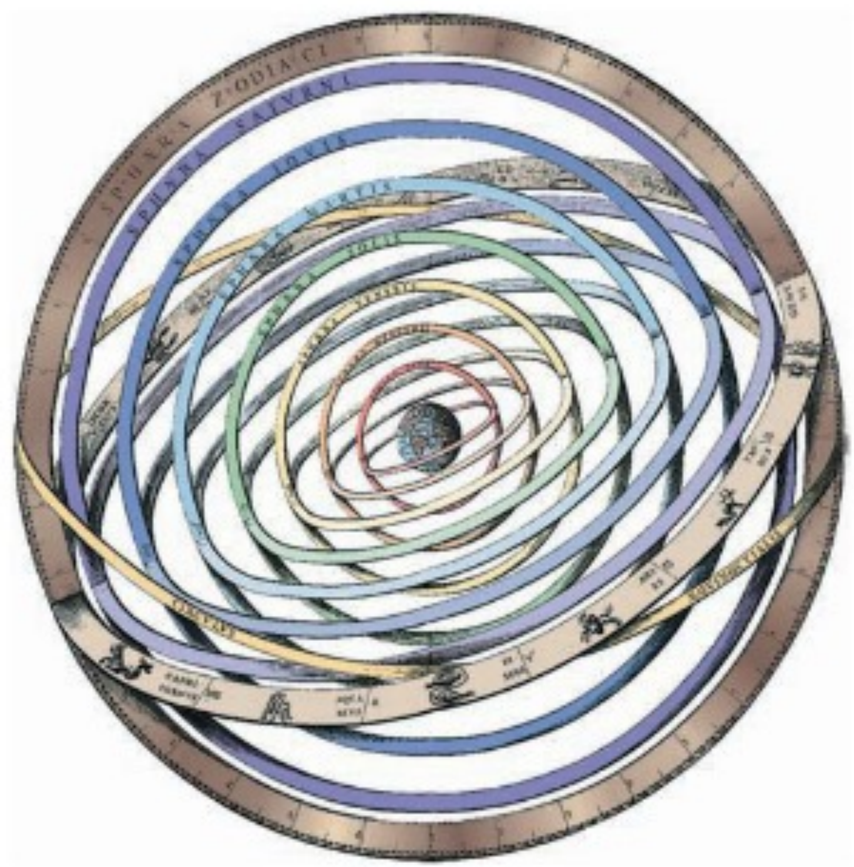


Figure 3.1 | This model represents the Greek idea of the heavenly spheres (c. 400 B.C.). Earth is a sphere that rests in the center. The Moon, the Sun, and the planets each have their own spheres. The outermost sphere holds the stars.

THE PTOLEMAIC (170) MODEL

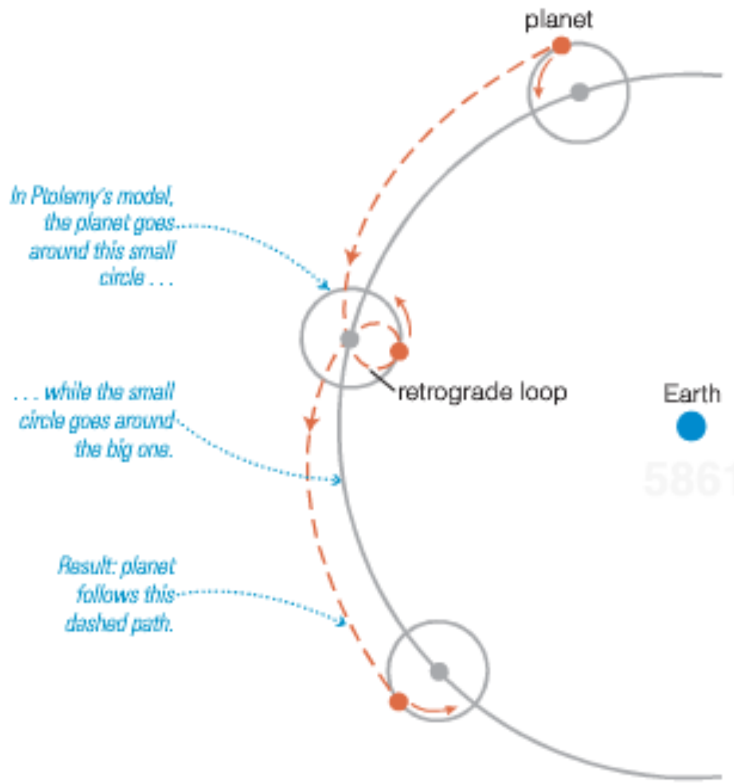


Figure 3.2 | This diagram shows how the Ptolemaic model accounted for apparent retrograde motion. Each planet is assumed to move around a small circle that turns upon a larger circle. The resulting path (dashed) includes a loop in which the planet goes backward as seen from Earth.

Figure 3.2. Page 38. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley. © 2

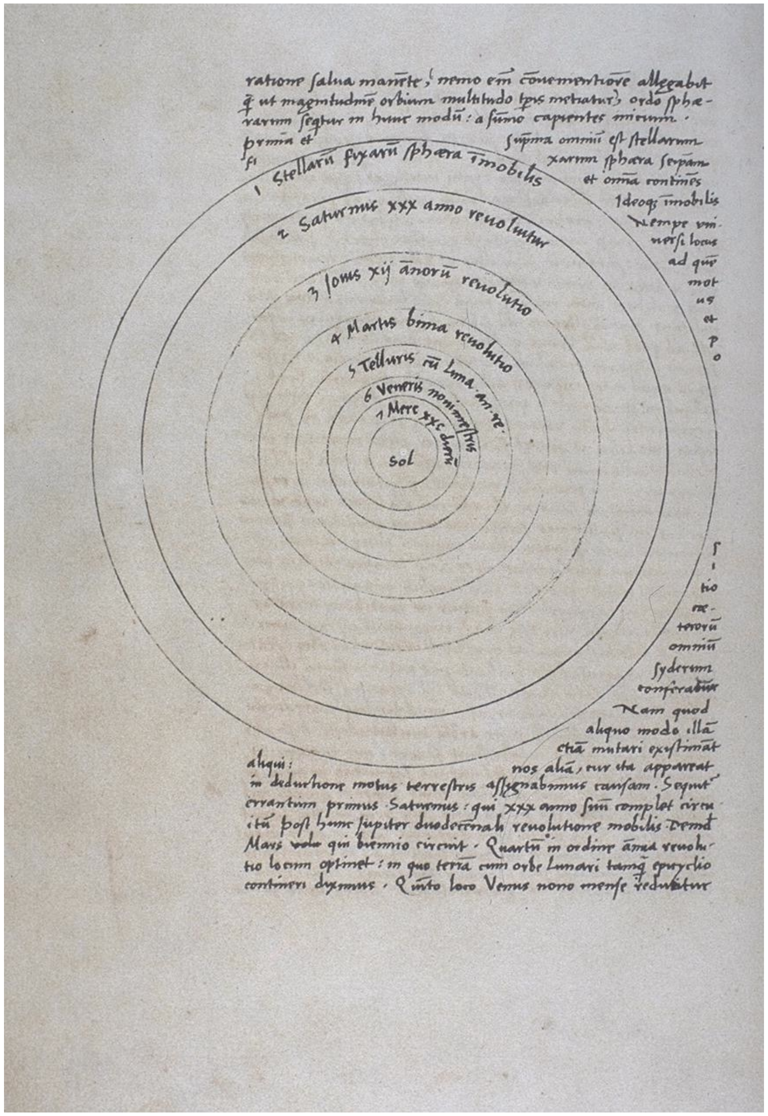
NICHOLAS COPERNICUS (1473-1543)

Around 1514 Copernicus wrote the following axioms:

- *The Earth's centre is not the centre of the universe.*
- *The rotation of the Earth accounts for the apparent daily rotation of the stars.*
- *The apparent annual cycle of movements of the sun is caused by the Earth revolving round it.*
- *The apparent retrograde motion of the planets is caused by the motion of the Earth from which one observes.*
- *The distance from the Earth to the sun is imperceptible compared with the distance to the stars.*

Courtesy Prof Dale Gary

THE HELIOCENTRIC MODEL OF THE SOLAR SYSTEM



TYCHO BRAHE (1546 – 24 OCTOBER 1601) INSTRUMENT BUILDER

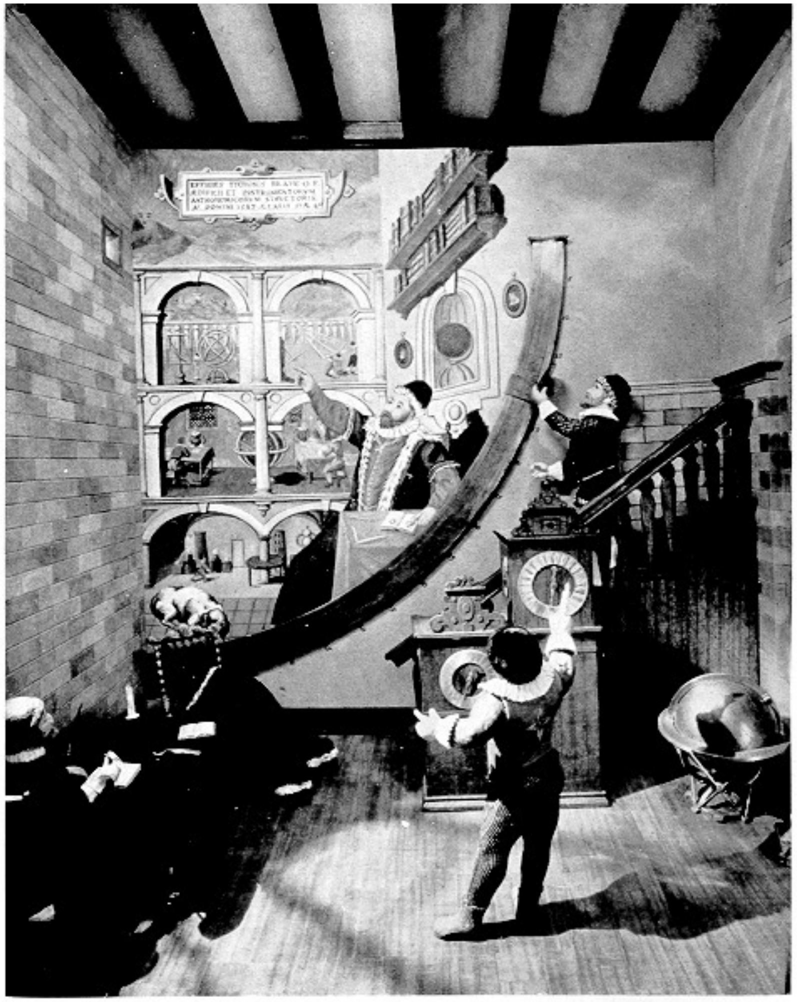
Tycho built three types of instruments:

- quadrants and sextants used for determining altitudes and azimuths
- armillary instruments for measuring right ascensions and declinations, or longitudes and latitudes with respect to the ecliptic
- instruments designed for the determination of angular distances between celestial bodies (sextants and the bipartite arc)

http://www.kb.dk/en/nb/tema/webudstillinger/brahe_mechanica/introduktion.html

http://www.csupomona.edu/~pbsiegel/phy303/ch1.html

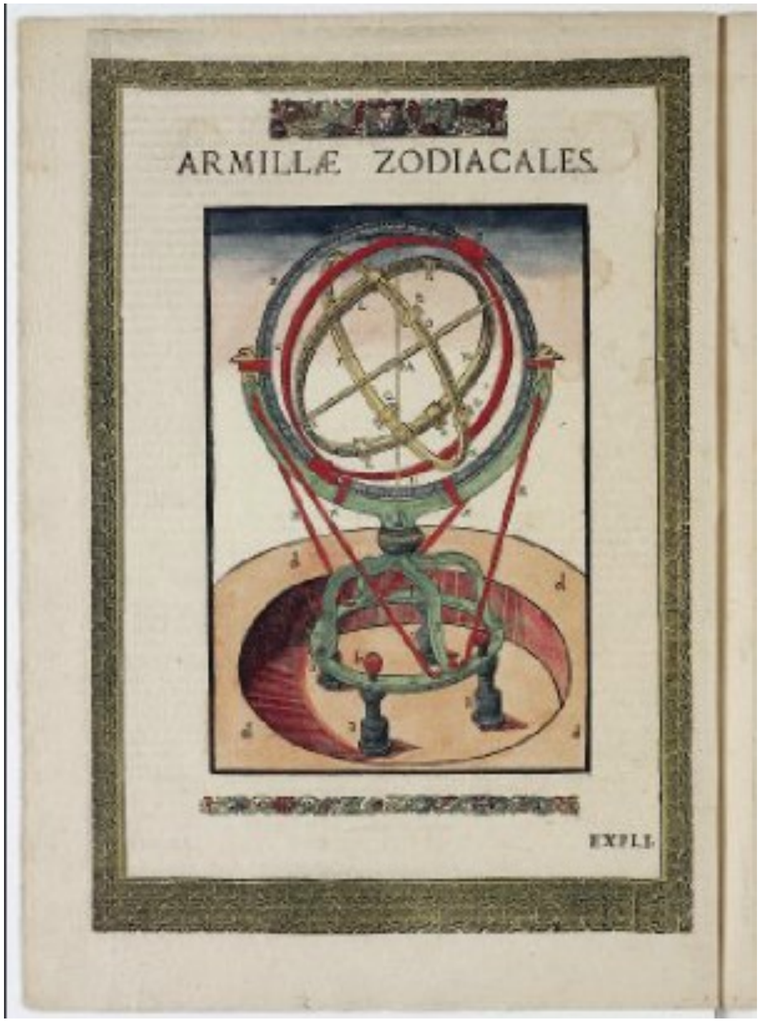
TYCHO BRAHE'S MURAL QUADRANT



http://buhlplanetarium2.tripod.com/Buhlexhibits.htm

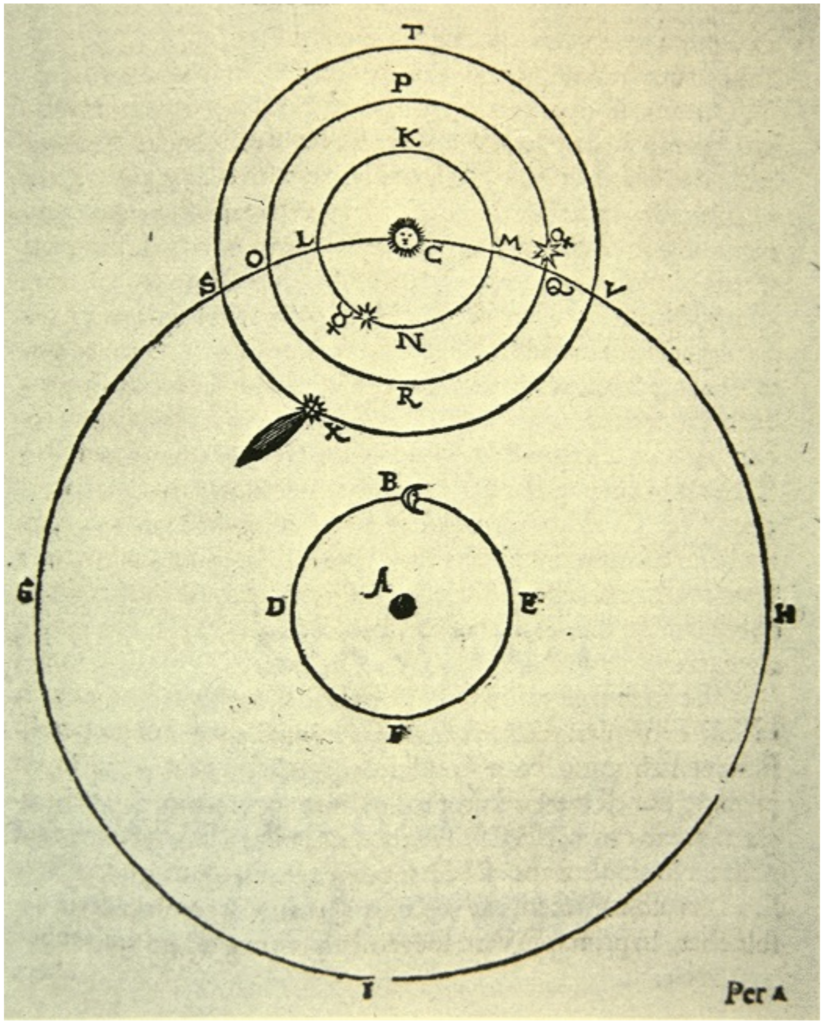
ZODIACAL ARMILLARY INSTRUMENT

The instruments hitherto described are particularly intended for observations of altitudes and azimuths, either separately or together. Since, however, the use of these instruments for astronomical purposes essentially requires trigonometrical
calculations which are not easily comprehensible to everybody and particularly cumbersome to certain people who shun labour, certain other appliances have been invented, with the aid of which the latitudes and longitudes of the stars, the two quantities particularly required, can be found with little inconvenience and without troublesome calculations.



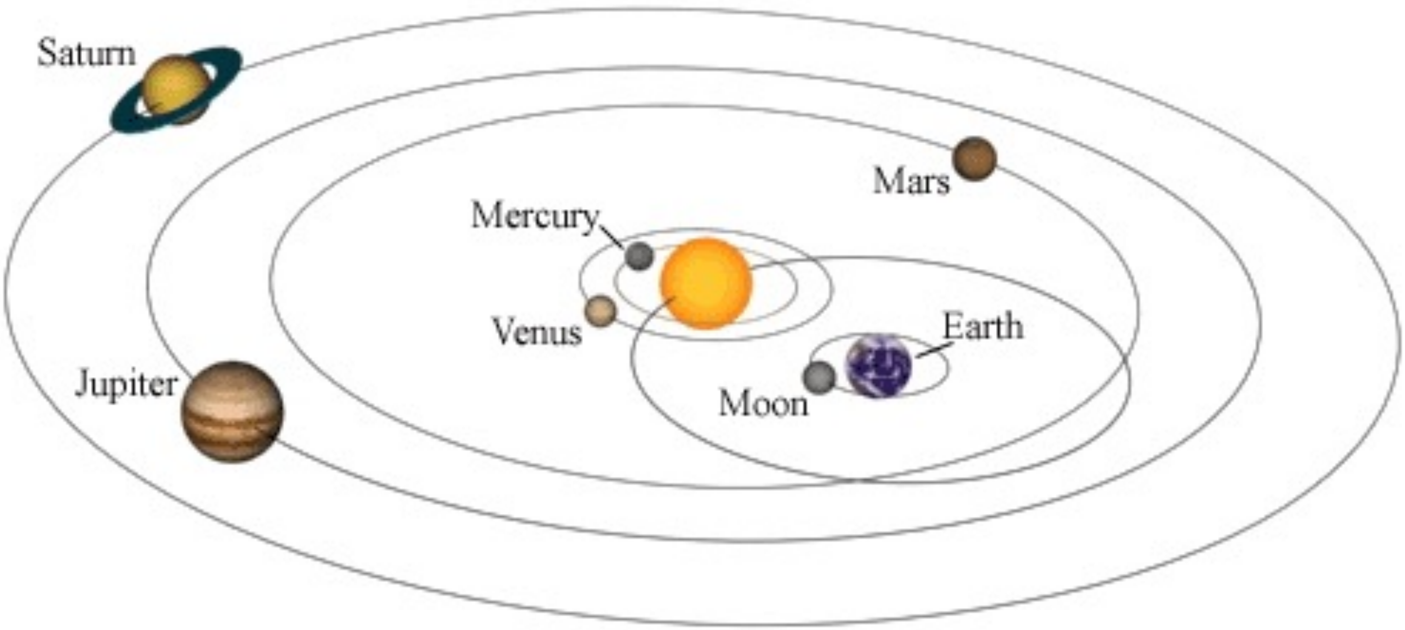
http://www.kb.dk/en/nb/tema/webudstillinger/brahe_mechanica/brahe_fsi.html?page=32

TYCHO’S MODEL



Courtesy Prof Dale Gary

TYCHO'S MODEL



http://www.polaris.iastate.edu/EveningStar/Unit2/unit2_sub3.htm

FIGURE 3.2

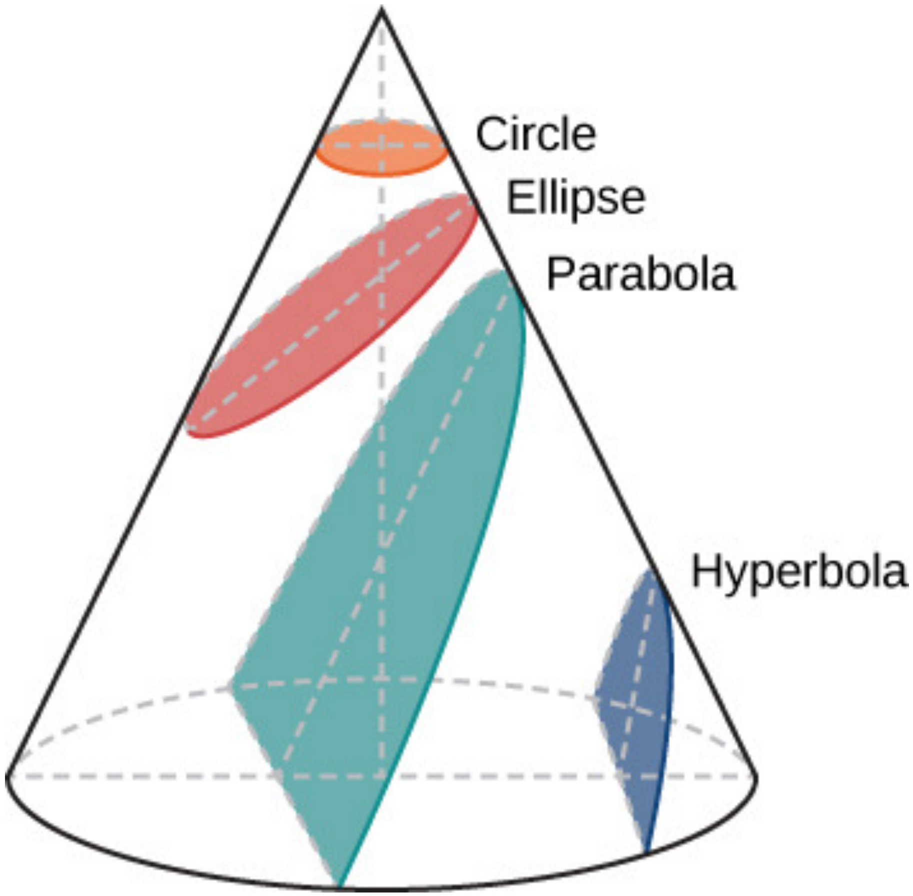
(a) (b)

Tycho Brahe (1546–1601) and Johannes Kepler (1571–1630).

(a) A stylized engraving shows Tycho Brahe using his instruments to measure the altitude of celestial objects above the horizon. The large curved instrument in the foreground allowed him to measure precise angles in the sky. Note that the scene includes hints of the grandeur of Brahe's observatory at Hven.

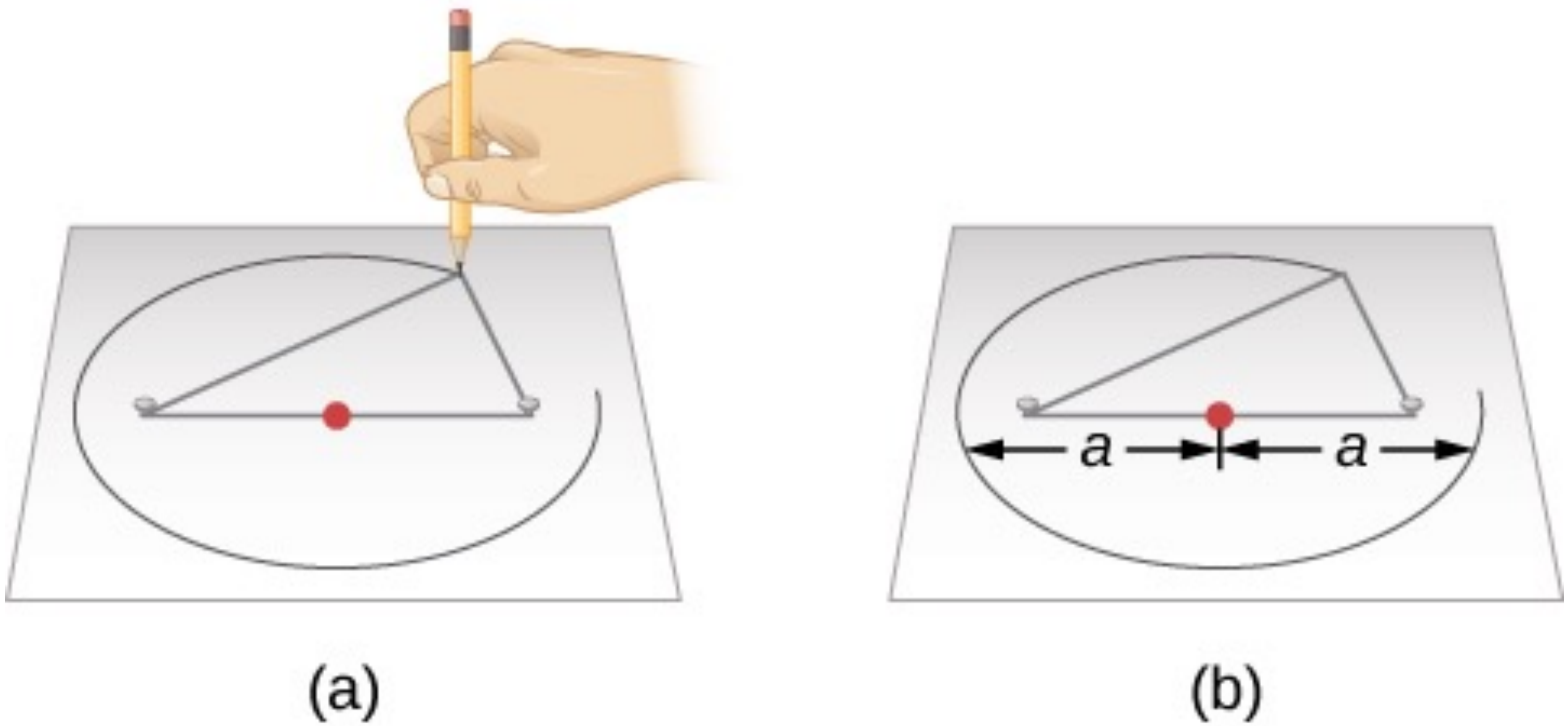
(b) Kepler was a German mathematician and astronomer. His discovery of the basic laws that describe planetary motion placed the heliocentric cosmology of Copernicus on a firm mathematical basis.

FIGURE 3.3



Conic Sections. The circle, ellipse, parabola, and hyperbola are all formed by the intersection of a plane with a cone. This is why such curves are called conic sections.

FIGURE 3.4



Drawing an Ellipse.

(a) We can construct an ellipse by pushing two tacks (the white objects) into a piece of paper on a drawing board, and then looping a string around the tacks. Each tack represents a focus of the ellipse, with one of the tacks being the Sun. Stretch the string tight using a pencil, and then move the pencil around the tacks. The length of the string remains the same, so that the sum of the distances from any point on the ellipse to the foci is always constant.

(b) In this illustration, each semimajor axis is denoted by *a*. The distance 2*a* is called the major axis of the ellipse.

IN 1600, TYCHO HIRED KEPLER

Kepler began by assuming circular orbits

But the assumption of circles would not fit Tycho's precise data

- Kepler wrote, *"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."*

And so Kepler considered other shapes that would fit the data, including the ellipse.

KEPLER'S FIRST LAW 1609

The orbit of each planet about the Sun is an ellipse with the Sun at one focus.

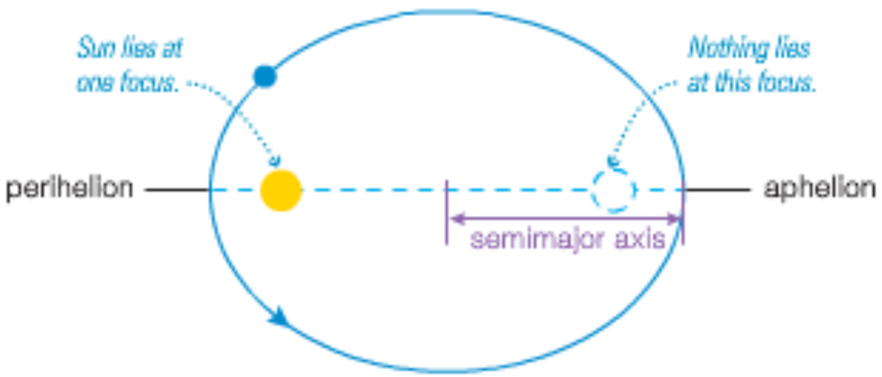
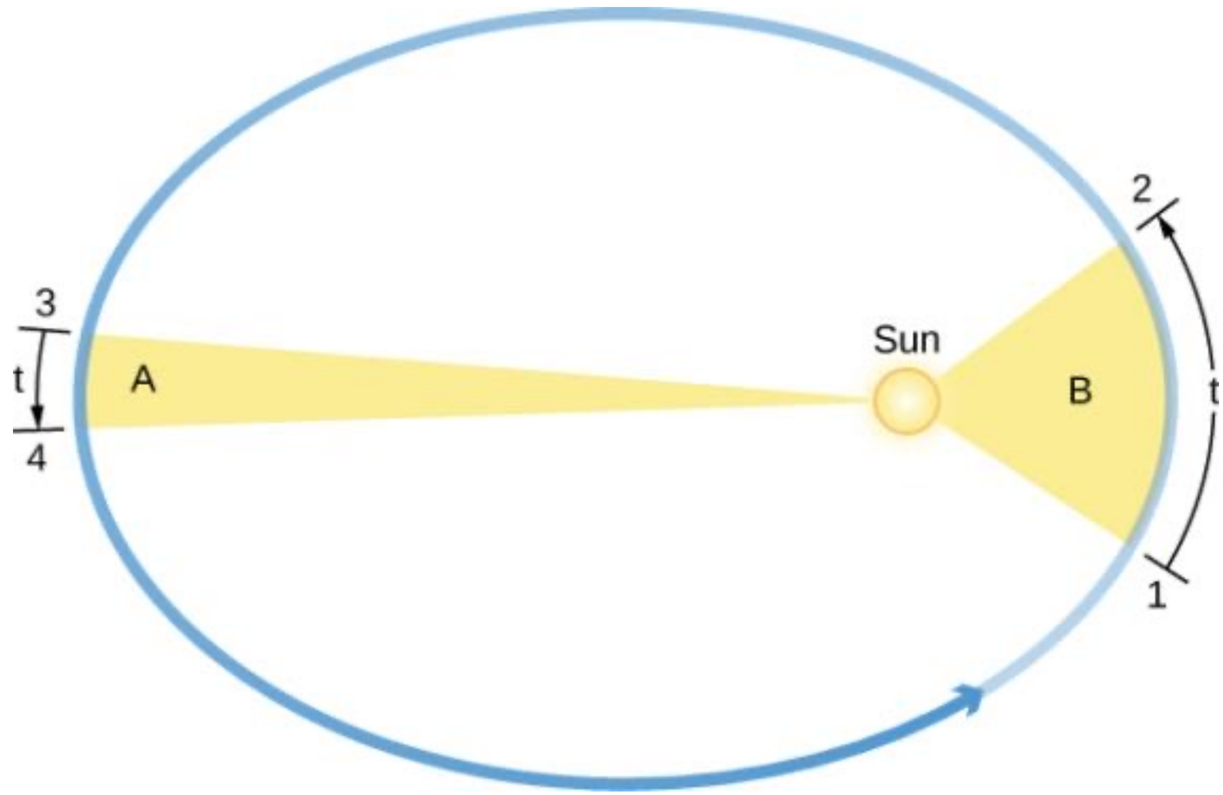


Figure 3.3 | Kepler's first law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus. (The ellipse shown here is more *eccentric*, or stretched out, than any of the actual planetary orbits in our solar system.)

Figure 3.3. Page 40. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley. © 2010

FIGURE 3.5



Kepler's Second Law: The Law of Equal Areas. The orbital speed of a planet traveling around the Sun (the circular object inside the ellipse) varies in such a way that in equal intervals of time (t), a line between the Sun and a planet sweeps out equal areas (A and B). Note that the eccentricities of the planets' orbits in our solar system are substantially less than shown here.

KEPLER'S THIRD LAW 1619

More distant planets orbit the Sun at slower average speeds

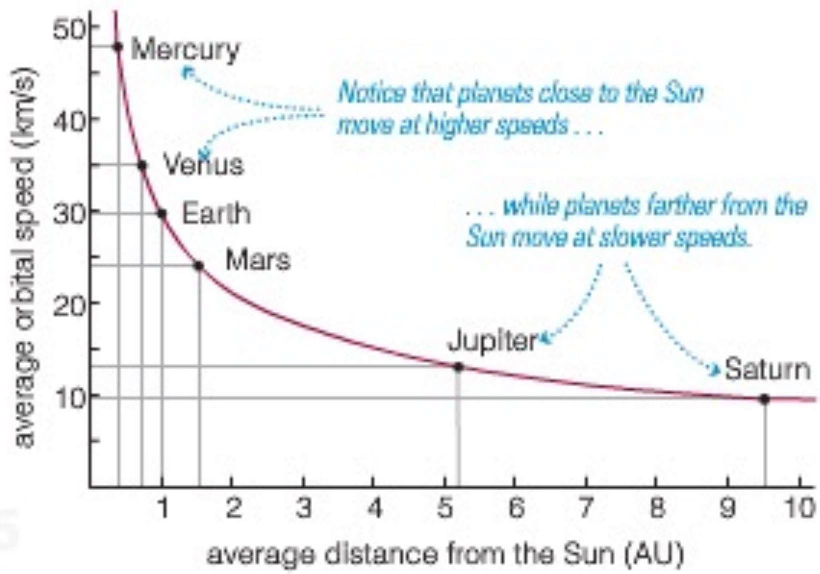
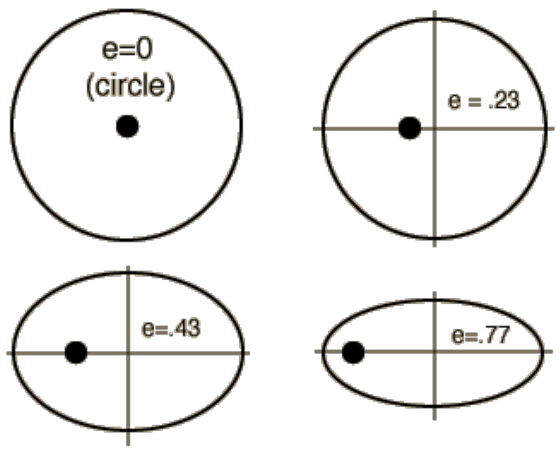


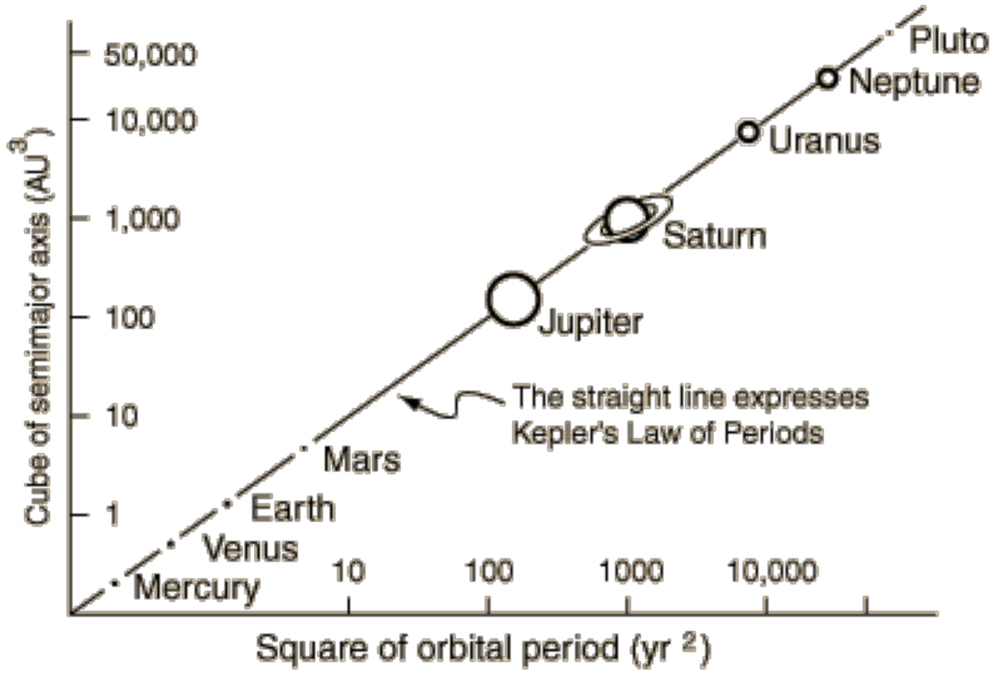
Figure 3.5 | This graph, based on Kepler's third law ($p^2 = a^3$) and modern values of planetary distances, shows that more distant planets orbit the Sun more slowly.

Figure 3.5. Page 41. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley. © 2010

EQUATION FOR KEPLER'S THIRD LAW

The square of the period of any planet is proportional to the cube of the semimajor axis of its orbit.





http://hyperphysics.phy-astr.gsu.edu/hbase/kepler.html

GALILEO: ADDRESSING THE REMAINING OBJECTIONS

1. Aristotle had held that Earth could not be moving because, if it were, objects such as birds, falling stones, and clouds would be left behind as Earth moved along.

2. The idea of noncircular orbits contradicted Aristotle's claim that the heavens—the realm of the Sun, Moon, planets, and stars—must be perfect and unchanging.

3. Despite many efforts, no one had detected the stellar parallax that should occur if Earth orbits the Sun.

GALILEO: THE MOVING EARTH

Experiments with rolling balls to demonstrate that a moving object remains in motion unless a force acts to stop it.

- an idea now codified in Newton's first law of motion.
- This insight explained why objects that share Earth's motion through space—such as birds, falling stones, and clouds—should stay with Earth rather than falling behind as Aristotle had argued.
- This same idea explains why passengers stay with a moving airplane even when they leave their seats.

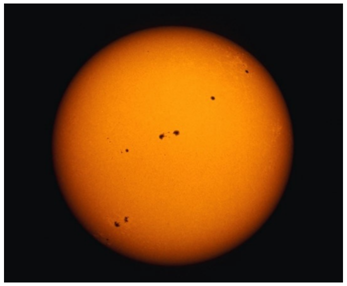
Page 41. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley.

GALILEO: IMPERFECTIONS & CHANGES

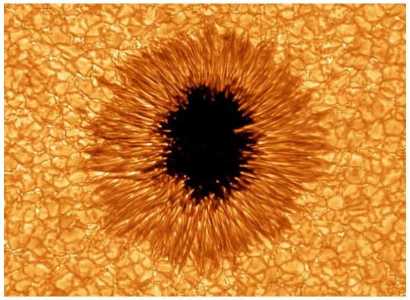
Tycho's supernova and comet observations already had challenged the validity of the second objection by showing that the heavens could change.

Galileo shattered the idea of heavenly perfection after he built a telescope in 1609.

- He saw sunspots on the Sun, which were considered "imperfections" at the time.
- He saw that the Moon has mountains and valleys like the "imperfect" Earth by studying the shadows cast near the dividing line between the light and dark portions of the lunar face.



http://zebu.uoregon.edu/~imamura/122/lecture-3/stellar_spectra.html



http://news.nationalgeographic.com/news/2010/08/photogalleries/100830-sunspot-sun-space-sharpest-view-pictures/

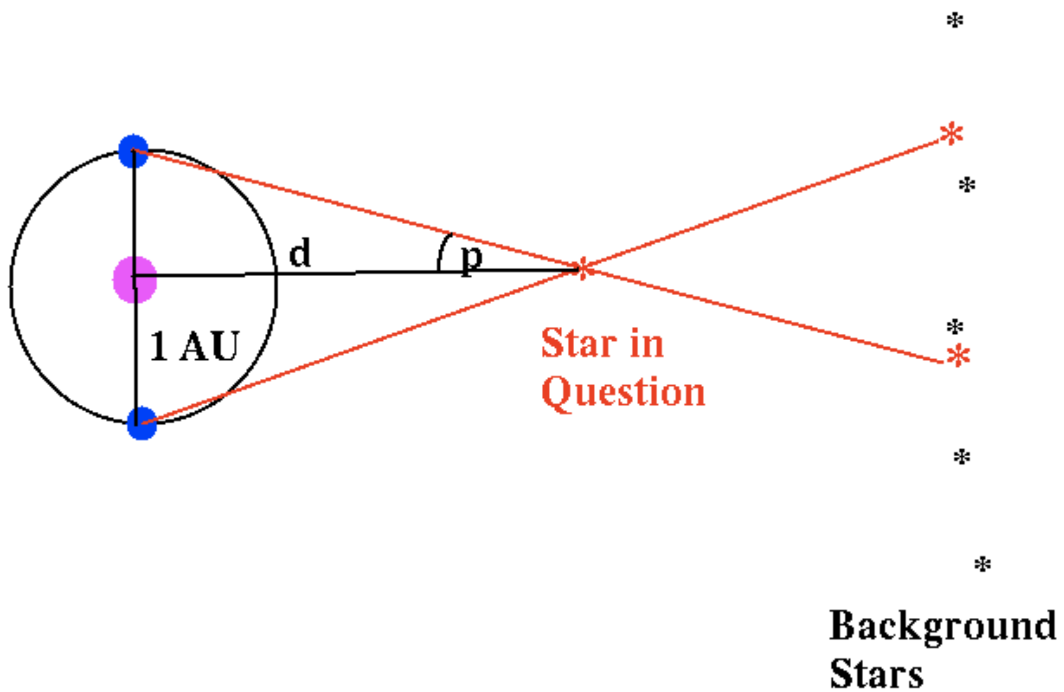
GALILEO: PARALLAX

Tycho was particularly concerned: he believed his observations were precise enough they should have detected parallax.

Refuting Tycho's argument required showing that the stars were more distant than Tycho had thought and therefore too distant for him to have observed stellar parallax.

Galileo was not able to prove this fact, but he saw with his telescope that the Milky Way resolved into countless individual stars. This discovery helped him argue that the stars were far more numerous and more distant than Tycho had believed.

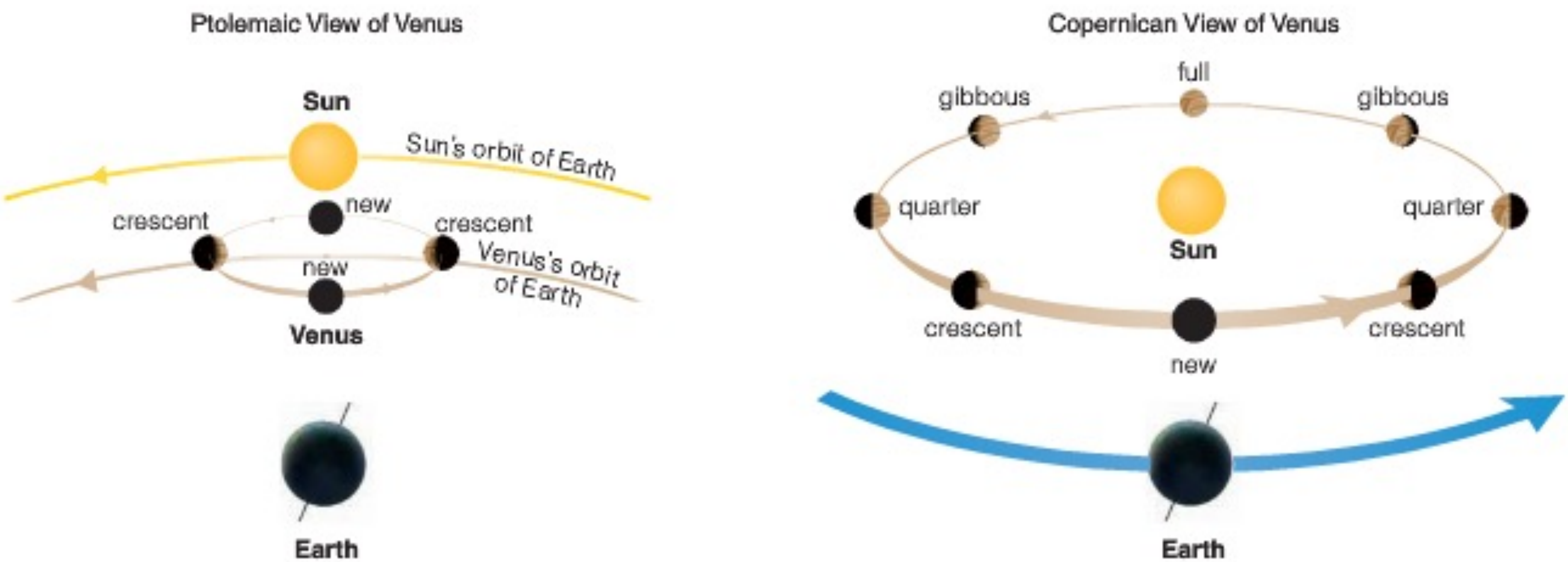
STELLAR PARALLAX



By definition, a parsec is the distance to a star which has a parallax angle of 1"

http://burro.astr.cwru.edu/Academics/Astr221/Light/parallax.html

IN ADDITION, GALILEO: PHASES OF VENUS



a In the Ptolemaic model, 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.

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

Figure 3.7. Page 42. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley. © 2010

INQUISITION

1633: Galileo was brought before a Church inquisition in Rome and ordered to recant his claim that Earth orbits the Sun.

1824: Galileo’s book, *“Dialogue Concerning the Two Chief World Systems”*, was removed from the index of banned books.

1992: Church formally vindicates Galileo.

GIORDANO BRUNO 1548-1600

His ideas went far beyond Copernicus:

- He proposed that the sun was a star and that the universe contained an infinite number of other worlds populated by intelligent beings.

http://en.wikipedia.org/wiki/Giordano_Bruno#Imprisonment.2C_trial_and_execution.2C_1593.E2.80.931600

THE SCIENTIFIC METHOD

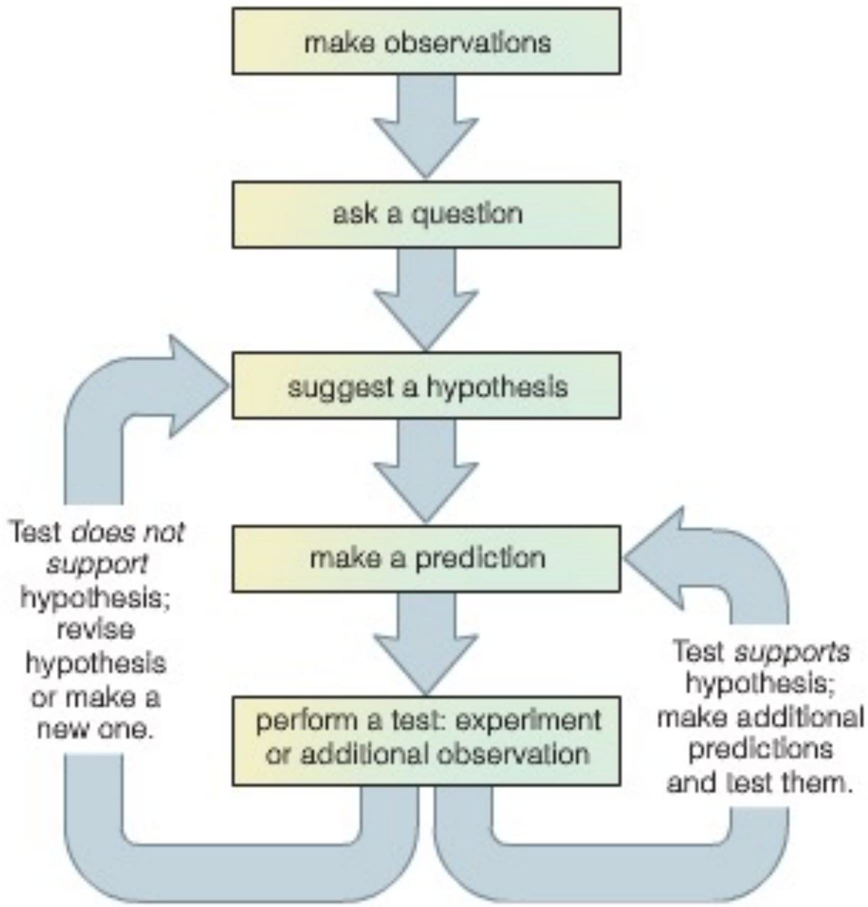


Figure 3.9 | This diagram illustrates what we often call the *scientific method.*

Figure 3.9. Page 45. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley. © 2010

HALLMARKS OF SCIENCE

- Modern science seeks explanations for observed phenomena that rely solely on natural causes.

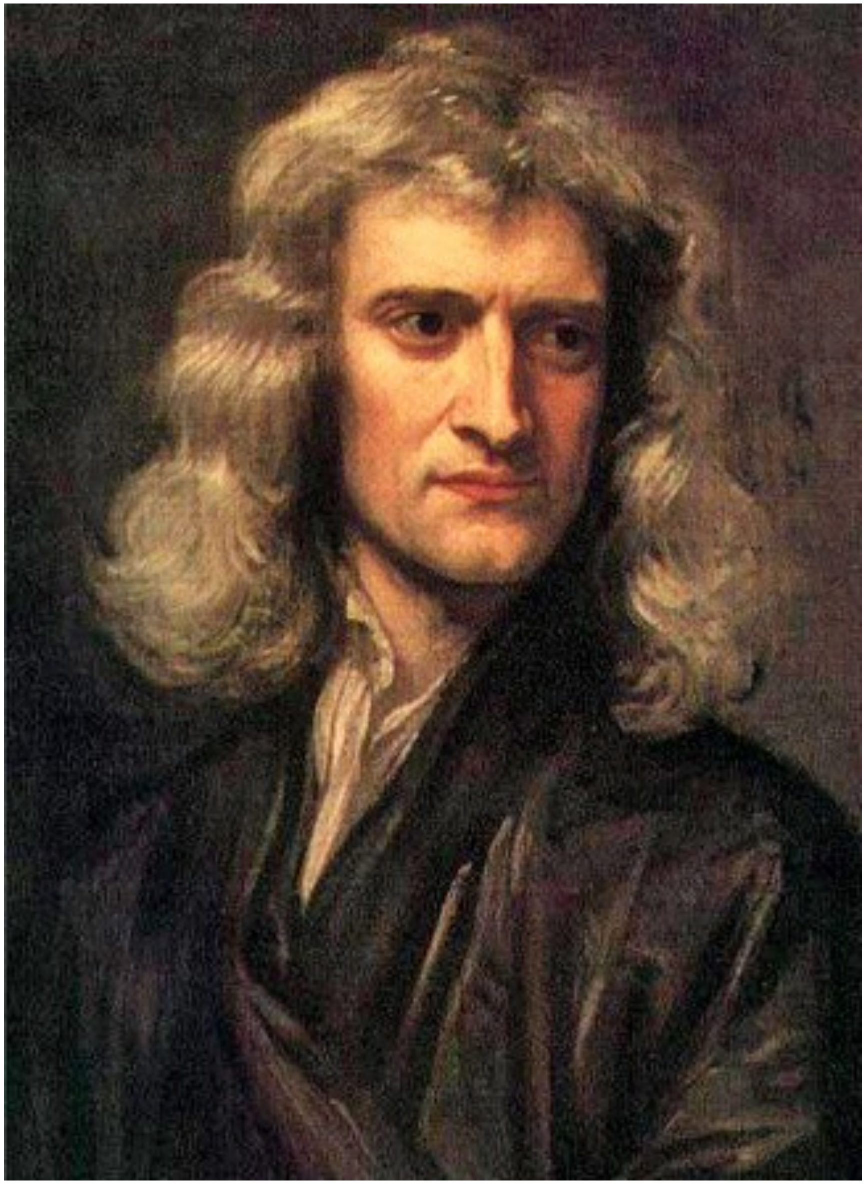
- Science progresses through the creation and testing of models of nature that explain the observations as simply as possible.

- A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions did not agree with observations.

Page 45. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley.

FIGURE 3.6

Isaac Newton (1643–1727), 1689 Portrait by Sir Godfrey Kneller. Isaac Newton’s work on the laws of motion, gravity, optics, and mathematics laid the foundations for much of physical science.



NEWTON'S THEORY OF GRAVITY

• Every mass attracts every other mass through the force called gravity.

• The strength of the gravitational force attracting any two objects is directly proportional to the product of their masses.

- -For example, doubling the mass of one object doubles the force of gravity between the two objects.

• The strength of gravity between two objects decreases with the square of the distance between their centers.

- We therefore say that the gravitational force follows an inverse square law with distance. For example, doubling the distance between two objects weakens the force of gravity by a factor of 2 squared, or 4.

Page 50. *The Cosmic Perspective Fundamentals*. Publisher: Addison-Wesley. © 2010

NEWTON'S THEORY BOTH EXPLAINS & ALLOWS PREDICTIONS

Galileo's experiment on falling bodies

Kepler's Laws

Prediction of the return of comet Halley

- Comet returned in 1758 as predicted

1846 Prediction of the location of a new planet

- From effect on orbit of Uranus
- Neptune found within 1 degree of predicted position

NEWTON'S LAWS OF MOTION

1. *Every body continues in a state of rest or uniform motion (constant velocity) in a straight line unless acted on by a force.*

   - This tendency to keep moving or keep still is called "*inertia.*"

2. *Acceleration (change in speed or direction) of an object is given by Force = Mass * Acceleration*

   - usually written as $F = ma$

3. *To every action, there is an equal and opposite reaction*

http://www.as.utexas.edu/astronomy/education/fall10/scalo/secure/301.F10.2.KeplerToNewton.

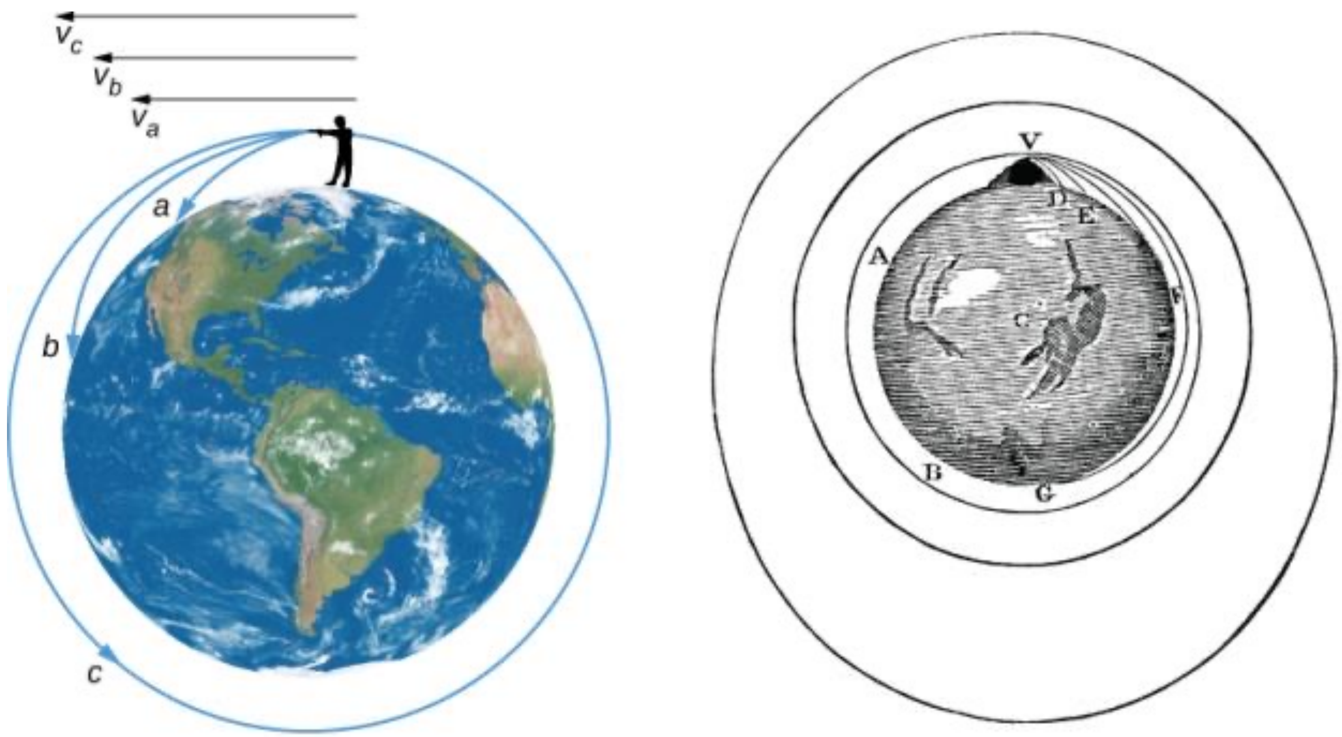
FIGURE 3.7

Demonstrating Newton's Third Law. The U.S. Space Shuttle (here launching Discovery), powered by three fuel engines burning liquid oxygen and liquid hydrogen, with two solid fuel boosters, demonstrates Newton's third law. (credit: modification of work by NASA)

FIGURE 3.8

Conservation of Angular Momentum. When a spinning figure skater brings in her arms, their distance from her spin center is smaller, so her speed increases. When her arms are out, their distance from the spin center is greater, so she slows down.

FIGURE 3.11. FIRING A BULLET INTO ORBIT



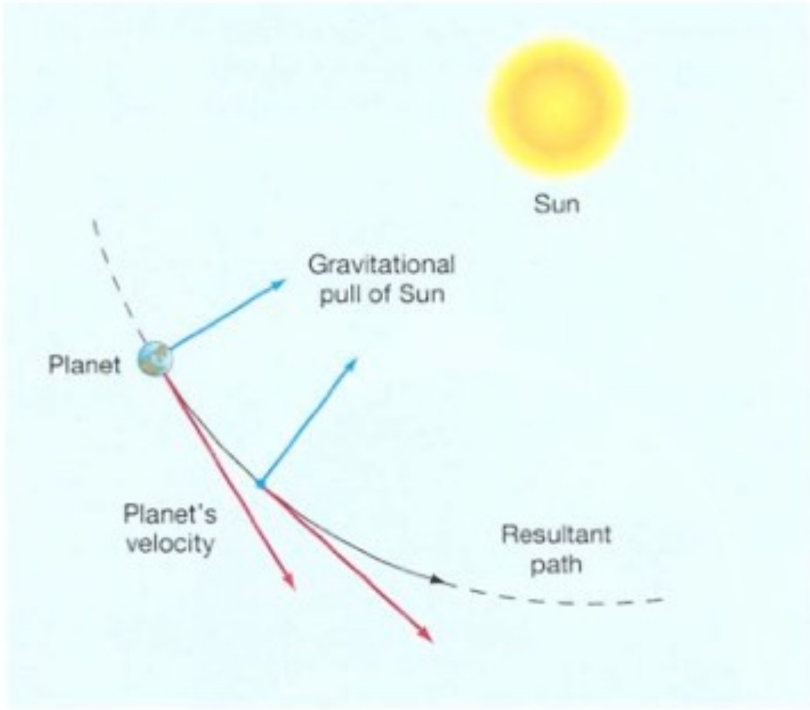
(a) (b)

Firing a Bullet into Orbit.

(a) For paths *a* and *b*, the velocity is not enough to prevent gravity from pulling the bullet back to Earth; in case *c*, the velocity allows the bullet to fall completely around Earth.

(b) This diagram by Newton in his *De Mundi Systemate*, 1731 edition, illustrates the same concept shown in (a).

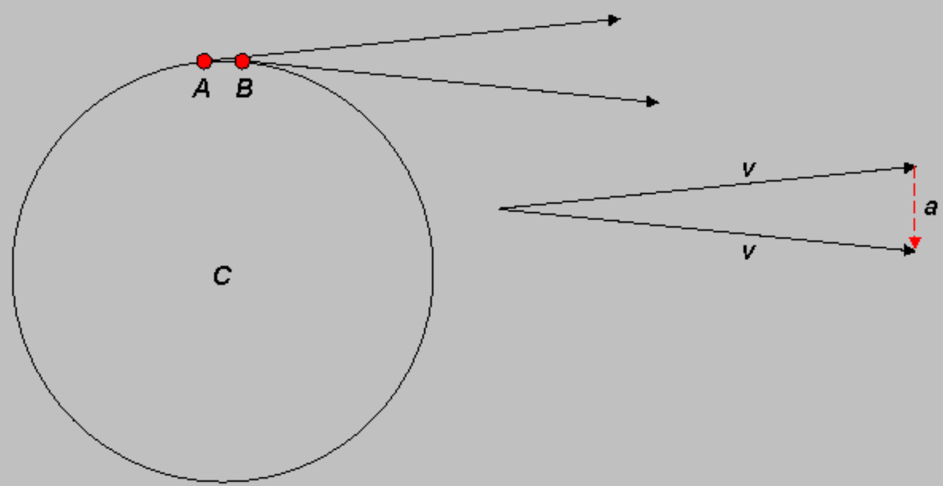
NEWTONIAN ORBIT



▲ **FIGURE 2.24 Solar Gravity** The Sun's inward pull of gravity on a planet competes with the planet's tendency to continue moving in a straight line. These two effects combine, causing the planet to move smoothly along an intermediate path, which continually "falls around" the Sun. This unending "tug-of-war" between the Sun's gravity and the planet's inertia results in a stable orbit.

http://www.as.utexas.edu/astronomy/education/fall10/scalo/secure/301.F10.2.KeplerToNewton.pdf

ACCELERATION IN CIRCULAR ORBIT



The velocity vectors (length *v*) for a ball moving at steady speed in a circle are shown one second apart. To find the acceleration—the difference between these two vectors—we must put their tails together and draw a new vector (the red dotted one) from the head of the first to the head of the second. This new vector (length *a*) is the difference: what must be added to the first to give the second.

The change in velocity in one second is the (average) acceleration in that second.

$$a/v = v/r$$

http://galileoandeinstein.physics.virginia.edu/lectures/newtongl.html

NEWTON EXPLAINS KEPLER LAWS

Force to move in a circle:

$$(M_{planet} * v^2) / R$$

NEWTON EXPLAINS KEPLER LAWS

Force to move in a circle:

$(M_{planet} * v^2) / R$

Gravitational Force:

$F_{grav} = (G^* M_{planet} * M_{Sun}) / R^2$

NEWTON EXPLAINS KEPLER LAWS

Force to move in a circle:

$$(M_{planet} * v^2) / R$$

Gravitational Force:

$$F_{grav} = (G * M_{planet} * M_{Sun}) / R^2$$

Set these equal because gravity is the force making the planet orbit

$$(M_{planet} * v^2) / R = (G * M_{planet} * M_{Sun}) / R^2$$

NEWTON EXPLAINS KEPLER LAWS

Force to move in a circle:

$$(M_{planet} * v^2) / R$$

Gravitational Force:

$$F_{grav} = (G^* M_{planet} * M_{Sun}) / R^2$$

Set these equal because gravity is the force making the planet orbit

$$(M_{planet} * v^2) / R = (G^* M_{planet} * M_{Sun}) / R^2$$

Velocity is circumference divided by time for one orbit

$$v = 2\pi R/T$$

NEWTON EXPLAINS KEPLER LAWS

Set these equal because gravity is the force making the planet orbit

$$(M_{planet} * v^2) / R = (G * M_{planet} * M_{Sun}) / R^2$$

Velocity is circumference divided by time for one orbit

$$v = 2\pi R/T$$

Substitute for velocity

$$(M_{planet} * 4 * pi^2 * R^2) / (R \bullet T^2) = (G * M_{planet} * M_{Sun}) / R^2$$

NEWTON EXPLAINS KEPLER LAWS

Set these equal because gravity is the force making the planet orbit

$$(M_{planet} * v^2) / R = (G * M_{planet} * M_{Sun}) / R^2$$

Velocity is circumference divided by time for one orbit

$$v = 2\pi R/T$$

Substitute for velocity

$$(M_{planet} * 4 * pi^2 * R^2) / (R \bullet T^2) = (G * M_{planet} * M_{Sun}) / R^2$$

Simplify

$$(\cancel{M_{planet}} * 4 * pi^2 * R^{\cancel{2}}) / (\cancel{R} \bullet T^2) = (G * \cancel{M_{planet}} * M_{Sun}) / R^2$$

$$(4 * pi^2 * R) / T^2 = (G * M_{Sun}) / R^2$$

NEWTON EXPLAINS KEPLER LAWS

$$(4 * pi^2 * R) / T^2 = (G*M_{Sun}) / R^2$$

Multiply both sides by R squared and by T squared

$$4 * pi^2 * R^3 = (G* M_{Sun}) * T^2$$

NEWTON EXPLAINS KEPLER LAWS

$$(4 * pi^2 * R) / T^2 = (G*M_{Sun}) / R^2$$

Multiply both sides by R squared and by T squared

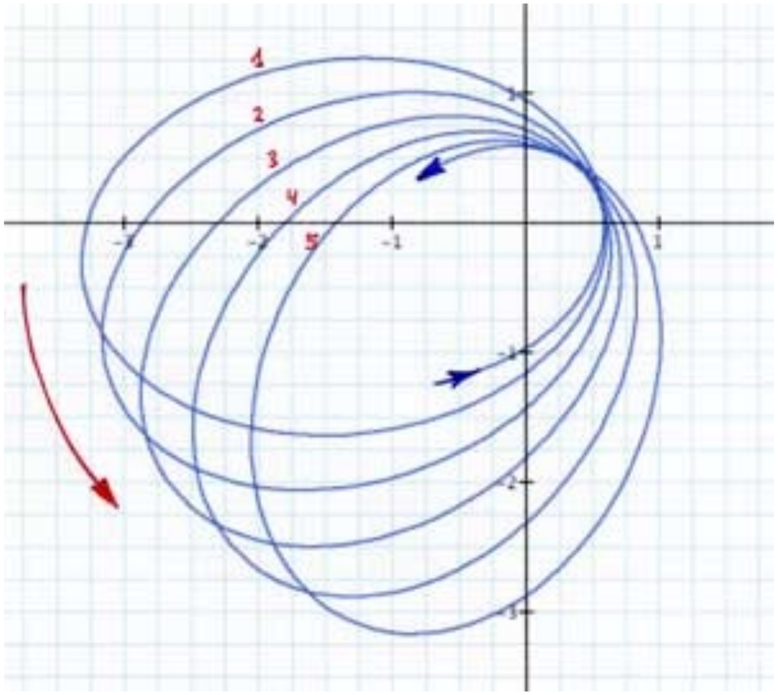
$$4 * pi^2 * R^3 = (G* M_{Sun}) * T^2$$

- The square of the period of any planet is proportional to the cube of the semimajor axis of its orbit. Kepler’s Third Law.

NEWTON’S THEORY HAS ITS LIMITS

Precession of the perihelion of Mercury

- Discrepancy is 43 arc seconds per century



http://www.relativity.li/en/epstein2/read/i0_en/i1_en/

EINSTEIN'S GENERAL THEORY OF RELATIVITY

Explained precisely the precession of the perihelion of Mercury

Was tested at a total eclipse of the sun in 1919

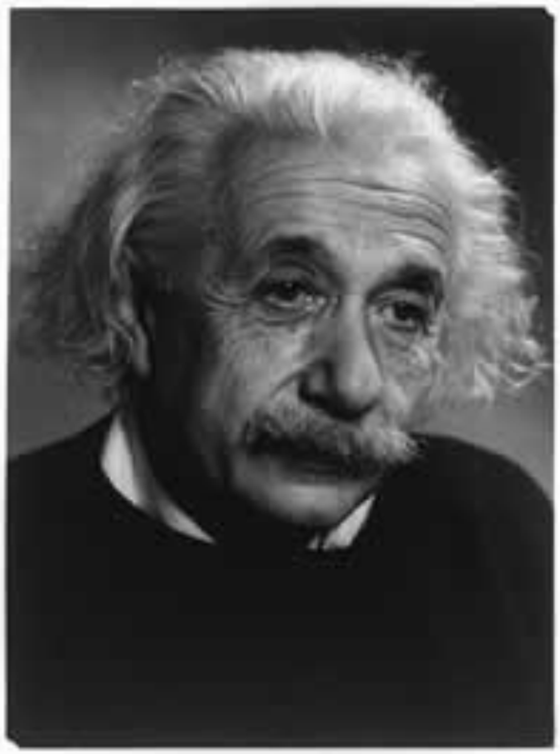
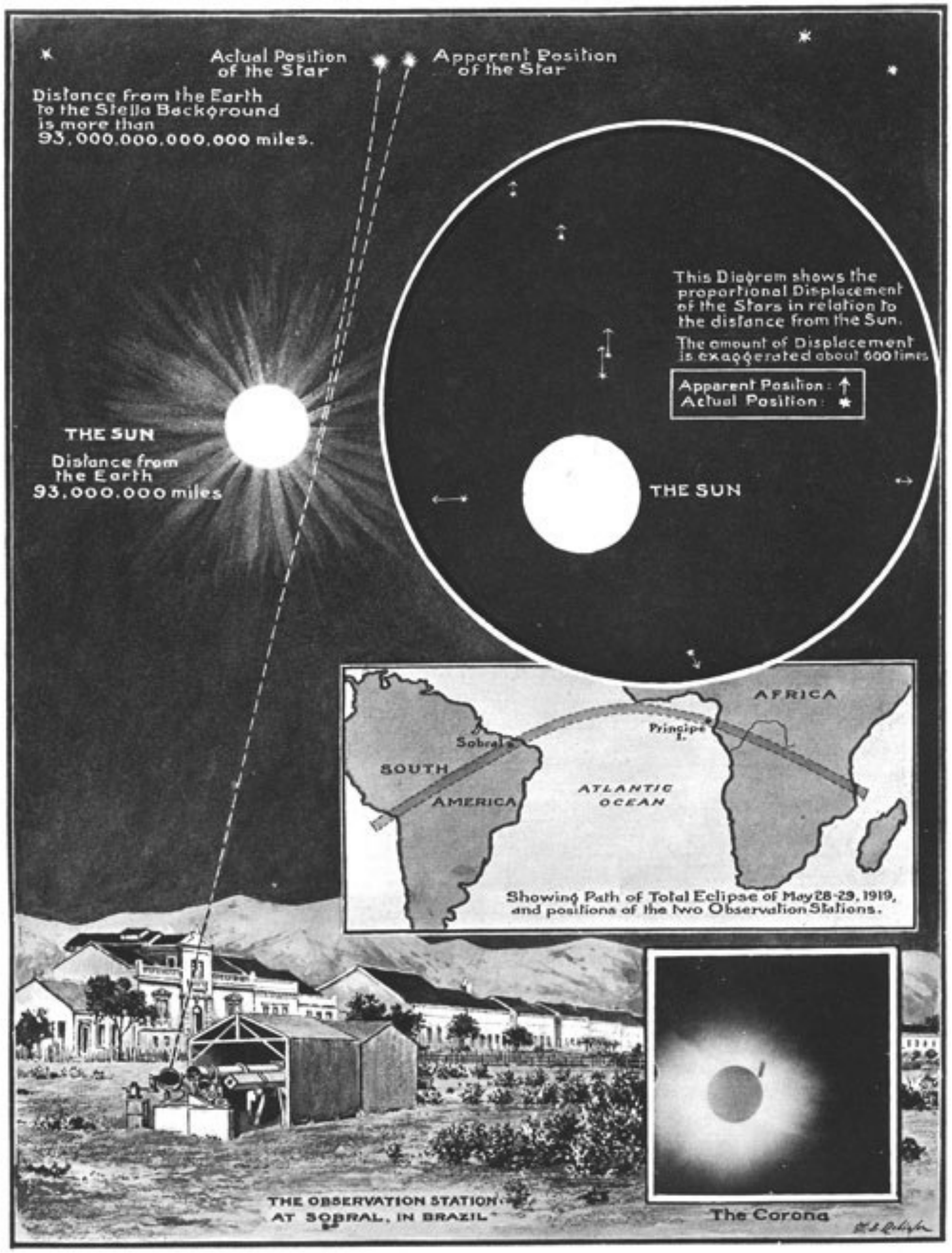


Photo: Albert Einstein. From Prints & Photographs Div., Library of Congress



From *The Illustrated London News* 22 Nov 1919

http://www.astro.caltech.edu/~rjm/Principe/1919eclipse.php

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

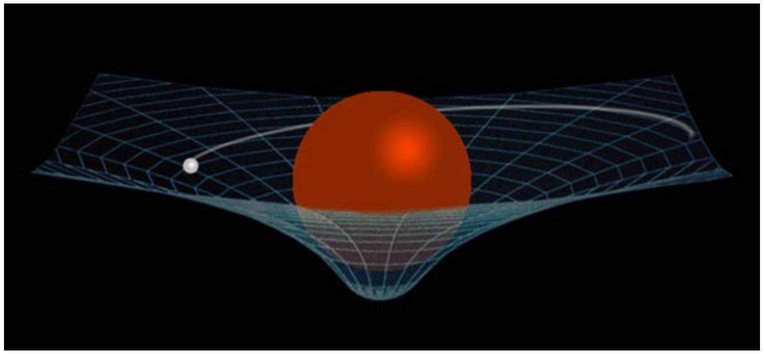
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

From *The New York Times*

http://www.astro.caltech.edu/~rjm/Principe/1919eclipse.php

CURVED SPACETIME

Einstein showed that spacetime itself is curved by the presence of mass (and hence energy) and that the gravitational force results from spacetime curvature.



https://theconversation.com/rippling-space-time-how-to-catch-einsteins-gravitational-waves-7058

Physicist John Wheeler summarized this by saying: — "*Mass tells spacetime how to curve and spacetime tells mass how to move*"

http://dirac.physics.pacific.edu/lat11/relativity/sp.pdf

SUMMARY

Ptolemy's earth-centered universe

- When it was developed and how long it was the leading model
- How it dealt with the problem of retrograde motion of planets
- The order of celestial spheres (the order of objects) in the model

Famous people, when they lived, and their contribution to astronomy

- Tycho Brahe
- Copernicus
- Kepler
- Galileo
- Ptolemy

The statement and meaning of **Kepler's three Laws of Planetary Motion**

The statement and meaning **of Newton's three Laws of Motion**

Newton's Law of Universal Gravitation, as an inverse square law