HISTORY AND OVERVIEW

Geocentric Model of Solar System: To the ancient Greeks, it seemed obvious that the sun, moon, and stars revolved around a stationary earth. "Geocentric" means earth-centered, and until the 17th Century it was widely believed that the earth was the center of the universe. The Greek philosopher Aristotle wrote that the universe was fixed and unchanging, with the earth at its center. The scientist Ptolemy agreed that the earth was the center, and his model of the solar system, first proposed about A.D. 150, was accepted almost without question for more than a millennium.

Heliocentric Model of Solar System: The Polish astronomer Nicolaus Copernicus (1473-1543) rejected the Ptolemaic model. He found that it was easier to describe the motion of the planets mathematically if he assumed they all revolved around the sun. Because it was contrary to the doctrines of the Catholic Church to assert that the earth moved in its orbit, Copernicus was careful to insist that he was making such an assumption only for the sake of mathematical convenience. Copernicus’s ideas were supported by the observations of Tycho Brahe (1546-1601), a Danish astronomer who precisely charted the positions of the stars and planets. Brahe’s data was interpreted by a colleague who worked with him, the German mathematician Johannes Kepler (1571-1630). Kepler proposed three laws of planetary motion based on the data he had. It took him about 10 years to reach his conclusions.

Kepler’s Laws: 1) All the planets move in elliptical (but nearly circular) orbits with the sun at one focus. 2) An imaginary line from the earth to the sun will sweep out equal areas in equal time periods. 3) The period of a planet’s rotation depends, in a precise mathematical way, upon its distance from the sun. In mathematical terms, if \( r \) = the distance from the planet to the sun and \( T \) = the time for one revolution about the sun, then the ratio \( r^3/T^2 \) is the same for all the planets. (Kepler believed his third law proved the existence of God, because only a supreme intelligence could have designed a universe so mathematically perfect.) The satellites we put into orbit above the earth verify Kepler’s third law every day.

Galileo (1564-1642): With his telescope, Galileo saw three or four moons of Jupiter clearly revolving about that planet, an observation that contradicted Aristotle’s belief that everything had to revolve about the earth. Galileo also saw the planet Venus undergoing phases, like the earth’s moon, as if it were reflecting light from a source it was rotating around. Galileo believed the sun had to be at the center of the solar system with the earth and the other planets revolving about it. Like Copernicus, he tried to excuse his "heresy" by claiming that it was merely a mathematical assumption, but the Church, in this case, didn’t allow him to do so. (The Protestant Kepler was not subject to Catholic authority.) Galileo was condemned as a heretic and his ideas were proscribed. The idea that the earth moved around the sun contradicted some Bible passages, notably the story of Joshua, who, at the battle of Jericho, made the sun stand still in the heavens to frighten his
enemies—not much of an achievement if it was already standing still. (The Catholic Church officially changed its mind in 1992, finally exonerating Galileo of heresy.)

**Newton (1642-1727):** Newton may be best known for his three laws of motion, but his law of universal gravitation was perhaps his most original achievement. He asserted that every mass attracts every other mass with a force proportional to the product of the masses and inversely proportional to the square of the distances between their centers. In formula form:

\[
v = \sqrt{\frac{Gm}{r}}
\]

\[
F = \frac{Gm_1m_2}{r^2}
\]

The force is negligible if the masses are small, but the force of gravity exerted by a mass as large as the sun acts over the huge distances in the solar system. Kepler’s 3rd Law turns out to be a special case of Newton’s Law of Universal Gravitation combined with his formula for centripetal motion. Newton was able to derive a formula for the speed of bodies orbiting around a central mass:

\[
v = \sqrt{\frac{Gm}{r}}
\]

In the formula, \(v\) = velocity, \(G\) = the gravitational constant, \(m\) = the central mass (the sun in the case of the earth revolving around the sun; the earth in the case of the moon or satellites revolving around the earth), \(r\) = the distance between the centers of the masses. The mathematics is beyond the regular 6th grade curriculum, but students may be able to perform the calculations with a calculator (see Activity 2). They should also appreciate how important the investigations of Kepler and Newton were to modern technology. Satellites, space exploration, planetary probes, etc., would not have been possible without the work of these giants, whose mathematics is the foundation of space travel.

When the Apollo 11 astronauts were returning to earth from their historic moon landing, they were asked by ground control in Houston "Who’s navigating up there?" One of the astronauts replied, "Newton."

**ACTIVITIES**

1. **Satellite Orbits**

The formulas of Kepler and Newton help scientists place satellites in precise orbits about the earth. Kepler proved that the period of rotation of the satellite depends on its distance from the earth. Since the period of rotation is related to the speed at which the satellite moves, Kepler’s third law also states that the speed of the satellite determines its height above the earth. A **geosynchronous** satellite, one that has an orbital period of approximately 24 hours, must be released when it is traveling at just the right speed (about 3100 meters/sec or slightly less than 7000 miles/hour). In space, it will maintain its final velocity indefinitely, and remain at the same height above the earth. The equations for satellite motion are complicated for 6th graders. First, it would be easier to analyze data like the following:

<table>
<thead>
<tr>
<th>Period of Satellite in</th>
<th>Distance from Center of Earth in</th>
</tr>
</thead>
</table>
Students will graph the data. The horizontal axis should be labeled "Distance in Thousands of Miles"; the vertical axis should be labeled "Period of Orbit in Hours." Students should find an appropriate scale, plot the data points, then draw a line connecting them. The graph should be an enlarged version of the following:

```
<table>
<thead>
<tr>
<th>Hours</th>
<th>Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4836</td>
</tr>
<tr>
<td>5</td>
<td>8910</td>
</tr>
<tr>
<td>10</td>
<td>14,142</td>
</tr>
<tr>
<td>15</td>
<td>18,534</td>
</tr>
<tr>
<td>20</td>
<td>22,452</td>
</tr>
<tr>
<td>25</td>
<td>26,052</td>
</tr>
<tr>
<td>30</td>
<td>29,418</td>
</tr>
</tbody>
</table>
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To determine the radius of the orbit of a geosynchronous satellite, find the point on the horizontal axis that corresponds with 24 hours on the vertical axis. Note the following: (1) Since the radius of the earth is approximately 4000 miles, subtract 4000 from the radius to get the height above the earth. (2) The distance from the moon to the earth is approximately 250,000 miles. (3) Therefore, a geosynchronous satellite must be placed in an orbit about one-tenth of the way to the moon.

Make sure the students understand the meaning of "geosynchronous." Roughly speaking, a geosynchronous satellite is one that stays above the same point on the earth all the time.

The formula that applies to satellites can also be used to find the speed of a planet around the sun; this is done in Activity 2.
Connections: mathematics; interpolating graphical data; communications and broadcasting; weather; spy satellites; aerial photography and mapping.

2. Orbital Speed

To demonstrate the relative speed of orbits of varying distance have students attach 50 cm, 100 cm, and 150 cm cords to three tennis balls. To attach the cords to the balls, poke a hole through each ball with a nail. Tie a knot at the end of the cord and poke it through the hole in the ball. In an open space have students swing the balls above their heads. Make sure the balls are moving in a horizontal plane. The goal of this activity is to observe how the radius of a particular orbit determines its speed. The satellite must also maintain this speed in order to remain in the orbit. The closer the ball is to the pivot point, the faster it must move in order to remain in orbit. Centripetal force generated by the orbit counter-balances the gravitational pull thereby keeping the object a certain distance from its fixed point. The physics formula for centripetal force is $F = \frac{mv^2}{r}$; as the value of $r$ (the radius) decreases, the value of $F$ (the force) increases. The velocity increases at the same time. Students whirling the ball around can easily detect the variation in force; to emphasize the different forces required, the string can be tied to a spring scale before spinning the ball around.

The formula for the speed of a planet orbiting around the sun (and held in place by gravitational forces) is

$$v = \sqrt{\frac{GM}{r}}$$  The formula for the speed of a planet orbiting around the sun (and held in place by gravitational forces) is

The formula looks complicated; a calculator is necessary. Correct units must be used. In the formula, $M$, the magnitude of the central mass, must be expressed in kilograms; $r$ must be in meters; the gravitational constant $G$, verified many times over in laboratory experiments, is

$6.67 \times 10^{-11}$. The speed will come out in meters/sec. We can find the speed of the earth around the sun using the following data: mass of the sun $= 2 \times 10^{30}$ kg; the distance from earth to sun, in meters, is $1.49 \times 10^{11}$ m. Use the gravitational constant and the formula above to calculate the speed. The answer will be about 30,000 m/sec. Note particularly that there is no place in the formula for the mass of the earth. The speed of an orbiting body depends on the mass of the body around which it orbits.

The speed of a planet around the sun can also be approximated by using the relationship

$$v = \frac{2\pi r}{t}$$, where $r$ = distance of the planet from the sun, $t$ = the time for one revolution around the sun, and $2\pi r$ is the approximate circumference of the orbit. (The formula is a form of the basic rule that distance = speed × time.) The planet Mercury is about 36 million miles from the sun; that makes the circumference of its orbit about 226 million miles. It takes 88 days to complete one revolution, so its speed around the sun is 226 / 88, or about 2.57 million miles per day. Jupiter is about 483 million miles from the sun; the circumference of its orbit is 3 billion miles, or, to keep the measurements consistent, 3000 million miles. It takes Jupiter 11.86 years, or 4300 days to complete one revolution,
so its speed around the sun is $3,000 \div 4300$, or about 0.7 million miles per day. Other calculations—and they are difficult for $6^{th}$ graders—will show the relationship between the speed of a planet and its distance from the sun. The greater the distance, the slower the speed.

3. Drawing an Ellipse

The orbits of the planets are nearly circular ellipses. An ellipse is the conic section obtained by slicing through a cone, from side to side, with a plane that is not parallel to the base. It is fairly easy to draw an ellipse:

First, let’s draw a circle. Hammer a nail into a board (a strong pin pushed into styrofoam works just as well). Tie a piece of string into a loop, loop one end around the nail, stretch the string taut by putting a pencil at the other end, then move the pencil around in a circle while keeping the string taut. To draw an ellipse, hammer two nails into a board, not too far apart. Loop one end of the string around both nails, stretch the string taut by putting a pencil at the other end, and proceed as before. The pencil will trace out an ellipse.

The ellipse represents the orbit of the earth around the sun, which is at one focus. (The other focus has no physical significance; it is only used for drawing and can be ignored.) It is fairly easy to see that the distance from the earth to the sun is not constant. When the earth is closest to the sun, its speed must increase—remember the previous experiment where the force on the tennis ball was greatest when the "orbit" of the ball had the smallest radius. If the earth didn’t increase its speed, the gravitational pull of the sun might draw it closer; the earth’s climate might cataclysmically change. When the earth is farthest from the sun, its speed is slightly slower. What may be difficult for students to understand is that the earth is closest to the sun when it is winter in the northern hemisphere, and farthest when it is summer. The change in seasons is due to the tilt of the earth on its axis. When the northern hemisphere tilts toward the sun, the sun’s rays strike the atmosphere more directly and we have summer—even though the actual distance to the sun is slightly more than it is in the winter.

Kepler’s law of equal areas, which confirms the varying distance between sun and earth, is a difficult concept for $6^{th}$ graders. A picture like the following might help:

It takes as long to get from A to B as it does from C to D.

The areas of the triangles APB and CPD are the same.

The following are helpful websites for understanding Kepler’s laws.

http://observe.ivv.nasa.gov/nasa/education/reference/orbits

www.cvc.org/science/kepler.htm
4. Weight on Other Planets

Weight is the same thing as the gravitational force a planet exerts on a body. The more massive the planet, the greater the gravitational force. Have students find their weights on other planets by completing the following:

My weight on earth is __________________ lbs.

<table>
<thead>
<tr>
<th>Place</th>
<th>Gravity Factor</th>
<th>My Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>Venus</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Mars</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>Jupiter</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Saturn</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>Uranus</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>Neptune</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Pluto</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Moon</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Sun</td>
<td>27.8</td>
<td>Example: A person who weighs 120 lbs on earth will weigh 45.6 lbs on Mercury.</td>
</tr>
</tbody>
</table>

Related questions: (1) Which planets have close to the same surface gravity as the earth? (2) Should Pluto really be considered a planet? (3) How do you think Jupiter’s gravity would affect any astronauts who land there?

Application to metric system: have students change their weight from pounds to kilograms on each planet, starting with earth. Conversion formulas: weight in pounds × 0.45 = weight in kg.

Enrichment: have students investigate gravity more thoroughly by exploring the reasons why their weight on earth, Neptune, and Saturn are fairly close, even though both of those planets are far huger than earth. The reason is that weight on the surface depends on
both the mass of the planet and its diameter. On Saturn, an object on the surface is so far from the center that the gravitational pull is weakened. Saturn, for example, has about 100 times the mass of the earth, but its radius is 10 times bigger; the gravity factor depends on the size of the mass and the square of the radius. In Newton’s formula, force depends on mass \(m\) divided by radius squared \(r^2\). 

\[
100 \div 10^2 = 1; \text{ on Saturn, the mass and radius balance each other so that gravity on the surface is close to earth’s.}
\]

5. Scale Model of the Solar System

A model showing the relative distances of the planets from the sun can be made in the classroom, even though the solar system is vast. The requisite materials are about 20 feet of adding machine tape, pencils, and meter sticks (with centimeter gradations). Suppose the sun is at one corner of the room. Then the locations of the other planets should be marked on the adding machine tape according to the following table. Scale: 1 cm = 10 million km or approximately 6 million miles. (Note the change from cm to m for Saturn and beyond.)

<table>
<thead>
<tr>
<th>Planet</th>
<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
<th>Pluto</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td>5.8 cm</td>
<td>10.8 cm</td>
<td>15 cm</td>
<td>22.8 cm</td>
<td>77.8 cm</td>
<td>1.43 m</td>
<td>2.87 m</td>
<td>4.5 m</td>
<td>5.9 m</td>
</tr>
</tbody>
</table>

The students should clearly see that the inner planets are much closer to the sun than the outer planets. Among the reasons life exists on earth, according to some theorists, is its proximity to the sun—just the right distance to keep it warm enough for life. Also, the large outer planets protect the earth from bombardment by space debris (meteors, etc.); they attract debris to themselves, or else their gravitational pull can cause the debris to change course and head out into space.

Once the class has constructed its model, the students can make paper rockets and shoot them out into the solar system by blowing into straws. The activity is fun, but it also provides an opportunity to talk about the design of actual rockets, which depend on thrust to launch them into space. Fuel burns, gas is produced, the force of the expanding gas acts in one direction (thrust), and, according to Newton’s Third Law of Motion ("For every action there is an equal and opposite reaction"), the rocket must move in the other direction.

Supplementary activity: Have students use the internet to find out how to represent the relative sizes of the planets by using various objects. For instance, if Jupiter were the size of a basketball, Saturn might be as big as a grapefruit, and so forth.

6. Some Inventions from Space

1. Freeze-Dried Food: to save room on a spacecraft, astronauts add water to food that has had the water taken out of it. The food reconstitutes and can be eaten.
2. In-Suit Drink Bag: When astronauts are on long space walks, they can sip drinks from a juice pouch built into their spacesuits.

3. Temperature Controls: Special devices built into space suits control temperature. If the astronaut gets too warm, the suit cools off, and vice versa.

Ask the students to imagine ways in which any of the above inventions can be useful on earth. Have them research other technological innovations inspired by space travel.

7. Graphing Constellations

The ancient Greeks and Romans saw pictures in the fixed patterns of stars in the sky: Orion with his sword and his belt in the winter; the hooked shape of the Scorpion placed low in the southern sky in the summer (so it would never again meet Orion, whom it killed); the W-shape of Cassiopeia the Queen; the cross-shaped Cygnus (the Swan, but also known as the Northern Cross). We know now that the patterns are not eternally fixed, but the stars move so slowly that we can see the same constellations the Greeks saw. In another ten thousand years, the Big Dipper will no longer be recognizable; and the star Vega, almost directly overhead on summer nights, will become the North Star. We can count, however, on the constellations remaining constant in our lifetimes; and because so little time has elapsed on a cosmic scale since the ancient Greeks looked at the sky, we can be certain we are seeing the same things.

Diagrams of constellations can be drawn by plotting coordinates on a graph. Only positive axes (i.e., the first quadrant) will be needed. Give the students graph paper, have them label the positive x- and y-axes, and call out the points in order for each constellation. These coordinates are not exact positions; they were obtained by drawing the given constellations on graph paper and approximating positions of the stars as closely as possible.

Orion: (12.5, 7), (16, 7.5), (14, 4), (15, 4.5), (16, 5), (14, 1), (17.5, 2)

Ursa Major (Big Dipper): (1, 6), (2.5, 5.5), (4, 5), (5, 4.5), (5.5, 3), (7.5, 3), (8, 5)

Cassiopeia: (2, 10.5), (3, 12.5), (4, 11.5), (4.5, 12.5), (5.5, 11.5)

Orion will look something like the following:
From the earth, the seven major stars of Orion appear to be in the same plane; in fact, they are not. Because they are all moving, and because the solar system itself is moving around the center of the Milky Way galaxy, our perspective will change in several thousand years and Orion will appear different. After mapping the constellations, suggest that students try to locate them in the night sky. (The Big Dipper and Cassiopeia are toward the north; Orion is best seen in winter, toward the south.)

Connections: Greek mythology (part of the 6th grade curriculum); navigation; telescopes. Explain how the "pointer stars" of the Big Dipper point toward Polaris, the North Star, whose position was essential in navigation before the discovery of the magnetic compass. Explain also that stars are "suns," but so far away it is difficult to determine whether any of them are part of solar systems. One of the stars closest to earth can be found by following the line of Orion’s "belt" toward the left. The belt points toward Sirius, the brightest star in the sky. It is approximately 8 light years away from earth, which means that the light we see coming from it has been traveling for 8 years. An observer near Sirius would not be able to see our sun with the naked eye—even though by astronomical standards, the distance from Sirius to the sun is fairly small.