PLANETARY MOTIONS

Goals:

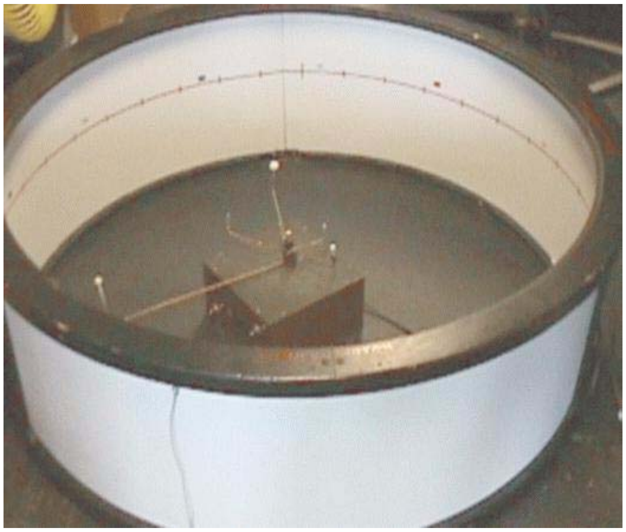
- To develop a 3-D sense of the locations and motions of the planets in the solar system
- To recognize how solar illumination of planetary bodies and our viewing perspectives affect what we see of the planets
- To gain a sense of the relative sizes and periods of the orbits of the planets
- To see how retrograde motion arises naturally in the solar system
- To gain a sense of the difficulty faced by ancient peoples in trying to understand the motions of the planets.

Equipment:
Shadow Orrery, Wristwatch, Meter Stick, Lab Books (recording paper)

Methods:

- Observe locations and motions of planet shadows cast by a light bulb at the Sun's location.
- Observe illumination of planetary surfaces by the Sun, as viewed from the Earth's location
- Observe locations and motions of planet shadows cast by a light bulb at the Earth's location.
- Observe retrograde motion of planets, as viewed from the Earth's location.

Introduction - In this exercise you will examine the motions of the planets, how the planets appear to an Earth-bound observer and how they would appear to an "outside" observer far from the Solar System. The tool we will use to illustrate planetary motion is a mechanical model of the Solar System called a **Shadow Orrery**, named after Charles Boyle Orrery (1676-1731), the fourth Earl of Orrery, in England, for whom one of these devices was made.



The Shadow Orrery

The Planets - To the Greeks, the planets (which means "wanderer" in Greek) were celestial objects which moved with respect to the "fixed stars." There were seven known planets in ancient times: Mercury, Venus, Mars, Jupiter, Saturn, the Sun, and the Moon. All other celestial objects were fixed stars and moved together - their positions with respect to one another did not change. Planetary motions seen against the fixed stars take place over periods of months and years.

The apparent motion of the Sun among the stars is difficult to observe because it is so bright compared to the stars. One early realization of ancient astronomers is that the stars are still present in the sky during the day, but are not visible due to the glare from the Sun. We must, therefore, infer the Sun's motion among the stars by noting which stars are visible at sunset. The Sun moves completely around the celestial sphere in one year; 360 degrees in just over 365 days.

The Zodiac - The Solar System is basically flat. All the planets (including the Earth) orbit the Sun in roughly the same plane. From the Earth, the "planets" are always found in the sky somewhere along a circular band called the **Zodiac**. In the center of the Zodiac is the **Ecliptic**, the line along which the Sun appears to move among the stars. Because the Solar System is so flat and the planets are always somewhere along the circular path of the zodiac, describing planetary motion is relatively simple, as we only have to follow motions along the zodiac. The motions perpendicular to the ecliptic are small and can often be neglected. Thus the models of Ptolemy, Copernicus, and others can be drawn on flat sheets of paper and do not require three dimensional (3-D space) models.

Planetary Configurations - The planets in the solar system are separated into two groups. **Inferior planets,** Mercury and Venus, are those which orbit closer to the Sun than the Earth. **Superior planets,** Mars, Jupiter, Saturn, Uranus, Neptune and Pluto, have orbits farther from the Sun. As a planet orbits the Sun, there are many arrangements possible between the Earth, the planet, and the Sun. Astronomers have identified some particular geometric arrangements of a planet's position relative to the Sun and Earth.

Conjunction is when two objects are seen close to each other in the sky. When either Mercury or Venus is along a line between the Earth and the Sun, the planet is said to be in **inferior conjunction**. When an *inferior planet* is on the opposing side of the Sun with respect to the Earth, the planet is in **superior conjunction**. Inferior and superior conjunctions occur only for inferior planets. Since inferior planets are in close proximity to the Sun during conjunctions, for Earth observers the planet is usually lost in the glare of bright sunlight. Occasionally, an event known as a **transit** occurs. An observer on Earth, with proper viewing precautions taken for the bright sunlight, will see the inferior planet pass across the face of the Sun. The precise alignment of the planet's orbital plane and the short duration of the inferior conjunction required for a transit event make this a rare occurrence.

The angular distance between a planet and the Sun, as viewed from Earth, is called the **elongation** angle. Since the inferior planets orbit closer to the Sun, Earth observers always see these planets close to the Sun's position in the sky. **Greatest elongation** is the maximum angular distance between the two bodies. During greatest elongation an observer has the longest time to view Venus or Mercury without interference from sunlight. Greatest eastern elongation is when a planet is the furthest east from the Sun. At that time, after the Sun sets in the west, the planet is observed to be near the western horizon as an "**evening star**". Conversely, at greatest western elongation, a planet is farthest west of the Sun and is thus a "**morning star**" in the eastern sky shortly before sunrise.

Conjunction for a *superior planet* is when the planet and the Sun appear together in the sky, so that the Earth, Sun, and planet are aligned. Since superior planets orbit outside the Earth's orbit, they have no inferior conjunctions.

Opposition is when a superior planet is found opposite the Sun in the Earth's sky. At opposition, the planet crosses the observer's meridian at midnight, and the Earth is between the Sun and planet. Opposition provides an observer with the maximum amount of planet viewing time with the Sun set.

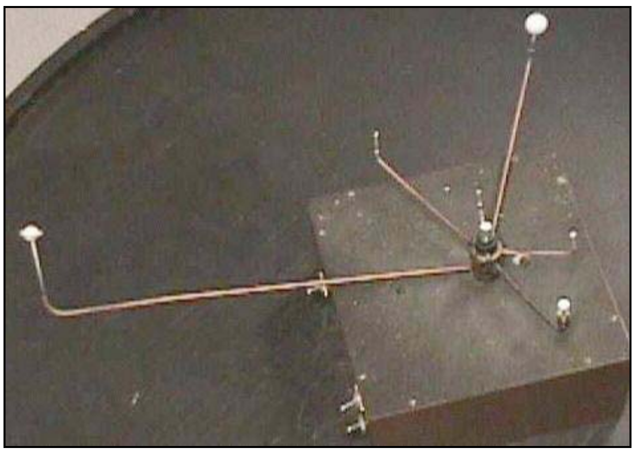
Quadrature is when the direction to a superior planet is perpendicular to the Earth-Sun line. The superior planet, the Earth, and the Sun form a right angle with the Earth at the vertex. Both eastern and western quadratures of the superior planets occur.

Retrograde Motion - The motion of all the planets around the zodiac is generally from west to east. This west to east motion is called **prograde** motion. However, all the planets (except the Sun and Moon) spend a fraction of their time moving from east to west among the stars. This is called **retrograde** (backward) motion. Mercury and Venus spend almost half their time in retrograde motion;

the outer planets spend much less of their time in retrograde motion. It took many years of observations for astronomers to realize that these motions repeat themselves in a regular fashion.

The **synodic period** is the time between similar alignments of the Earth, the planet, and the Sun, for example, from one opposition to the next opposition. The Earth makes one orbit of the Sun in one year while Mars takes 1.88 years. If we start a clock at the next opposition of Mars, then the time it takes until the following Mars opposition will include the time needed for the Earth to orbit the Sun once and then "catch up" to Mars, which by then will have moved over halfway around the Sun in its own orbit. It takes the Earth almost another full year to catch up to Mars.

The **solar day** is the time between sunrises, due to the earth spinning on its axis. The **sidereal day** is the time between a star rising to its next star rise. The difference between a solar day and a sidereal day is that the earth has moved in its orbit around the sun about one degree during each day, so the sun has changed positions eastward from our viewpoint. This change makes each sunrise 4 minutes later every day when you compare the time it takes a star to rise on successive days. This is the reason the constellations change season to season. The sidereal day is shorter than the solar day.



Our orrery has six arms, representing the Earth and five planets. The Sun (at center) and Earth are each light bulbs.

Shadows cast by planets onto orrery wall from light originating at the Sun's location (center).

The Shadow Orrery -

Instead of watching the planets for several years, we will use a mechanical device, the **orrery** to represent planetary motions in an accelerated fashion. An orrery is *a mechanical model of the Solar System*. The model Sun is at the center and the model planets are driven around by a system of gears. Sometimes, on more elaborate orreries, some of the many satellites (moons) are also included, orbiting their respective planets. Many fine orreries were built during the 17th and 18th centuries when Kepler's and Newton's discoveries were still new and exciting. These orreries were clockwork driven, made of brass, and highly decorated. They are now found in museums.

Our orrery is a shadow orrery - two of the bodies, the Sun and the Earth, are represented by small light bulbs. Whenever the orrery is switched on, one or the other of these bulbs is lit. Five planets are represented by small solid spheres, with Saturn displaying rings. These are the planets visible without the aid of a telescope and were the only planets known in Newton's day (Uranus was not discovered until 1781). From the Sun outwards they are: Mercury, Venus, Earth, Mars, Jupiter and Saturn. When the room lights are dimmed, the bulbs (Earth or Sun) will cast shadows of the other planets onto the circular screen surrounding the orrery. Imagine the screen is the sky of stars, the celestial sphere, and the strip of the sky along which the planets are seen is the zodiac. There is a red line in our orrery which represents the ecliptic.

As the orrery arms move, the projected shadows will model the motions of the planets against the background of stars. The sizes of the shadows correspond to the brightness of the objects casting the shadows. So, a large shadow represents a bright object in the sky.

When the "Sun" is lit, the motions seen are those representing the "perfect motion" or Aristotelian view of the Universe. The apparent motions are simple: circular planetary orbits with constant orbital speed and perfect spherical bodies of unchanging size and brightness (constant shadow sizes, as represented by the orrery). When the “Earth” bulb is lit, the motions represent those seen by an Earth observer and model the complicated apparent motions of the planets.

PLANETARY MOTIONS

Name/ID\#______________________________ TA's Initials:________

Class/Section: AS101/ ______ Date due:____________

Procedure -

1. Your teaching assistant will identify and explain the functions of the parts of the orrery.

2. The orrery will be turned on and run initially with the room lights illuminated. (Try to predict how the orbits for each planet, the sizes of the spheres, and the times for each to complete their orbits will produce the movements of the shadows.)

3. Next, the room lights will be darkened and you will follow the motions of the orrery planet shadows. First, the "Sun" light will be lit. (Examine the locations, sizes, and periods of the planet shadows.) Next, the "Earth" light will be lit and the "Sun" light darkened. (Examine the locations, sizes, and periods of the planet shadows.)

1. With the room lights on, examine the orrery and the planet spheres

- Which planet is represented by the largest sphere? ________________________
- Which planet is represented by the smallest sphere? ________________________
- Which planet is represented by the largest orbit? ________________________
- Which planet is represented by the smallest orbit? ________________________

- What is the ratio of the size of Jupiter's orbit to the size of Mercury's orbit in this model?
  - Measured size of Jupiter's orbit in orrery = ________________________
  - Measured size of Mercury's orbit in orrery = ________________________
  - Ratio of measured sizes (Jupiter/Mercury) = ________________________

- Jupiter's actual average orbital distance is 7.78×10^{13} cm, and that of Mercury is 5.79×10^{12} cm.
    - True ratio of orbit sizes (Jupiter/Mercury) = ________________________

- Why do you think this orrery was not built to scale?

2. Turn the room lights off, and turn on the orrery mechanism.

- From the vantage point of the Sun (i.e. turn on the "Sun" light bulb),
    - Which planet appears brightest? ________________________
    - Which planet appears dimmest? ________________________

- Do the apparent brightness of the planets (that is, their cast shadows sizes) change during their orbits? ________________________
    - Please explain your previous answer.

- Which planet (shadow) moves fastest in its orbit? ________________________
- Which planet moves the slowest in its orbit? ________________________
- Does the apparent speed of any planet vary in the orrery "sky" during an orbit? ________________________

- Please explain your answer.

- Using a watch with a second hand, measure the time it takes Mercury and Mars to orbit the orrery Sun.
  - Measured orbital period of Mars = ________________________
  - Measured orbital period of Mercury = ________________________
  - Ratio of the periods (Mars/Mercury) = ________________________
- The true orbital period of Mercury is 88 days and of Mars is 687 days.
  - Ratio of true periods (Mars/Mercury) = ________________________
- Why do you think the orrery was not built to the correct time scale? ________________________

3. Turn on the "Earth" light bulb.

- Which two planets (shadows) appear largest when viewed from the Earth, ignoring the Sun's shadow? ________________________ ________________________
- Does the answer depend on when you look? ________________________
- Explain your answers

- Draw the arrangements of the Sun, Earth, and the following planets when each planet appears largest and smallest in the Earth's sky.

A) Jupiter: Largest	B) Jupiter: Smallest
C) Venus: Largest	D) Venus: Smallest

- What are the astronomical names for these configurations?

A) ______________________________

B) ______________________________

C) ______________________________

D) ______________________________

- Which orrery planet changes the most in apparent brightness? ____________________

- Which planet moves the fastest across the orrery sky? ____________________

- Which planet moves the slowest across the orrery sky? ____________________
- Does the apparent speed of any planet's motion vary in the orrery sky? ____________________

- Does any planet's motion change direction in the orrery sky? ______________________

    - Please explain these last two answers:

- Focus only on the **superior planets** motions.

    - What is the synodic period you measure for Mars? ___________________
    - What is the synodic period you measure for Jupiter? ___________________
    - Which superior planet makes the smallest retrograde loop on the orrery sky? ___________________
    - Which superior planet makes the largest retrograde loop? ___________________
    - Which superior planet moves retrograde most frequently (i.e., it has the smallest synodic period)? ___________________
    - Which superior planet moves retrograde least frequently (i.e., largest synodic period)? ___________________
    - Is the apparent size of a planet related to its retrograde motion? ___________________

        - Please explain your answer.

- Focus only on the **inferior planets** motions

- Draw accurate, scale diagrams of the positions of Mercury and Venus for greatest elongation.

Mercury: greatest **eastern** elongation

Venus: greatest **western** elongation

- Using the scale on the orrery wall, what is the value of Mercury's greatest elongation? ___________________

- Similarly, what is the value of Venus' greatest elongation? ___________________

- In your drawings, when would an observer see the planets? In the morning or in the evening? (i.e. which would be seen first, the planet or the Sun?) Remember the Earth rotates counter clockwise on its axis as viewed from above the ecliptic.

  - Mercury: ___________________

  - Venus: ___________________

- At greatest elongation, how much of Venus' surface is illuminated as viewed from Earth? (Draw a picture of how Venus would look from Earth at this time. Use dark shading to indicate the portion which is dark and a lack of shading to indicate which portion is bright.)