Chapter 2: Copernicus, Brahe, and Kepler

Student Worksheet

Objective: Use simple activities to understand the concepts of retrograde motion, parallax, and ellipses, and to develop awareness of the contributions of Nicolaus Copernicus, Tycho Brahe, and Johannes Kepler to our modern understanding of the universe.

Engage: Imagine for a moment that you do not know whether we live in a heliocentric or a geocentric solar system. Make an argument for each case using what you could observe without a telescope. If you lived thousands of years ago, how would you think of the map of our solar system and why?

Introduction: These days it seems wild to think of the Sun and the planets of our solar system revolving around the Earth. But it took a very long time for people to move from this Ptolemaic, geocentric view to a sun centered or heliocentric view of our solar system. Nicolaus Copernicus re-proposed Aristarchus's idea of heliocentric solar system after being unable to make a working geocentric model that explained retrograde motion. Tycho Brahe also sought a better model than the geocentric model, but he did not embrace a heliocentric model due to the problem of parallax. Brahe was an excellent observer. His observatory was full of new instruments to precisely calculate the positions of the planets, although his observatory lacked the instruments we most commonly associate with observatories –i.e., telescopes. The telescope was invented just a few years after Brahe's death. Johannes Kepler worked to solve the problems of planetary motion that Copernicus and Brahe could not solve. Kepler published three laws of planetary motion that solved the puzzle – elliptical orbits.

In this investigation you will do three short experiments – one related to each of the three thinkers: Copernicus and retrograde motion, Brahe and parallax, Kepler and the ellipse.

Retrograde, or backward motion, of planets is observable from Earth. Typically, planets appear to move eastward relative to the background stars. At times though, they appear to move westward. This puzzled humans for quite a long time. Part 1 is dedicated to enhancing your understanding of retrograde motion.

Parallax is defined in astronomy as the shift of a star's apparent position due to the motion of the Earth. By measuring parallax , sky watchers have long been able to measure the distances to nearby stars and planets. The closer the object, the greater the apparent shift. Hence, planets display a great shift, while stars exhibit a miniscule shift. In Part 2 you will measure the distance to an object using parallax.

An ellipse is a shape that looks like an elongated circle. The long diameter (the major axis) and the short diameter (the minor axis) define ellipses. Kepler proved that planets travel in ellipses around the Sun, a discovery which lead to his three laws of planetary motion:

1st Law: Planets move in ellipses about the Sun at one focus.

2nd Law: Planets sweep out equal areas in equal times.

3rd Law: The period of a planet squared is equal to the semi-major axis cubed. $P^2 = a^3$.

In Part 3 you will draw ellipses and learn about the ellipse terms used in astronomy.

Procedure:

Part 1: Copernicus and Retrograde Motion

1. Your teacher will give you a diagram entitled *Copernicus and Retrograde Motion*.
2. On this diagram, use a straight edge to draw a line from each Earth position through the Mars position for the same month. Extend the line approximately 1 cm past the curved line on the right hand side of the page. Place a dot at the end of the line and label the dots in order, with the dot on the January line being number 1, the dot on the February line being number 2, and so on. Note: If paths cross, draw the lines slightly long and place the dots slightly farther away than you did for the other lines. Notice that the line for January is already drawn and the dot is labeled.

3. Next, start with the dot labeled "1" and carefully connect the dots in order. (This line represents the path the planet Mars would follow in its orbit around the sun as seen from Earth.)

   The dots you plotted represent the positions where an observer on Earth would see Mars. The line you drew connecting the dots represents the path Mars appears to follow.

Part 2: Brahe and Parallax

1. Review *angular size* with your instructor. When star-gazing at night, it is useful to use your hands as an angular measurement reference. For this activity we will want to be as precise as possible so we will use a makeshift astrolabe based on a protractor to help us.

2. Make your measuring tool.
   a. Place two coffee straws together. Stick a safety pin through the straws, pinning them together about a centimeter from the end.

b. Pin the safety pin through the hole in the flat edge of the protractor.
c. Close the safety pin.
d. You should now be able to move the coffee straws independently of one another. Eventually each straw will point at the background location of your object as viewed from two different observing places.

3. Do a thumb parallax demonstration.
   a. Hold out your thumb with your arm straight.
   b. Close one eye. Notice where your thumb appears. For example, it might be covering a certain letter on a poster on the wall behind you or it might be covering someone's face across the room.
   c. Keeping your thumb where it is, close the other eye. Notice what your thumb now covers.
   d. This apparent shift in the background position of your eye is due to the distance between the two view points, or in this case, the distance between your eyes. This apparent shift also occurs with nearby stars and planets. It is parallax, and it can be used to measure and calculate distances to these nearby celestial objects.
   e. Hold your astrolabe in your line of sight, keeping the flat edge of the protractor closest to you and parallel to your object. Arrange the coffee straws so that one is pointed in the direction of where your thumb appeared with the first eye closed, and the other points to the location where your thumb shifted when looking through the other eye.
   f. The separation between the coffee straws is your angular separation, or parallax shift. For example: if one straw points to 36 degrees and the other points to 43 degrees, your angular separation is 7 degrees. Your parallax angle is half of this. So, in this example your parallax angle would be 3.5 degrees.

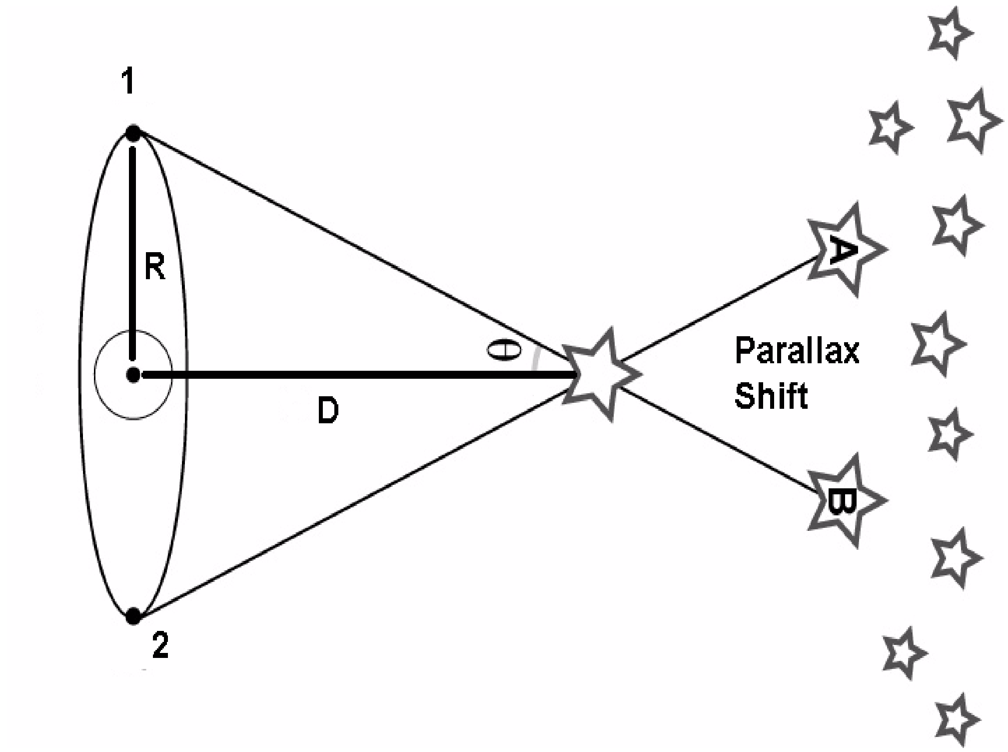

Figure 1: Parallax Shift NASA/GSFC

4. Now, take a look at Figure 1 which shows how parallax is measured in astronomy. The measurements are taken 6 months apart so the baseline is as long as possible – in this case twice the distance of the Earth to the Sun.

5. Choose an object to which you will determine the distance using parallax. Your object should be easily moveable (a chair, a backpack, a stick in the ground…) It is best if there are some things in the distant background behind your object for use in comparing the apparent shift when viewed from a different place.

6. Place your object a few meters in front of you.

7. Choose two locations from which to measure your object. The distance between your two measuring points is called your baseline. In the thumb demo your baseline was the distance between your two eyes. Your new baseline can be a few meters in length. Figure 2 below shows an example of what this may look like.

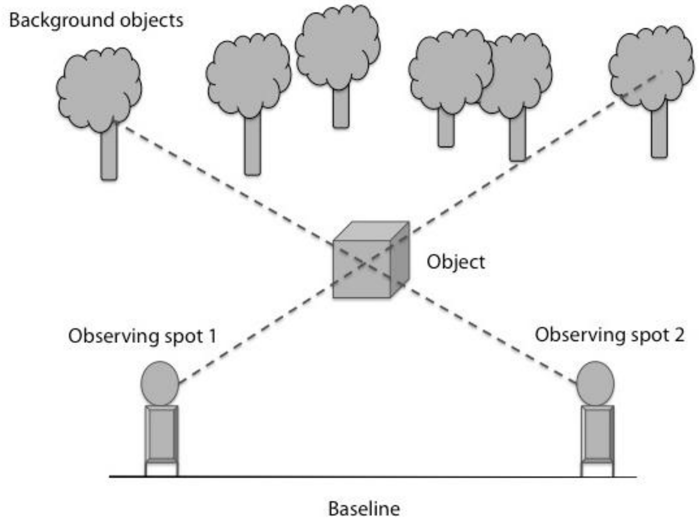

Figure 2

8. Measure the length of your baseline in meters. Record this length.

9. Make a sketch of the set up. Include the baseline, your object, and a brief sketch of the background.

10. Stand at one of your two observing sites (one of the ends of your baseline). Hold your protractor in front of you so the straight edge of the protractor is parallel to your baseline and the round edge points away from you. Align your coffee straw to point at your target object while keeping the flat edge of the protractor parallel to your baseline. Keep this coffee straw in place.

11. Notice and record what appears behind your object from this vantage point.

12. Move to the other observing site. Note how your object now appears in front of a different part of the background. Arrange your second coffee straw to point to it. You now have an angular separation or a parallax shift. You will use the parallax angle in your calculation. It has a value of half the parallax shift you measured.

13. You can now calculate the distance to your object. As you can see in Figure 3 below, you have a right triangle. When you know an angle and a side you can know any other angle or side of the right triangle. The distance you will calculate is represented by the dashed line extending from the baseline to the object. This is the opposite side to your angle. The side you know the length of is the adjacent side (half the length of the baseline).

$$\tan\theta = \frac{B}{D}$$

Rearranged for the distance, D:

$$D = \frac{B}{\tan(\theta)}$$

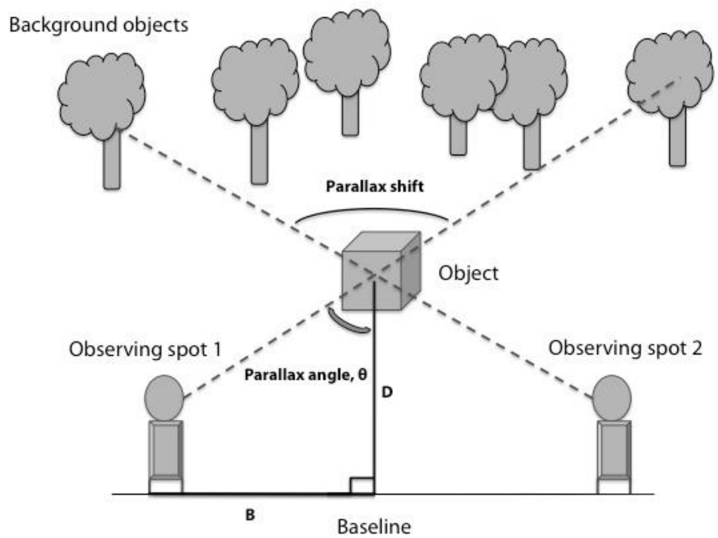

Figure 3

14. Record your calculation.

15. With a meter stick, measure the distance you just calculated. Record your measurement.

16. Move your object closer to or further from the baseline along the same center-line. Repeat the angle measurements along the baseline and repeat your calculations. Notice how the objects in the background have shifted.

Part 3: Kepler and Ellipses

1. Assemble your ellipse drawing materials:
   a. Tape your piece of paper firmly to the cardboard
   b. Tie a piece of string in a loop 10-20 cm in circumference
   c. Push one pushpin firmly into the cardboard at the center of your page

   d. Put your pencil in the loop of your string at on end, and loop the string around the pushpin at the other. Pull your pencil away from the pushpin until the string is taut.

2. Trace around the push pin (in a circle)
3. Now place the second pushpin in the cardboard just a few centimeters from the other pushpin. Loop the string and pencil around both pins and trace around. You have now drawn an ellipse.
4. Experiment with the elongation of your ellipse by moving the pushpins closer and farther from one another and tracing the ellipses that result. Draw three ellipses total.
5. Eccentricity is the term to describe the elongation of the ellipse. A circle has an eccentricity of zero and a highly elongated ellipse has an eccentricity closer to 1. The formula for finding the eccentricity of an ellipse is: $e = \frac{c}{a}$

   Measure the lengths of *a* and *c* in your ellipses to calculate the eccentricities of the ellipses you drew. Figure 4 below shows how a, b, & c are defined.

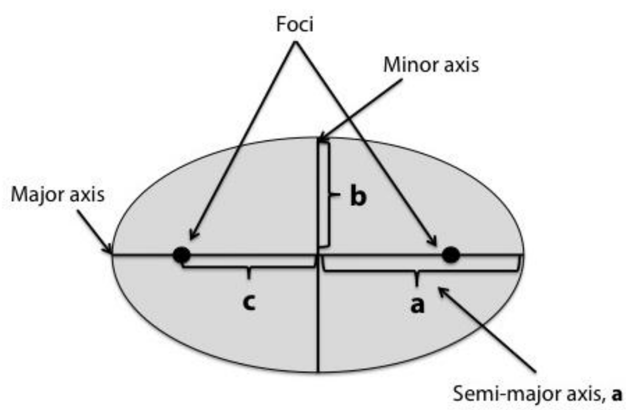

Figure 4

Conclusion:

Part 1:

1. Describe the motion of Mars as seen from the Earth during the months you plotted. How did Mars appear to move during July and August?

2. How did Mars actually move during July and August?

3. What causes this apparent backward motion?

4. Would it be possible to see this sort of motion with all the planets?

5. Why would it be especially difficult to observe the retrograde motion of Venus and Mercury? If you need help with this question draw a new set of lines beginning on Mars's orbit and passing through Earth's orbit to the left edge of the page. Number them as you did before.

Part 2:

6. Describe the accuracy of your calculations for the distance to your object. What would you change to make this more precise?

7. Did you notice a larger shift in the background of your object when it was closer to you or further away?

8. The following three diagrams in Figure 5 below represent the measure of parallax of three different stars. Rank them from closest to furthest.

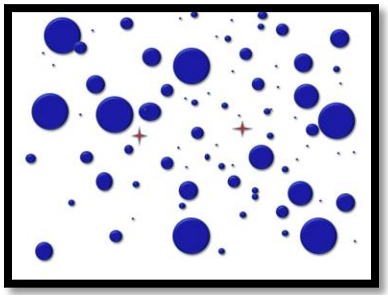

Figure 5 (a)

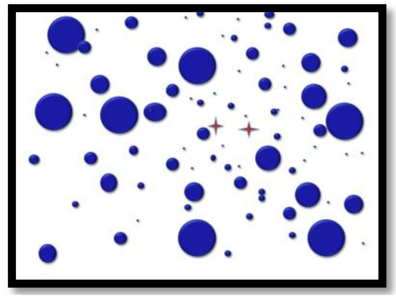

Figure 5 (b)

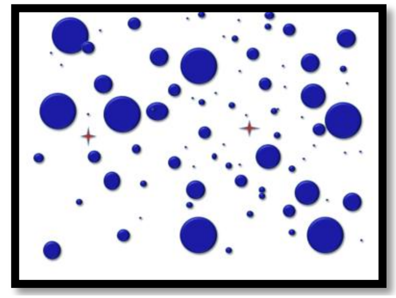

Figure 5 (c)

Part 3:

9. Earth's orbit has an eccentricity of 0.017. Describe this shape. If it has a value of 1 A.U. for the semi-major axis, a, then what must be the distance of c in A.U.?

10. Look at the planetary data below in Figure 6. Which solar system body has the most eccentric orbit?

Solar System Body	Semi-major axis	Period of revolution	Eccentricity
	a	**P**	**e**
Mercury	0.387 A.U.	87.969 d	0.2056
Venus	0.723 A.U.	224.701 d	0.0068
Earth	1.000 A.U.	365.256 d	0.0167
Mars	1.524 A.U.	686.98 d	0.0934
Jupiter	5.203 A.U.	11.862 y	0.0484
Saturn	9.537 A.U.	29.457 y	0.0542
Uranus	19.191 A.U.	84.011 y	0.0472
Neptune	30.069 A.U.	164.79 y	0.0086
Pluto	39.482 A.U.	247.68 y	0.2488

Figure 6

11. Calculate the c value for the ellipse that represents Pluto's orbit. Do your best to draw this ellipse with your pushpin/ cardboard set- up.

12. Kepler's third law is $P^2 = a^3$. Use the data in Figure 6 above to show that this holds true. For example: for Saturn does $29.457^2 = 9.537^3$? Kepler's third law says it should. Remember, the period has to be in the unit, years.

13. What would you expect the semi-major axis of a planet with a period of 50 years to be?

Extend:

- Tycho Brahe has a very colorful history. Do some research into his life. In your opinion, what are some of the most interesting things about the man, Tycho Brahe?
- Johannes Kepler dealt with more than his fair share of heartache. What are some emotional trials suffered by Kepler?
- Nicolaus Copernicus waited until he was near death to publish his work *De Revolutionibus Orbium Coelestium* (On Revolutions of Heavenly Spheres). Why do you think he waited?