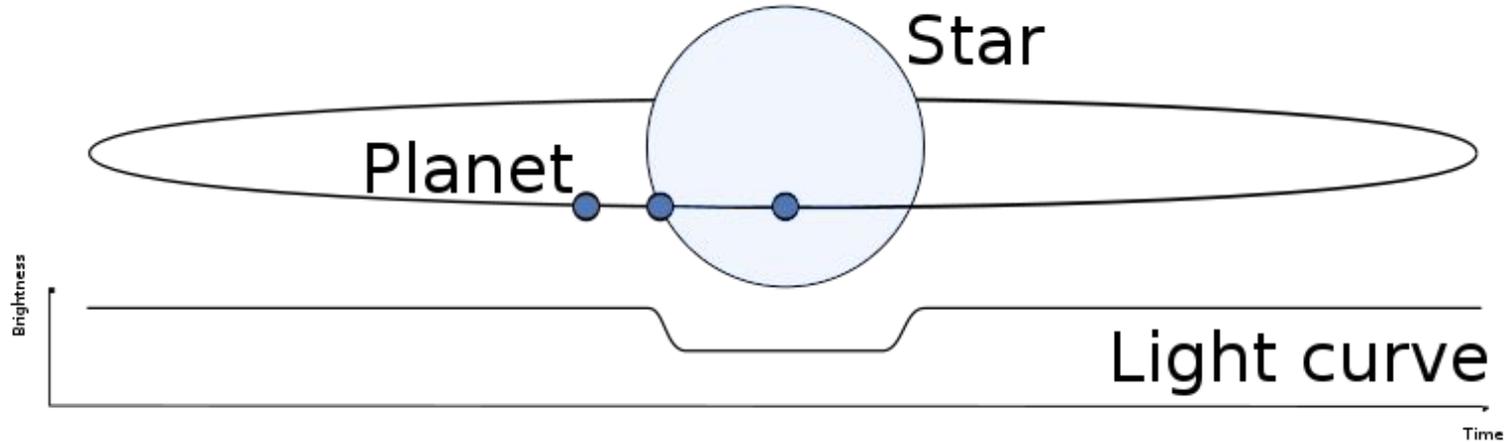# Kepler's Third Law in Exoplanet Transit Data

Brittany Tompkins

Setting:

AP Physics C: *Mechanics*

15 students - 12 boys, 3 girls
14 seniors, 1 sophomore
No 504s, IEPs, ELLs

Class periods last 43 minutes, with alternating-day double periods.

These activities were implemented over 2 days (3 class periods).

Standards Addressed:

AP Physics C: Mechanics Standards:

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
CON-6.C Describe a linear relationship to verify Kepler's third law.	**CON-6.C.1** Verifying Kepler's third law with actual data provides experimental verification of the law.

JPL also aligns this activity with **NGSS HS-ESS1-4: Earth's Place in the Universe** *"Use mathematical or computational representations to predict the motion of orbiting objects in the solar system."*

Instructional Context:

Prior to these lessons:
- Just finished Rotational Motion unit, leaving off on Angular Momentum
- Start of Unit 7: Gravitation & Orbits
- Students used data from our Solar System to look for trends between R and T → discovered Kepler's 3rd Law, $R^3 = T^2$
- Mini-lesson about what exoplanets are and how we detect them (focus on radial velocity and transits)

After these lessons:
- Kepler's 2nd & 1st Laws; Angular momentum in orbits; Newton's Universal Gravitation

I attempted to integrate the "*JS9 Exoplanet Activity*" and the "*Exploring Exoplanets with Kepler Activity*" into a 5E lesson format:

<u>Engage</u>: Students discuss the search for exoplanets: Why might we be looking for them, and how do we look for them? What can we observe and measure that can help us identify whether there is an exoplanet around a star? Students receive a mini-lesson (lecture, presentation, and discussion) that introduces them to detection methods such as radial velocity and transit.

<u>Explore</u>: Students use the JS9 Exoplanet Activity to look at real astronomical data and explore the process of creating a light curve.

<u>Explain</u>: Students learn how light curves can help scientists better understand exoplanetary transits and identify potentially habitable exoplanets. Students describe the properties of the exoplanets that may be detectable with this method of detection.

<u>Elaborate</u>: Students do JPL's Exploring Exoplanets with Kepler Activity, using light curve data from four confirmed exoplanets to determine their orbital periods.

<u>Evaluate</u>: Students use Kepler's Third Law to calculate the orbital radii of those four planets using the mass of the central star and the orbital period data they collected from the light curves, completing the chart in JPL's Exploring Exoplanets with Kepler Activity.

Course Resources Used:

1. **JS9 Exoplanet Activity**
Sonoma State University Astronomy from Home
https://afh.sonoma.edu/js9-exoplanet-activity/

Students create a light curve by plotting relative brightness of a target star over 5 images.

My goals: Students get an experience working with real astronomical images.

Students gain context for how light curves are created, to give background knowledge of the upcoming JPL Exploring Exoplanets with Kepler activity.

Students get more exposure to the scientific process.

JS9 Exoplanet Activity

Introduction   **Build a Light Curve**

The goal of this procedure is to obtain the relative brightness of a target star with respect to two (or possibly more) comparison stars. Below are two windows: the window on the left shows an image of the target star and two comparison stars. You will use the window on the right to use JS9 to perform the image analysis. First, you will select a region that includes the target star, and measure the brightness in that region. Then you will select each of the two comparison stars and measure their brightnesses. The comparison stars were chosen because they are known to have a constant brightness. By comparing the brightness measurement of the target to the average brightness of the two comparison stars, you will be able to tell if the target star has changed brightness.

However, there is a limitation with this data analysis approach. – it cannot measure the true brightness of the target, only relative brightness. Relative brightness is a number which can be close to 0.0 (zero, target is very faint), near 1.0 (one, targ near the average brightness of the comparison stars), or greater than 1.0 (target is brighter than the average brightness o comparison stars). Measuring relative brightness for a series of images creates a plot called a light curve. Follow these ste JS9 to create a light curve for the star as the exoplanet partially obscures its view.

1. Press the T1 (Time 1) Button to load the first image

2. Press the LOG button to make it easier to see the stars. If you click and drag the mouse across the JS9 window you will be able to adjust the contrast of the image.

3. On the finder chart below, your target star is in the small green circle closest to the bottom of the chart compared to the other circles.

4. Open the Magnifier Box by pressing the Magnifier Button.

5. Move the Magnifier Box so it doesn't block buttons or boxes.

6. Press the Add Region Button to load in a circle that you will use to measure the brightness of the target star as well as the brightness of the different comparison stars. Once you have clicked on the circle, use the arrow keys on the keyboard to move the circle more precisely. If you end up with more than one circle click your extra circle and press the delete key on your keyboard.

7. Drag the circle to your target star and click the Target Button.

| T1 | T2 | T3 | T4 | T5 |

LOG

Magnifier   Add Region

Target   Comp 1   Comp 2

Region Pixel Counts:

7. Drag the circle to your target star and click the Target Button.

8. Drag the circle to comparison star 1, as shown circled and labeled on the finder chart and click the Comp 1 Button.

9. Drag the circle to comparison star 2, as shown circled and labeled on the finder chart and click the Comp 2 Button.

10. Click the Plot Button to plot the relative brightness, which is the regional pixel count of the target star divided by the average of the regional pixel counts of the comparison stars. The plot is drawn under the finder chart and JS9 window.

11. Repeat these steps for each of the available images taken at different times, (T1-T5).

Finder Chart
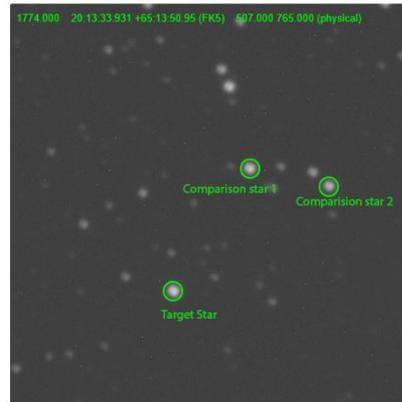
Region Pixel Counts:

Plot   Complete Chart
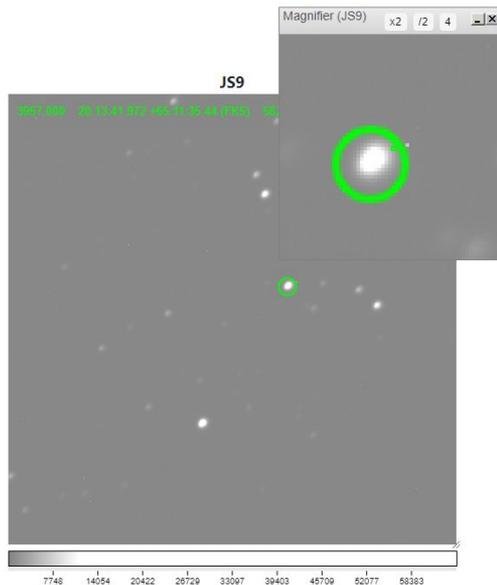
1. When you picture astronomers collecting and analyzing data, what do you picture? Explain.

Answer here...

2. Use the link below to access the JS9 Exoplanet Activity from Sonoma University's Astronomy from Home (AfH): https://afh.sonoma.edu/js9-exoplanet-activity/

After reading the Introduction, click on the "Build a Light Curve" tab and follow the instructions to collect and plot exoplanet transit data for the provided target star. Complete all of the data points yourself **(do not use the "complete light curve" option).**

Copy and paste a screenshot of your completed Light Curve in the space below:

Screenshot here...

3. As you collected data for your light curve, you had to use "comparison stars" in addition to your "target star." Why do you think this is important for collecting and analyzing data? Explain.

Answer here...

I also created my own set of questions for students to answer on Google Docs alongside the JS9 Exoplanet Activity.

4. Think back to your answer to question #1. How did the experience of building your light curve compare to what you picture astronomers doing when collecting/analyzing data? Was there anything you found to be particularly interesting, frustrating, surprising, etc. about the process? Explain.

Answer here...

5. When it comes to the exoplanets that are discovered using this transit light curve method, what is likely to be true about their orbital periods (T), and their average distances from their stars (R)? (i.e., What are the limitations of this method?)

Answer here...

JS9 Exoplanet Activity Artifacts

People with no life staring at the night sky, charting stars on old parchment paper with a telescope. A mental image of an old man with a big beard also arises (maybe due to the influence of Galileo and Kepler?)

1. When you picture astronomers collecting and analyzing data, what do you picture? Explain.

Answer here...

Scientists looking through a telescope every night and logging what they see as they contemplate how they should get out more and enjoy life instead of searching for life elsewhere but then realize that aliens are probably cooler than humans anyways, then they go watch the history channel (specifically ancient aliens with Giorgio Tsoukalos)

JS9 Exoplanet Activity Artifacts
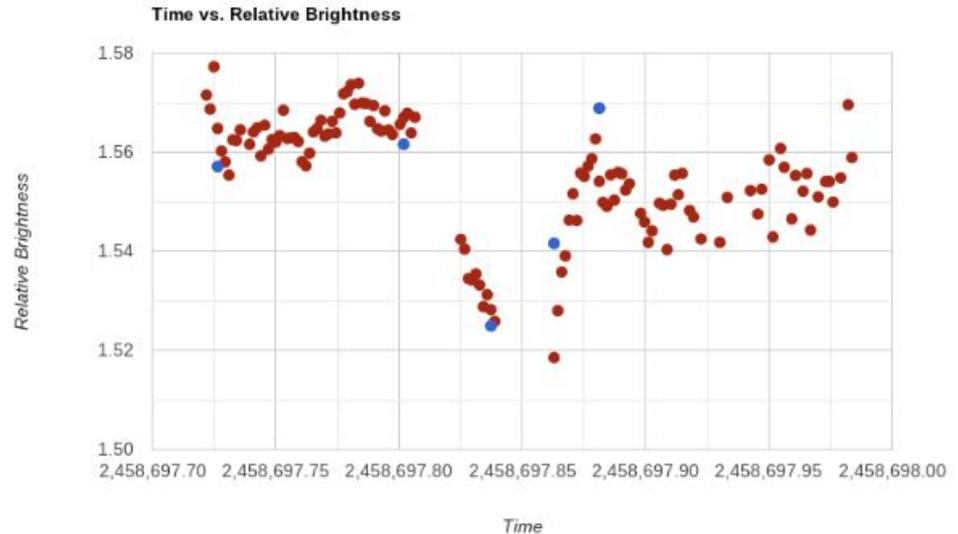
An example of a student's light curve

Student points are plotted in blue, and the online activity fills in the remainder of the light curve so students can see the bigger picture!

2. **Use the link below to access the JS9 Exoplanet Activity from Sonoma University's Astronomy from Home (AfH):** https://afh.sonoma.edu/js9-exoplanet-activity/

After reading the Introduction, click on the "Build a Light Curve" tab and follow the instructions to collect and plot exoplanet transit data for the provided target star. Complete all of the data points yourself **(do not use the "complete light curve" option).**

Copy and paste a screenshot of your completed Light Curve in the space below:

Screenshot here...

3. As you collected data for your light curve, you had to use "comparison stars" in addition to your "target star." Why do you think this is important for collecting and analyzing data? Explain.

Comparison stars reduce the likelihood of systemic errors such as faulty equipment or me being dumb, making sure no false conclusions are reached.

Answer here...

Using comparisons is like having a constant in an experiment

By measuring the brightness of comparison stars, it can be proved that the target star is actually changing in brightness and it is not merely being affected by the equipment that is taking the measurements. If the comparison stars experience the same changes, it is most likely the equipment and not the influence of a planet.

4. Think back to your answer to question #1. How did the experience of building your light curve compare to what you picture astronomers doing when collecting/analyzing data? Was there anything you found to be particularly interesting, frustrating, surprising, etc. about the process? Explain.

Answer here...
I realized there is a lot more that goes into analyzing data than just looking at space. I found the process very interesting and it made me realize a lot more math goes into this than I originally thought.

Answer here...
I could imagine the fact that this data takes like decades to gather would be the most frustrating part of doing this but it is at the same time, the most interesting part to me.

Today, astronomers use a lot more complicated equipment and software to make their observations. There is a lot more to astronomy than can be done by looking at the sky, and as technology improves, data collected can be more accurate and lead to greater breakthroughs. I think the process is very interesting and exciting. I had never really thought about how difficult it would be to find a planet in our own solar system. It is a sneaky way to discover planets, and I like how it proves the laws of physics.

5. When it comes to the exoplanets that are discovered using this transit light curve method, what is likely to be true about their orbital periods (T), and their average distances from their stars (R)? (i.e., What are the limitations of this method?)

The farther away the exoplanet is, the longer the period. If the period is really long, the difference in brightness will be less noticeable. It will take a long time to gather enough data. Exoplanets that this method is used for are probably relatively closer to the sun with a faster period. Planets with long periods will be difficult to discover this way.

Answer here...

The exoplanets' orbital periods are very quick, ranging from hours to maybe a week at most. This limits the usability of this method because it overlooks planets that are much farther away from their star, including the goldilocks zone (aka the planets that are useful). This is only useful for finding planets very close to their star, and those planets are essentially useless.

JS9 Exoplanet Activity

Pros & Cons

Pros:

- Authentic data! Real images from Kepler Space Telescope

- Students experience how numerical data is collected from images

- Option to auto-fill the remainder of the light curve after plotting data from 5 images – students get the idea, but don't have to spend forever on it

Cons:

- Not super user-friendly on a Chromebook or small monitor– lots of scrolling up & down the page; sometimes glitchy
  → (a pretty authentic experience!)

- Not much explanation of how pixels are counted, etc. → "black box" software

- Students think searching for exoplanets should be cooler/less boring
  → (again, a pretty authentic experience!)

2. Exploring Exoplanets with Kepler

Jet Propulsion Laboratory

https://www.jpl.nasa.gov/edu/teach/activity/exploring-exoplanets-with-kepler

Students analyze light curve data from four exoplanets discovered by the Kepler Space Telescope and utilize Kepler's 3rd Law in calculations.

My goals: Students get practice using Kepler's 3rd Law to calculate orbital period and radius.
Students analyze authentic NASA data.
Students see that Kepler's Laws are still being used in modern astronomy!

NASA Jet Propulsion Laboratory
California Institute of Technology

Exploring Exoplanets with Kepler: WORKSHEET

Kepler's Third Law states:

The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit (or the average distance to the sun).

For our solar system and planets around stars with the same mass as our sun, that simply states that $R^3 = T^2$, where R is a planet's distance from the sun in Astronomical Units (AU) and T is the planet's orbital period in years.

Because the distance between Earth and the sun (1 AU) is 149,600,000 km and one Earth year is 365 days, the distance and orbital period of other planets can be calculated when only one variable is known.

1. **Use Kepler's Third Law to calculate the missing data for these planets in our solar system.**

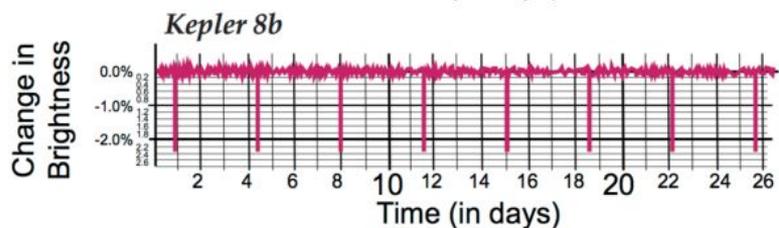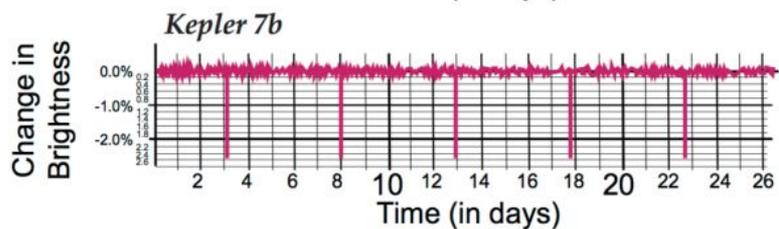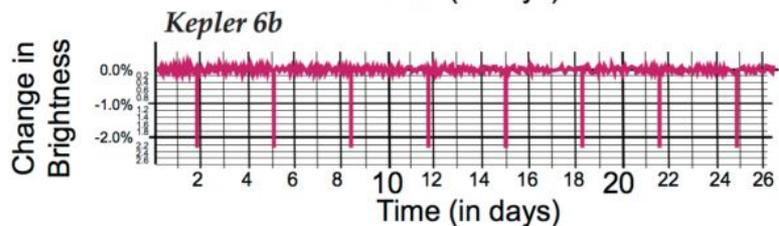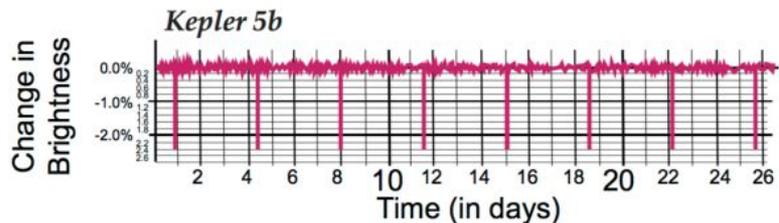| Planet	Orbital Period (years)	Orbital Period (days)	Distance from Sun (AU)	Distance from Sun (km)
Mercury			0.387 AU	
Venus		224.7 days		
Earth	1 year		1 AU	

For planets around other stars (exoplanets), we must modify the formula to account for the variation in the star's mass as compared with our sun. So we use $R = \sqrt[3]{T^2 \cdot M_s}$ where M_s = is the star's mass in relation to our sun's mass.

2. **Use Kepler's Third Law and the light curve data below to calculate the missing data for Kepler-5b, 6b, 7b and 8b. Then, calculate the missing information for Kepler-452b, the most Earth-like exoplanet yet discovered.**

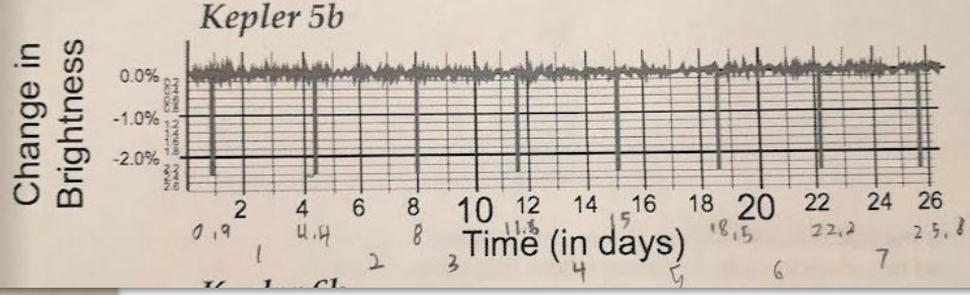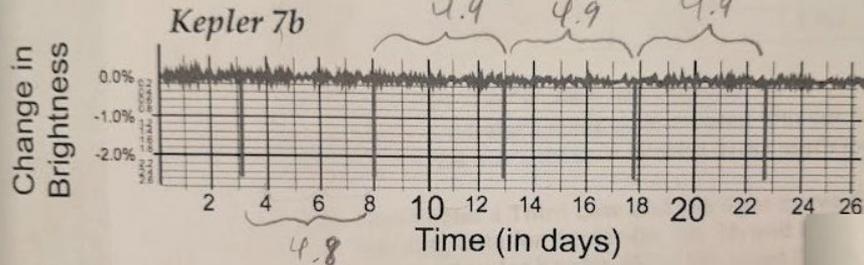| Planet	Mass of Parent Star (relative to sun)	Orbital Period (days)	Distance from Parent Star (AU)	Distance from Parent Star (km)
Kepler-5b			0.05064 AU	
Kepler-6b	1.21 M_s			
Kepler-7b				9,350,000 km
Kepler-8b	1.21 M_s			
Kepler-452b	1.04 M_s			156,500,000 km

FUN FACT: Stars observed by the Kepler mission with confirmed exoplanets are named Kepler-1, Kepler-2, Kepler-3, etc. The exoplanets around these stars are given a letter that corresponds to the order in which they were discovered, starting with *b*. So, Kepler-5b is the first exoplanet discovered around the fifth star found to have a planet.

Jet Propulsion Laboratory
California Institute of Technology
Exploring Exoplanets with Kepler: WORKSHEET

Kepler 5b

Kepler 6b

Kepler 7b

Kepler 8b

Screenshot from the Exploring Exoplanets with Kepler Activity, showing the light curve transit data for four exoplanets: Kepler 5b. 6b, 7b, and 8b.

Students determine the orbital period, in days, of each exoplanet by analyzing the light curve data. Then, they use these orbital periods and Kepler's 3rd Law ($R^3 = T^2$, or $R^3 = T^2 M_s$) to complete the chart in Question 2 on the first page of the activity.

Exploring Exoplanets with Kepler

Activity Artifacts

Students' recordings of the orbital periods of each of the four transits.
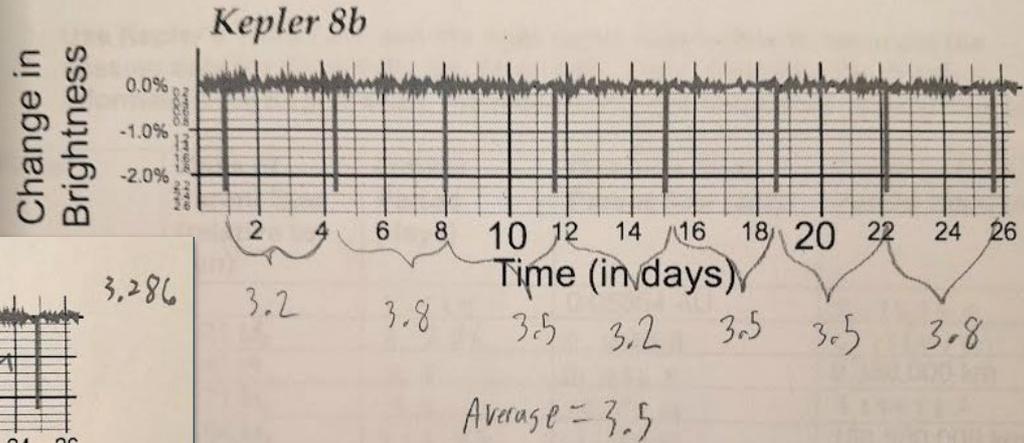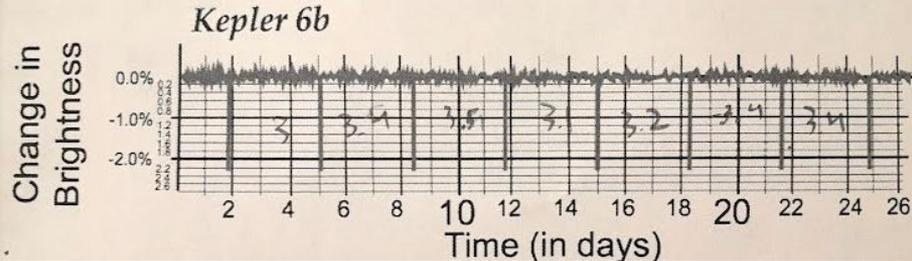
Planet	Mass of Parent Star (relative to sun)	Orbital Period (days)	Distance from Parent Star (AU)	Distance from Parent Star (km)
Kepler-5b	1.41 Ms	3.5	0.05064 AU	7575744 km
Kepler-6b	1.21 Ms	3.296	0.0461152973 AU	6898846.986 km
Kepler-7b	1.37 Ms	4.875	.0625 AU	9,350,000 km
Kepler-8b	1.21 Ms	3.5	.048096 AU	7195210.495 km
Kepler-452b	1.04 Ms	382.985	1.046 AU	156,500,000 km

Planet	Mass of Parent Star (relative to sun)	Orbital Period (days)	Distance from Parent Star (AU)	Distance from Parent Star (km)
Kepler-5b	1.41 Ms	3.5 days	0.05064 AU	7,575,744 km
Kepler-6b	1.21 Ms	3.2 days	0.04531 AU	6777946 km
Kepler-7b	1.41 Ms	4.8 days	0.0625 AU	9,350,000 km
Kepler-8b	1.21 Ms	3.7 days	0.0499 AU	7466767 km
Kepler-452b	1.04 Ms	382.96 days	1.0461 AU	156,500,000 km

Students' completed charts for the exoplanet data. Only a few students recorded the orbital period in days, as labeled in the chart header.

Most students recorded the orbital period in years, to make it easier when calculating using Kepler's Third Law!

Table 1:

Planet	Mass of Parent Star (relative to sun)	Orbital Period (days) years		Distance from Parent Star (AU)	Distance from Parent Star (km)
Kepler-5b	1.21 M$_s$	.0096		0.05064 AU	7575744 km
Kepler-6b	1.21 M$_s$	.009		.046106 AU	6897458 km
Kepler-7b	1.36 M$_s$	.0134		.0625 AU	9,350,000 km
Kepler-8b	1.21 M$_s$	.0096		.05064 AU	7575744 km
Kepler-452b	1.04 M$_s$	1.049		1.0461 AU	156,500,000 km

Table 2:

Planet	Mass of Parent Star (relative to sun)	Orbital Period ( ) years		Distance from Parent Star (AU)	Distance from Parent Star (km)
Kepler-5b	1.41 M$_s$	.0096		0.05064 AU	7575744
Kepler-6b	1.21 M$_s$	.0091		.046447	6948445
Kepler-7b	1.25	.014		.0625	9,350,000 km
Kepler-8b	1.21 M$_s$	.0096		.04813 AU	7,200,248
Kepler-452b	1.04 M$_s$	1.049		1.046	156,500,000 km

Table 3:

Planet	Mass of Parent Star (relative to sun)	Orbital Period (days)	yrs	Distance from Parent Star (AU)	Distance from Parent Star (km)
Kepler-5b	1.39 M$_s$	3.5	.010	0.05064 AU	7,575,744 km
Kepler-6b	1.21 M$_s$	3.2	.009	.04531	6,777,946 km
Kepler-7b	1.33 M$_s$	4.95	.014	.0625 AU	9,350,000 km
Kepler-8b	1.21 M$_s$	3.59	.010	.0489 AU	7,312,209 km
Kepler-452b	1.04 M$_s$	383	1.05	1.046 AU	156,500,000 km

Exploring Exoplanets with Kepler

Praises & Critiques

Praises

- Data! Real light curves from the Kepler Space Telescope

- Easy to use; felt that I could print the worksheet and use immediately

- Links our solar system with other solar systems – shows that physics works everywhere!

- Modern application of very old physics – makes Kepler's Laws seem more relevant

Critiques

- Missing an "Orbital Period (years)" column in exoplanet data → lack of clarity with units led to confusion for students

- Does not use SI units (uses years, days, AU, and km, when AP Physics uses seconds and meters)

- Kepler-5b and Kepler-8b appear to have the exact same light curve data - repetitive for students

With a few modifications, I will definitely be using this activity again in the future! I appreciated the accessibility of the data and it gave my students a chance to get a sense of how modern astronomy actually takes place.

Resources

Jet Propulsion Laboratory Education. (2020, December 31). *Exploring exoplanets with Kepler: Classroom activity*. NASA/JPL

Edu. https://www.jpl.nasa.gov/edu/teach/activity/exploring-exoplanets-with-kepler

Sonoma State University. (n.d.). *JS9 exoplanet activity*. AfH: Astronomy from Home.

https://afh.sonoma.edu/js9-exoplanet-activity/