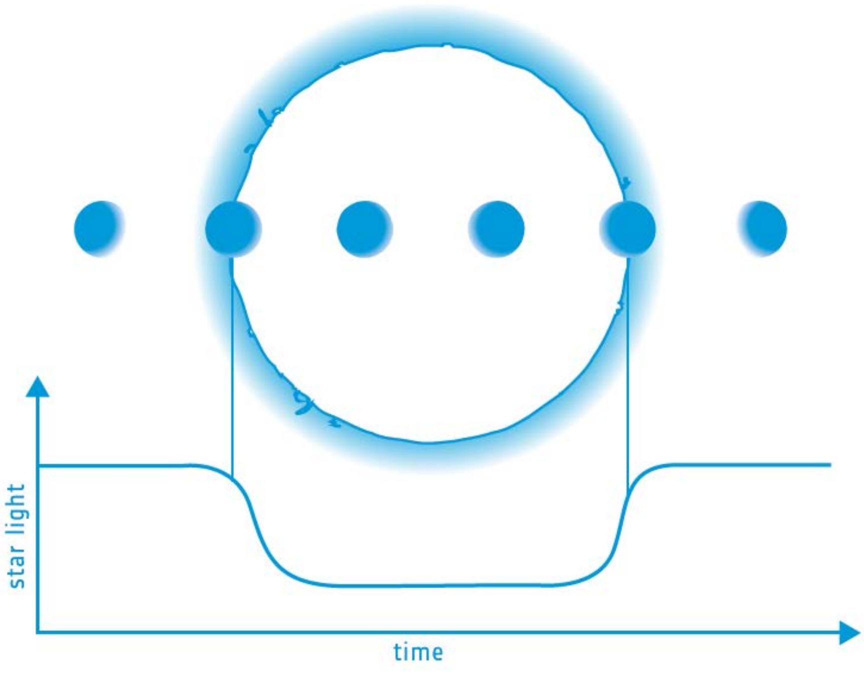
Physics | P31

teach with space

→ EXOPLANETS IN TRANSIT

Characterising exoplanets using satellite data



teacher guide & student worksheets

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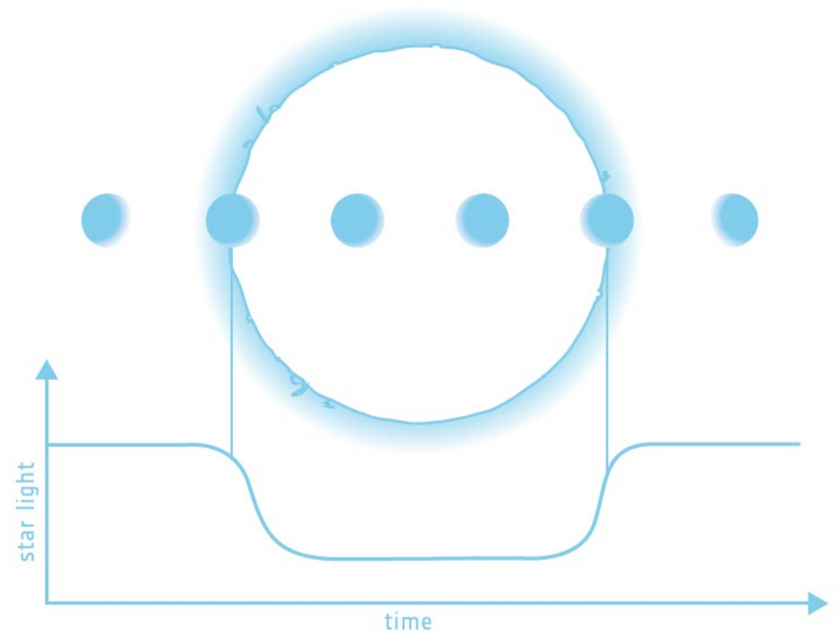

Teacher guide

teach with space – exoplanets in transit | P31
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→ EXOPLANETS IN TRANSIT

Characterising exoplanets using satellite data

FAST FACTS

Subject: Mathematics, Physics, Astronomy

Age range: 14-19 years old

Type: Teacher's guide and student worksheets

Complexity: Medium

Lesson time required: 45 minutes

Cost: Low (0-10 euros)

Location: Classroom

Keywords: Physics, Mathematics, Astronomy, Exoplanets, Light Curves, Transits, Orbits, Scaling, Graphs, Period

Brief description

In this set of activities students will learn how scientists study exoplanets with telescopes, using the transit method. Furthermore, they will characterise exoplanets using model and real satellite light curves data from ESA's satellite Cheops (CHaracterising ExOPlanet Satellite).

Students will practice data plotting and interpretation, and scaling of graphs in the context of exoplanet characterisation.

This activity is part of a series that includes "**Exoplanets in Motion**" where students build their own transit model and "**Exoplanets in a Box**" where students build a transit model inside a shoebox and calculate the size of an exoplanet.

Learning objectives

- Understanding what exoplanets are and how satellites investigate them.
- Understanding how the transit method is used for the characterisation of exoplanets.
- Enhancing experimental skills by observing and interpreting measured light curves.
- Thinking mathematically and converting an abstract model to a real model.
- Interpreting experimental data using mathematical models and plots.
- Drawing conclusions comparing a model to a real exoplanet system.
- Communicating scientific and mathematical findings to peers.

→ Summary of activities

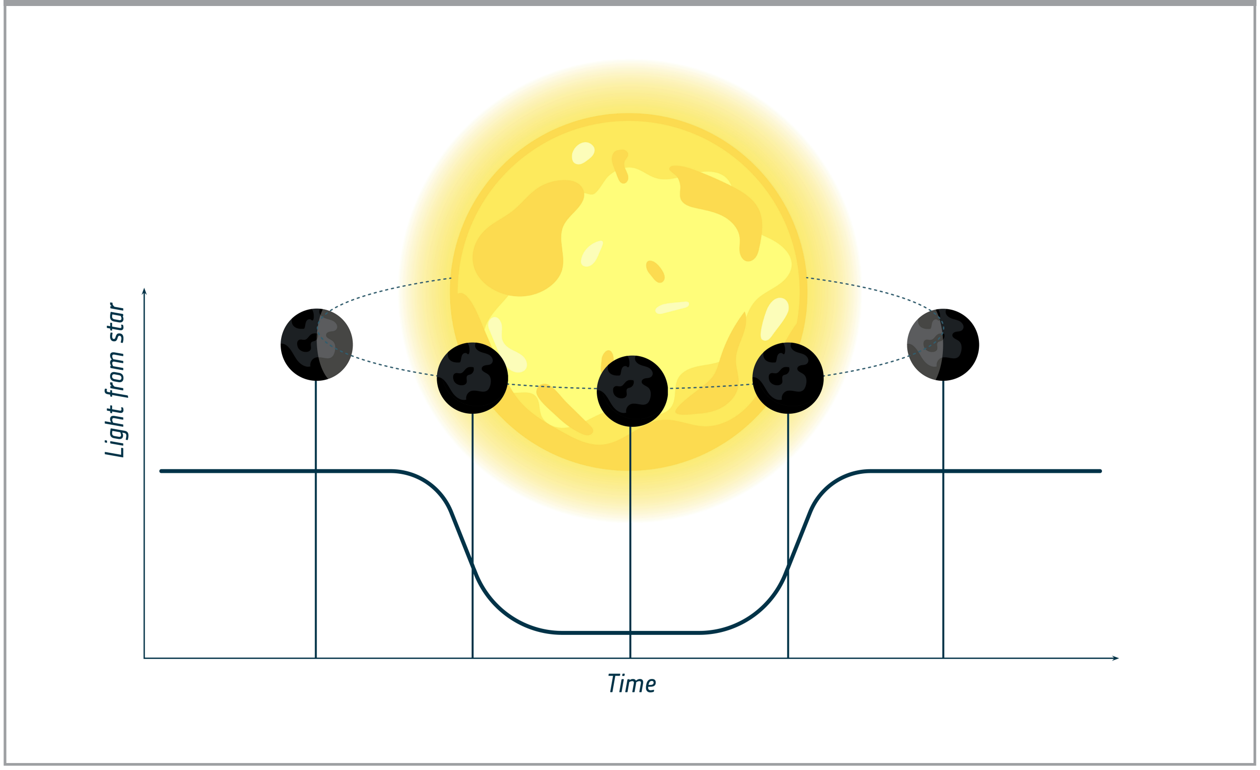
Summary of activities					
	Title	Description	Outcome	Requirements	Time
1	Understanding Light Curves	Analyse both synthetic and real light curves to determine what information they contain about the model or real exoplanetary systems.	Understand how to scale graphs and why. Develop graph interpretation skills and use these to draw conclusions about real exoplanetary systems.	None	30 minutes
2	Being an Exoplanet Detective	This activity aims to sum up the knowledge gained in the previous activities and describe what scientists can learn from light curves measured by satellites.	Relate the findings from a model to the real situation, using analogies.	None	10 minutes

→ Introduction

In this set of activities, we will focus on the analyses of light curves obtained using the transit method. This method has been used to detect and characterise many of the exoplanets that are known to-date. Using this technique, telescopes very precisely measure the amount of light emitted by individual stars over time spans of hours to months. This measurement of light from an object as a function of time is known as a light curve (see Figure 1). By analysing the shape of the light curve, and features in it, we can learn about both the star and any exoplanets that are orbiting it.

When an exoplanet passes in front of the star it is orbiting, it blocks a small fraction of the light from the star – known as a transit. If a telescope is observing the light from that star during that transit, it will measure a small dip in the light curve.

Figure 1



↑ Representation of the dip in a light curve of a star during an exoplanet transit.

The depth of the dip depends directly on what percentage of the light from the star is blocked by the passing exoplanet, which depends on the size of the exoplanet relative to the star. The bigger the planet is relative to the star, the more of the light it will block. If we know the size of the star, we can determine the size of the planet.

→ Activity 1: Understanding Light Curves

This exercise will cover scaling and interpreting graphs of both simulated and real satellite data.

As an introduction to exoplanets, the completion of the *Exoplanets in Motion* activity is suggested.

To introduce the students to the topic of exoplanets you can also use video material available in the links below or use the background information as a complementary resource.

Below are some suggestions of ESA video material:

- Meet the Experts series – Other Worlds: https://www.esa.int/ESA_Multimedia/Videos/2020/07/Meet_the_Experts_Other_worlds
- Meet Cheops, the Characterising Exoplanet Satellite: http://www.esa.int/ESA_Multimedia/Videos/2019/12/Meet_Cheops_the_Characterising_Exoplanet_Satellite
- Paxi explores exoplanets! https://www.esa.int/ESA_Multimedia/Videos/2019/12/Paxi_explores_exoplanets

Once the students have been introduced to exoplanets, the transit method and Cheops, they can work through Activity 1 in the student worksheet.

Exercise 1 – Scaling Graphs

Understanding the scaling of graphs is an important skill in both mathematics and science. In this exercise, students will see an example of real data taken by the Cheops satellite and will use this to see how graphs are scaled to get the most amount of information possible out of the data in them.

In these graphs, the light from the star on the y axis is shown as a percentage of the average value measured from that star during the observation period. The exact same data is plotted in both of the graphs in this exercise, but each display a different scale.

Note: As the graph displays the light from the star as a percentage of the average brightness value, this average brightness is considered to be equal to a value of 100% on the y-axis. If there are events occurring during observations which increase the amount of light that is measured, for example stellar flares, then brightness values above the average mark are measured and are represented in the graph as measurements above 100%.

Discussion

Below are the answers to Exercise 1. Discuss the answers alongside the principle of scaling with your students.

1.1. The students should recognise that in Figure 3, the transit is much easier to identify than in Figure 2, due to the different scaling in the y-axis.

1.2. In the Figure 2 the light curve looks almost constant, whilst in Figure 3 a decrease in the light from star percentage is visible in the curve between 6.5 h and 10.75 h.
The time (hours) displayed on the x-axis is the same for both graphs.
The values of the light from the star (%) shown on the y-axis are different. In the first graph the values range from 0% to 110%, whilst in the scaled graph where the dip is visible the values range from 99.3% to 100.1%.

Exercise 2 – Interpreting Light Curves

In this exercise students will be given examples of simulated transit light curves and guidelines on how to read and interpret the graphs of them. This exercise can be completed in pairs or individually.

Extra information: the amount of starlight blocked by the planet is directly related with the projected area of the planet. The light that the planet blocks is proportional to $\frac{R_p^2}{R_s^2}$, where R_p is the radius of the planet, and R_s is the radius of the star If a planet blocks twice as much light, it does not mean the planet is twice as big: to block twice the amount of light the planet must be $\sqrt{2}$ (= about 1.41) times bigger.

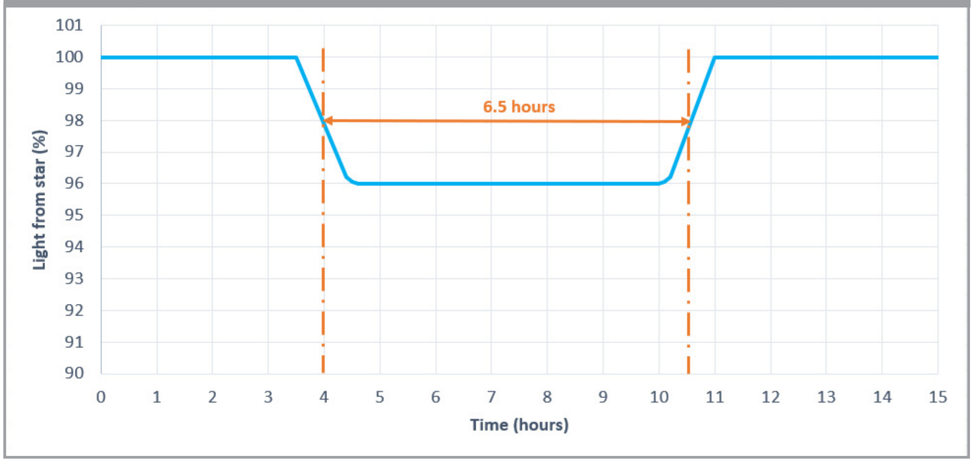
Discussion

Find the answers to Exercise 2 below:

2.1. The exoplanet that was observed to produce this light curve took **4.5 hours** to pass in front of the star, and it blocked **4%** of the light from the star.

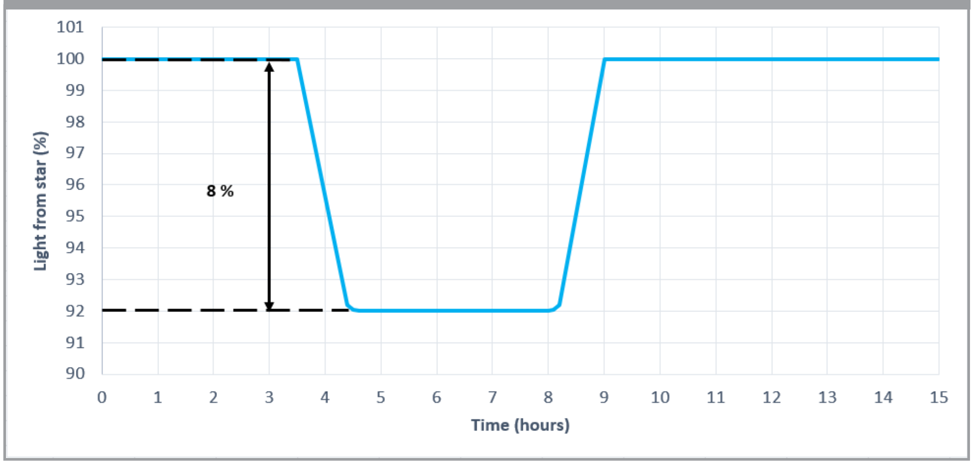
2.2.

Figure 4



2.3

Figure 5



After the students complete this exercise on their own or as pairs, discuss the results in the class to prepare the students for interpreting real Cheops data.

Exercise 3 – Interpreting real satellite data

In this exercise students will use the concepts learned in the previous exercises to interpret a transit light curve of WASP 189b observed with ESA's satellite Cheops.

Discussion

Find the correct answers indicated below.

3.1. 4.5 hours
3.2. 0.55%

Extra information:
When analysing the real data your students may notice some differences between the simulated data and the real data. The students may have questions regarding the fit or the gaps in the light curve.

Fitting is the process of constructing a curve based on a mathematical function that has the best fit to a series of data points.

There are two type of events which occur during the orbit of Cheops which mean that at times we cannot measure the light from a star continuously. These events create gaps in the light curve. The first is when the star is blocked by the Earth, known as an Earth Occultation. The second occurs when Cheops passes over a region in the South Atlantic where there is a lot of disturbance to the very sensitive instruments onboard the satellite. The disturbances have such a large effect that scientists do not even try to measure the light from the star when the satellite passes through this region.

Exercise 4 – Orbital Period

This exercise focuses on how the orbital period can be determined from a light curve.

Note: the orbital period of a planet is the time it takes the planet to complete one full orbit around its star. This can be measured by finding the centre of two consecutive transits of the same exoplanet and measuring the time interval between them.

Discussion

Find the correct answers indicated below.

4.1. 3 days
4.2. In this answer students should be able to describe in their own words that there are two exoplanets we can detect orbiting the same star in this exoplanetary system. Furthermore, the answer should include that the deeper dips in the curve indicate a larger planet that has a period of 3 Earth days, and blocks 2% of the light from the star, and that the shallower dips in the curve indicate a smaller planet that has an orbital period of 2.5 Earth days and blocks 1% of the light. If you have introduced the concept that the light that an exoplanet blocks is proportional to $\frac{R_p^2}{R_s^2}$, then students should be able to identify that the larger planet is therefore 1.4 times larger than the smaller planet.

→ Activity 2 – Being an Exoplanet Detective

In this activity, students will apply what they have learnt from analysing the previous light curves and interpret an observation of an exoplanetary system made by Cheops, like a real scientist.

Exercise 1: Describing exoplanets observations

The sentences should be completed as the following:

When an exoplanet passes between the ***satellite*** *and the star, it blocks a small fraction of the light from the* ***star****, causing a* ***dip*** *in the light curve. This is called a* ***transit****.*

If multiple ***orbits*** *of the same exoplanet are observed, then the* ***time interval*** *between the detected dips in the light curve is a direct measure of the orbital period of the planet.*

A ***larger*** *exoplanet produces a deeper dip in the measured light curve and a* ***smaller*** *exoplanet produces a* ***shallower*** *dip.*

Individual exoplanets can be distinguished from one another by the ***depth*** *of the dips they produce in the light curve, and their orbital* ***period****.*

If you would like to challenge students in your class, you could let them phrase their conclusion in their own words. Whilst discussing your students self-worded conclusions, make sure that observations and conclusions are not mixed up, and that their conclusions follow on from the observations.

Exercise 2: Observing Exoplanets

In the second exercise, students are asked to interpret real Cheops data just as a professional scientist would. If some students need assistance, you may support them by asking the questions displayed below to help them structure the interpretation of the light curve.

1. How many exoplanets does the observed system have?
2. What is the orbital period/ interval of each exoplanet?
3. How much light (in %) is blocked by each exoplanet?
4. Can you say something about the exoplanet's sizes?
5. Do you see anything else noticeable? Try to describe in your own words and interpret if possible.

Extra information: The TOI-178 system is located only 205 light years away from Earth. ESA's exoplanet mission Cheops has revealed it to be a unique planetary system consisting of six exoplanets, five of which are locked in a rare rhythmic dance as they orbit their central star. Please note that in this data set only 4 planets are identifiable (b, c, d and e).

This phenomenon is called orbital resonance, and it means that there are patterns that repeat themselves as the planets go around the star, with some planets aligning every few orbits. You can visualise this effect in this animation: https://youtu.be/-WevvRG9ysY

The two inner planets (b and c) have terrestrial densities, similar to Earth, and the outer four planets (d, e, f and g) are gaseous, with densities like Neptune and Jupiter.

While the planets in the TOI-178 system orbit their star in a very orderly manner, their densities do not follow any particular pattern. One of the exoplanets, a dense, terrestrial planet like Earth is right next to a similar-sized but very fluffy planet – like a mini-Jupiter, and next to that is one very similar to Neptune.

→ EXOPLANETS IN TRANST

Characterising exoplanets using satellite data

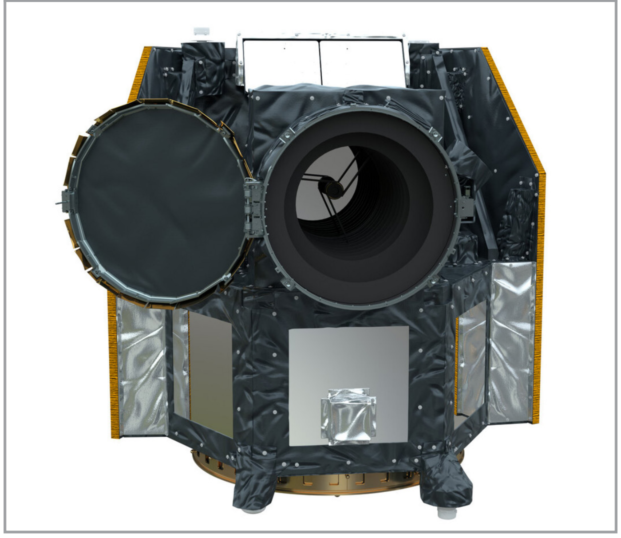
→ Introduction

By studying large numbers of different exoplanets scientists are able to understand how exoplanetary systems form and evolve. This is an important step in the path towards understanding our own Solar System and our place in the Universe.

In this set of activities, you will make use of real data collected by ESA's satellite Cheops (CHaracterising ExOPlanet Satellite).

Through the precise measurement of the light curves of nearby stars known to host a transiting exoplanet, Cheops is able to determine the sizes of these exoplanets. By combining this information with other measurements, scientists will be able to determine the density of the exoplanets. For some specific exoplanets we can even determine whether they have clouds.

Figure 1



↑ Cheops satellite

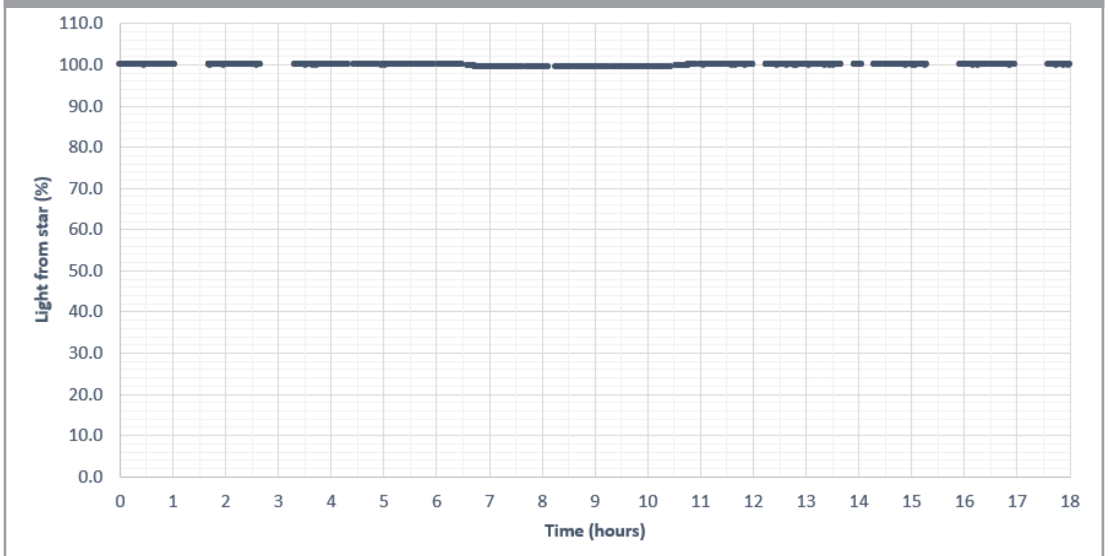
→ Activity 1: Understanding Light Curves

When a satellite observes exoplanetary transits, the depth, shape, and position of the dip in a light curve can give us information about the exoplanetary system. In this activity you will explore this idea further using real Cheops satellite data.

Exercise 1 – Scaling Graphs

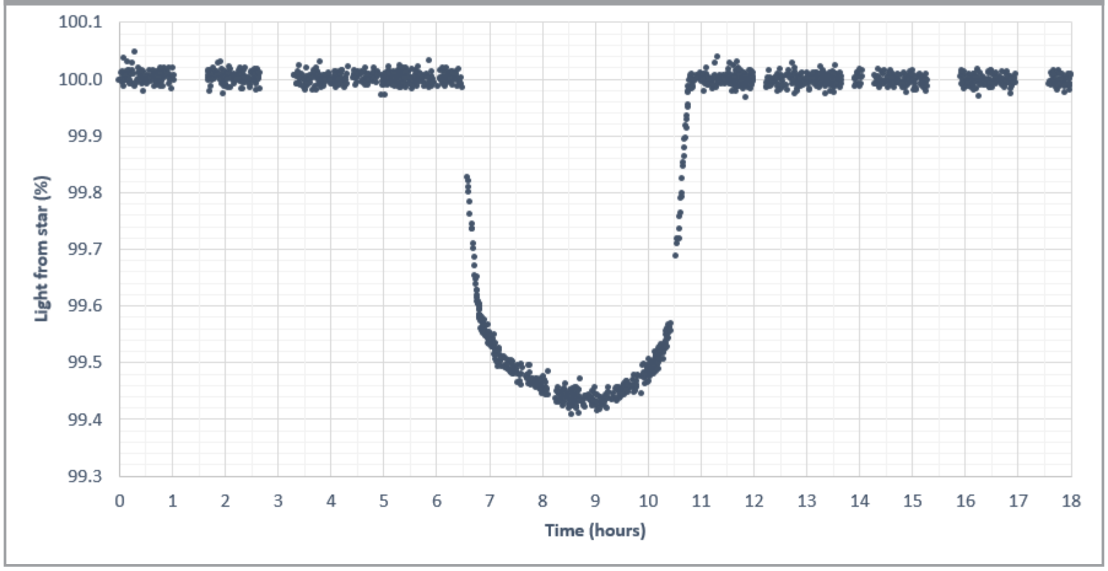
Exoplanets are generally much smaller than the star they are orbiting. For instance, the Earth's diameter is about 1/100th that of the Sun, while Jupiter's diameter is about 1/10th that of the Sun. The amount of light blocked is therefore typically less than one percent of the total light from the star.

Figure 2



↑ transit light curve of WASP 189b acquired with Cheops.

Figure 3



↑Same transit light curve curve of WASP 189b acquired with Cheops, with a different scale on the y axis.

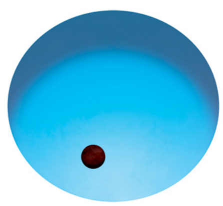
Consider the transit light curve of WASP 189b, taken with Cheops, shown on Figure 2 and Figure 3:

1.1. Can you identify the exoplanet transit light dip in both Figure 2 and Figure 3?

1.2. Compare both graphs and describe the differences below:

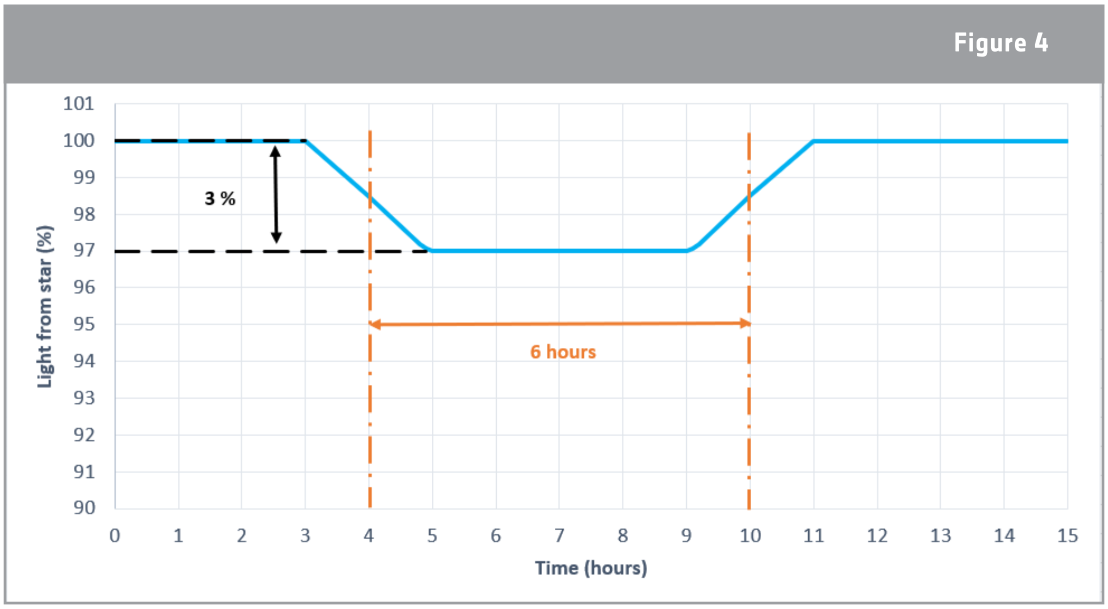
Did you know:

WASP 189 b is a large gas exoplanet that is about 50% bigger in radius than Jupiter. This giant exoplanet is in a 2.7 Earth days orbit around a star that is more than 2000°C hotter than our Sun, and almost 2.5 times as big in diameter.



Exercise 2 – Interpreting Light Curves

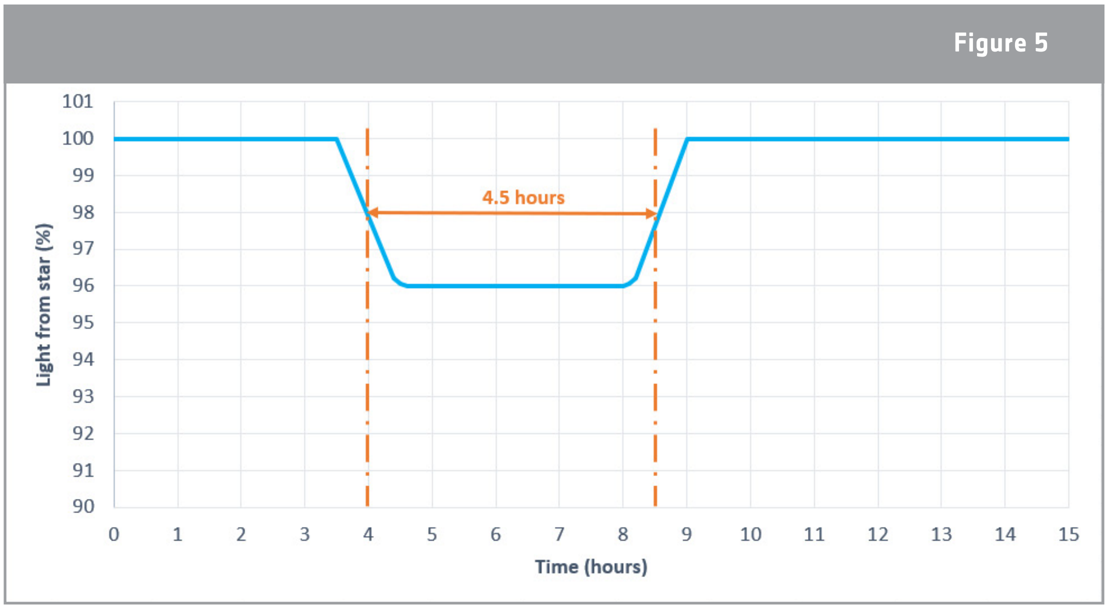
Below you can see a simplified representation of the light curve of a star measured around the time of an exoplanet transit. The dashed lines illustrate how you can determine some of the basic information about the exoplanet system from the graph:



↑ Example of a simulated light curve.

We can determine from the light curve, that the exoplanet that was observed took 6 hours to pass in front of the star, and blocked 3% of the star's light.

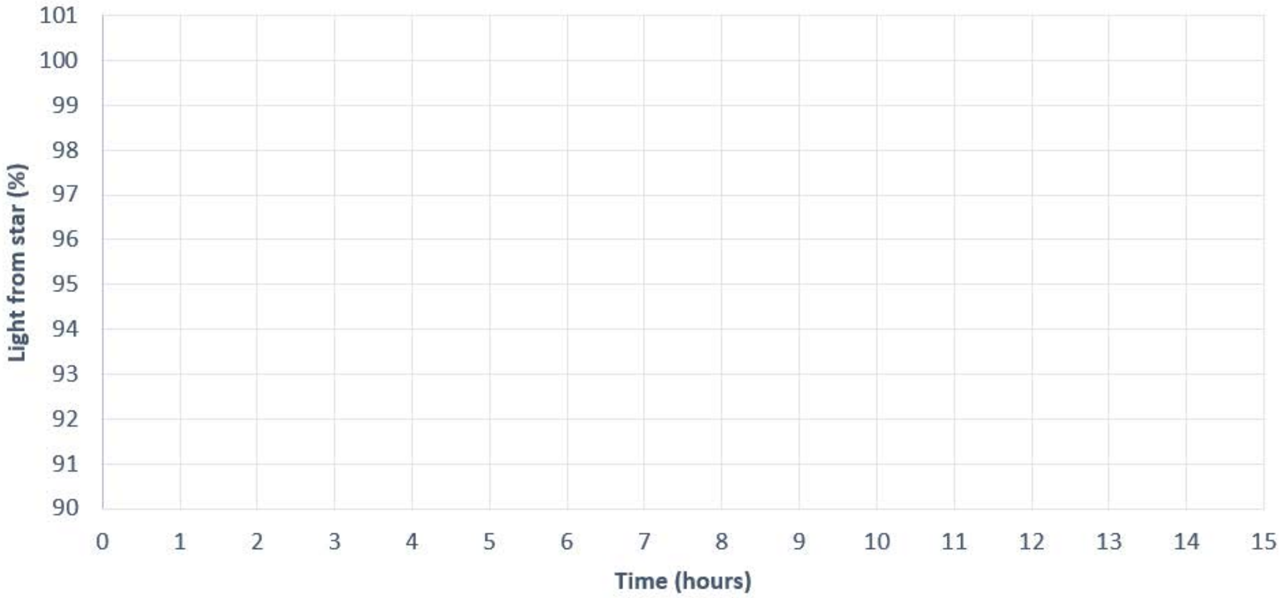
2.1. Examine the light curve in Figure 5, and fill in the missing information



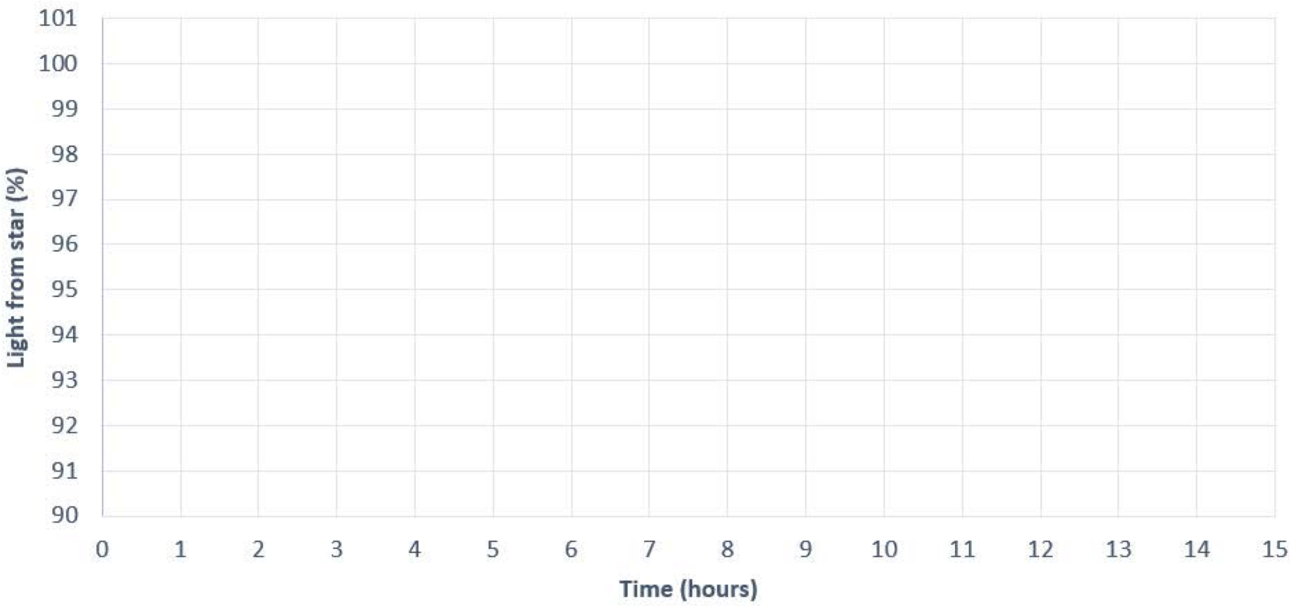
↑ Simulated light curve.

The exoplanet that was observed to produce this light curve took ____ hours to pass in front of the star, and it blocked ____% of the light from the star.

2.2. Sketch the expected light curve for an exoplanet that is the same size as that in Figure 5, but takes two hours longer to transit:

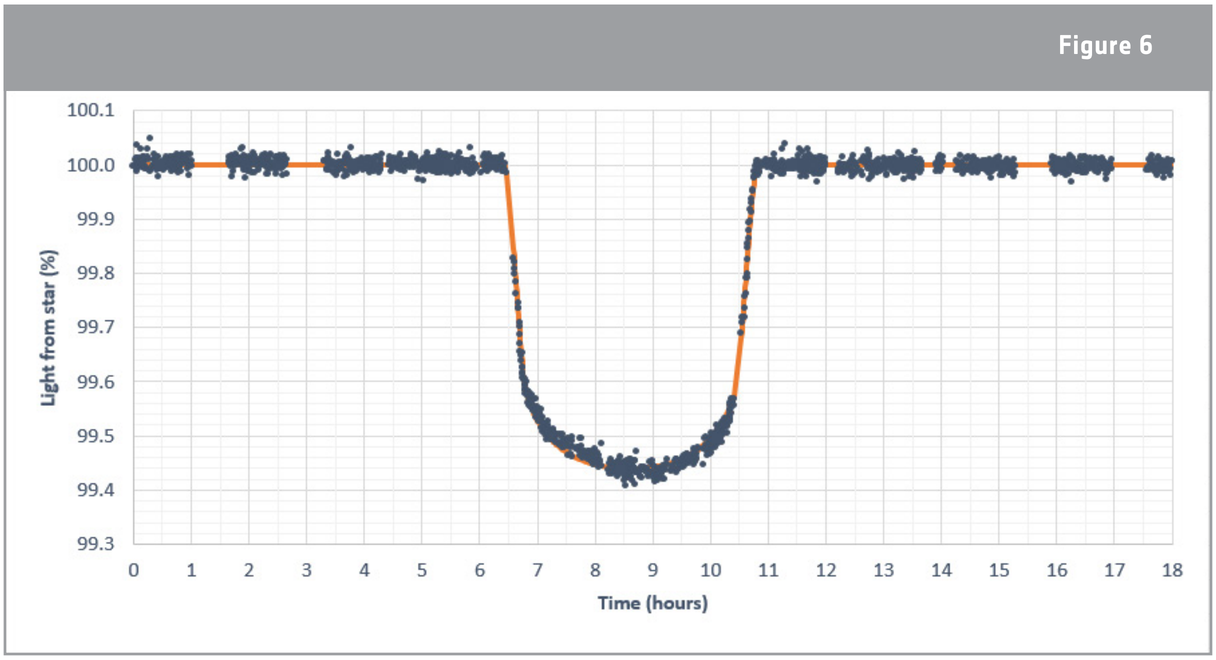


2.3. Sketch the light curve for a different exoplanet orbiting the same star as that in Figure 5, the exoplanet is larger than the previous exoplanet and it blocks twice as much light. Assume that the exoplanet takes the same time to transit the star as in Figure 5:



Exercise 3 – Interpreting real satellite data

Using what you have learnt so far, you can now analyse the WASP 189 b transit light curve from Cheops that you saw earlier in the activity (Figure 3).



↑ transit light curve of WASP 189 b, including the best fit model.

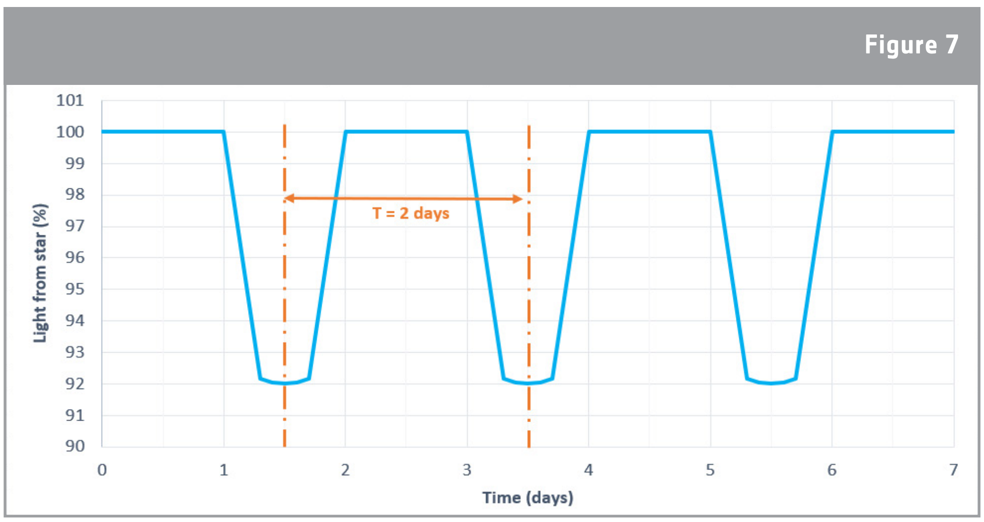
3.1. Approximately how long does WASP 189 b take to transit its host star? _________

3.2. Approximately what percentage of the star light does WASP 189 b block? ________

Exercise 4 – Orbital Period

Each time an exoplanet transits its host star there will be a dip in the light curve. If a star is observed for long enough for the exoplanet to complete more than one orbit, there will be more than one dip in the light curve. The time interval between the initial dip to the next dip is the **orbital period (**T**)** of the exoplanet.

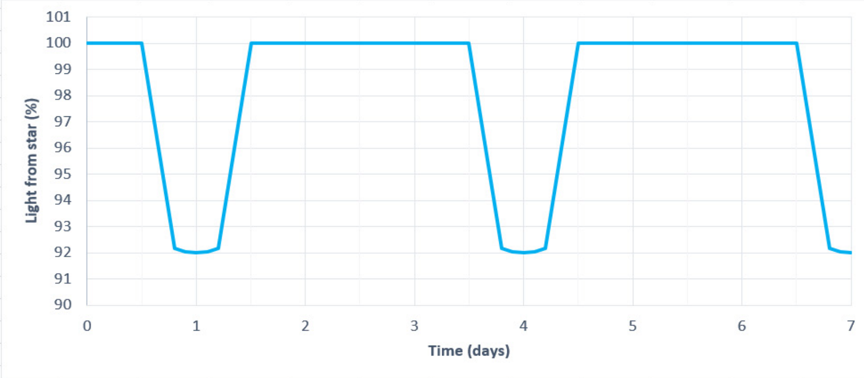
Figure 7 is a simulated light curve over a duration of 1 week. During this time the simulated planet transited three times. By measuring the distance between the dips in the light curve, we see that the orbital period of the planet is 2 days.



↑ Simulated light curve, including multiple transits.

4.1. Examine Figure 8 below:

Figure 8

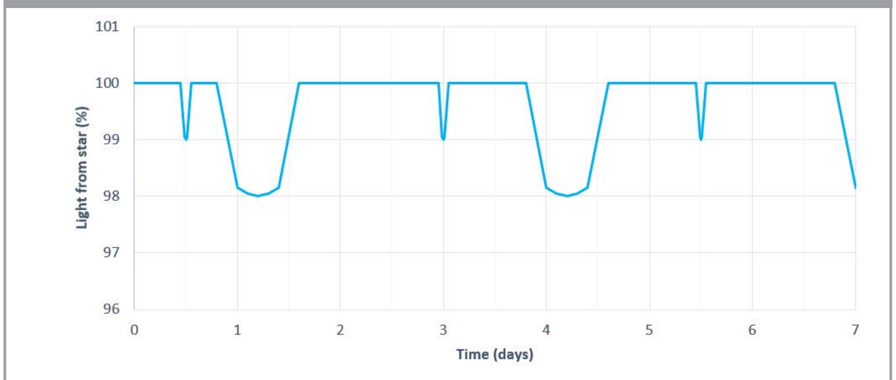


↑ Simplified sketch of a light curve.

What is the orbital period of the exoplanets whose transits are seen in the light curve in Figure 8?

4.2. Using the skills you have learnt so far, what can you say about the exoplanet system that was observed to produce the light curve shown in Figure 9:

Figure 9



↑ Simplified sketch of a light curve with multiple transits.

→ Activity 2 – Being an Exoplanet Detective

You are now ready to analyse real observations like a true exoplanet scientist and sum up what you have learnt. You will compare your observations from your own model exoplanetary system with those of real exoplanetary systems taken with Cheops.

Exercise 1: Describing exoplanets observations

Fill in the gaps using the words from the word cloud to sum up your learnings.
Each word will be used just one time.

satellite		*larger*	*shallower*	*star*	*transit*
period	*orbits*	*depth*	*dip*	*smaller*	*time interval*

When an exoplanet passes between the _______________ and the star, it blocks a small fraction of the light from the __________, causing a ___________ in the light curve. This is called a ______________.

If multiple _________ of the same exoplanet are observed, then the ___________________ between the detected dips in the light curve is a direct measure of the orbital period of the planet.

A ________________ exoplanet produces a deeper dip in the measured light curve and a ___________ exoplanet produces a _____________________ dip.

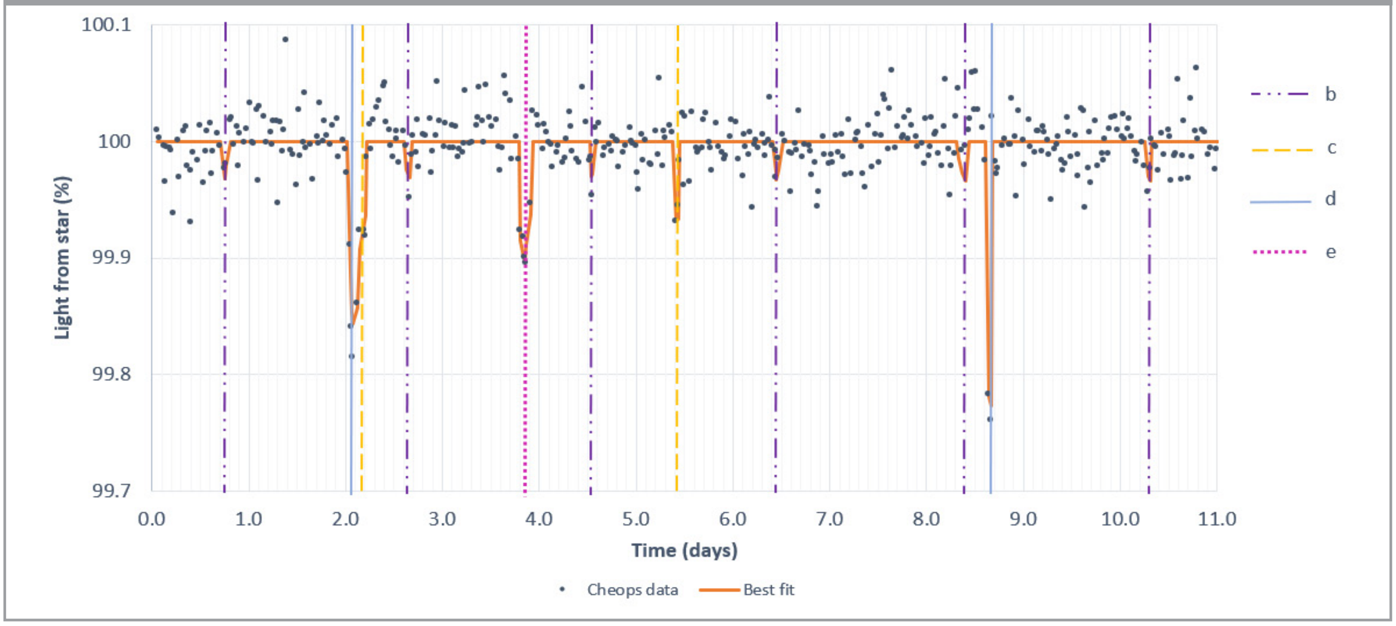
Individual exoplanets can be distinguished from one another by the _______________ of the dips they produce in the light curve, and their orbital ___________.

Exercise 2: Observing Exoplanets

You are now ready to interpret this light curve of the TOI-178 system observed over an 11-day period period by Cheops.

Analyse the light curve in Figure 10 and describe which information you can retrieve from this data set.

Figure 10



↑ Light curve from TOI-178 system observed by Cheops

→ Links

ESA resources

ESA classroom resources
esa.int/Education/Classroom_resources

Teach with exoplanets
esa.int/Education/Teach_with_Exoplanets

Meet Cheops: the Characterising Exoplanet Satellite
esa.int/ESA_Multimedia/Videos/2019/12/Meet_Cheops_the_Characterising_Exoplanet_Satellite

Meet the Experts series – Other Worlds
esa.int/ESA_Multimedia/Videos/2020/07/Meet_the_Experts_Other_worlds

Paxi explores exoplanets!
esa.int/ESA_Multimedia/Videos/2019/12/Paxi_explores_exoplanets

Hack an Exoplanet
hackanexoplanet.esa.int

ESA space projects

ESA's exoplanet missions
esa.int/Science_Exploration/Space_Science/Exoplanets

Cheops - CHaracterising ExOPlanet Satellite
esa.int/Science_Exploration/Space_Science/Cheops

Webb - James Webb Space Telescope
esa.int/Science_Exploration/Space_Science/Webb

Detecting exoplanets with Gaia
esa.int/Science_Exploration/Space_Science/Gaia

PLATO - PLAnetary Transits and Oscillations of stars
esa.int/Science_Exploration/Space_Science/Plato

ARIEL - the Atmospheric Remote-sensing Infrared Exoplanet Large-survey
esa.int/Science_Exploration/Space_Science/Ariel

Extra information

Artist's animation of the TOI-178 system orbits and resonances
https://youtu.be/-WevvRG9ysY