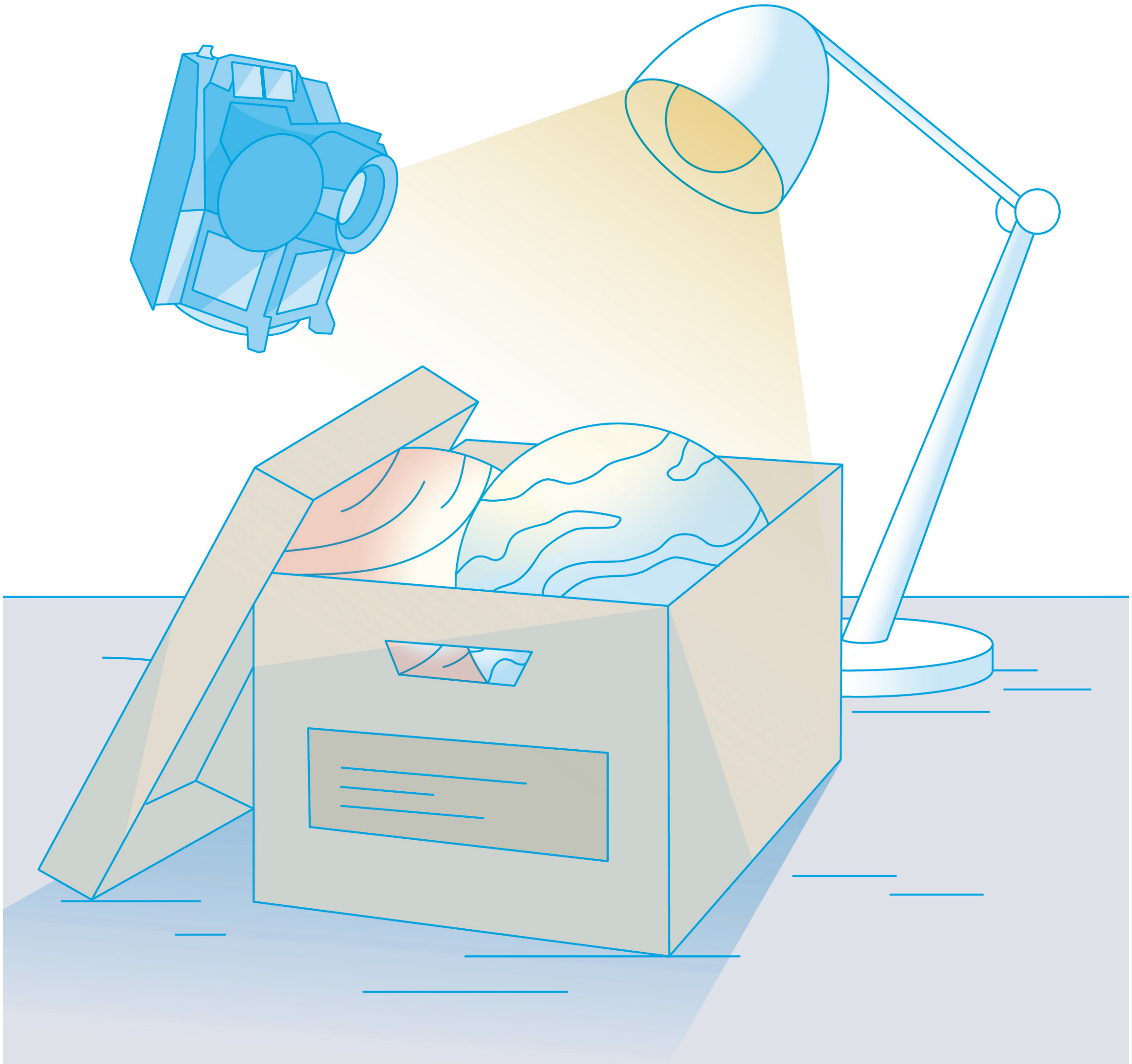
Physics | P30

teach with space

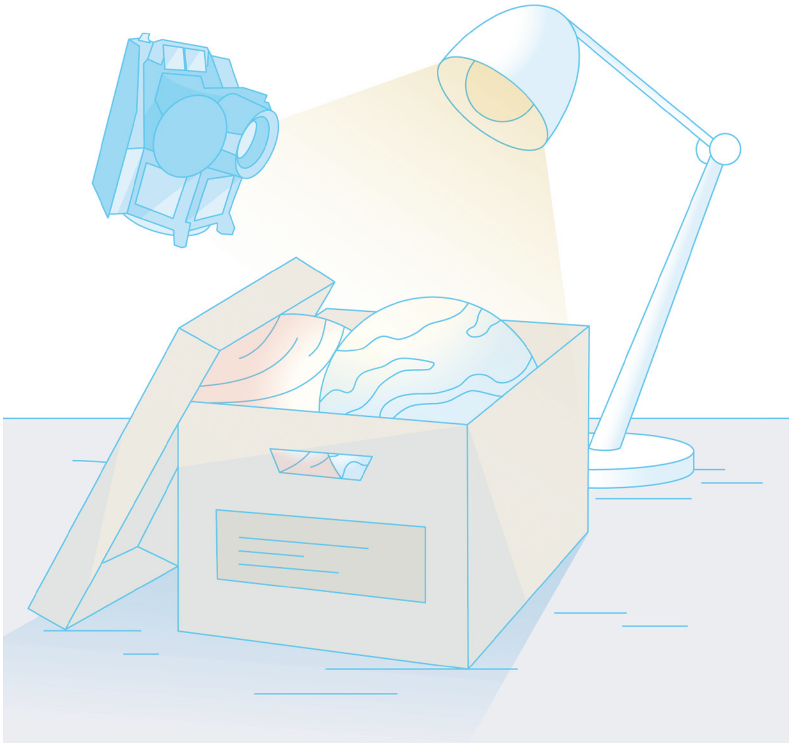
→ EXOPLANETS IN A BOX

Modelling exoplanet transits



teacher guide & student worksheets

→ THE EUROPEAN SPACE AGENCY



Teacher guide

teach with space – exoplanets in a box | P30
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→ EXOPLANETS IN A BOX

Modelling exoplanet transits

FAST FACTS

Subject: Physics, Mathematics

Age range: 14-19 years old

Type: Teacher's guide and student worksheets

Complexity: Medium

Lesson time: 90 minutes

Cost: High (> 30 euro per 'exoplanet in a box' set-up)

Location: Classroom

Includes use of: Data logger or smartphone with luminosity app

Keywords: Physics, Mathematics, Exoplanets, Light curves, Transits

Brief description

During these activities, students will work in small groups to model the transit of an exoplanet in front of its host star using an 'exoplanet in a box', and plot a light curve for this transit. Students will develop their own experiment: they will decide which variables to measure, what parameters to keep constant, and what equipment they need to take measurements. In addition, students will decide how to present their data and will develop their skills in data-logging and interpretation of graphs.

This activity is part of a series that includes "**Exoplanets in Transit**" where students analyse real data from ESA's Cheops satellite and "**Exoplanets in Motion**" where students build different transit models.

Learning objectives

- Understand the difference between a star and a planet.
- Learn about the properties of exoplanets.
- Understand how to model the detection of an exoplanet using the transit method.
- Understand how to work scientifically.
- Learn how to design an experiment.
- Learn how to use data-logging equipment.
- Develop skills for interpreting graphs.

→ Summary of activities

Summary of activities					
	Title	Description	Outcome	Requirements	Time
1	Exploring exoplanets	Introductory activity about exoplanets.	Learn what exoplanets are and the implications their study may have in our understanding of the Solar System.	None	20 minutes
2	Your exoplanet in a box	Design and construction of an exoplanet in a box model.	Learn to plan and design a scientific experiment.	None	25 minutes
3	Star light analysis	Analysis of the light curve of an “exoplanet“ transit.	Learn to collect and analyse data and display it in a graph using the model created in Activity 2.	Completion of Activity 2.	25 minutes
4	How big is an exoplanet?	Calculation of the size of an exoplanet.	Calculate the radius of an exoplanet using the data collected in Activity 3.	Completion of Activity 3.	20 minutes

→ Introduction

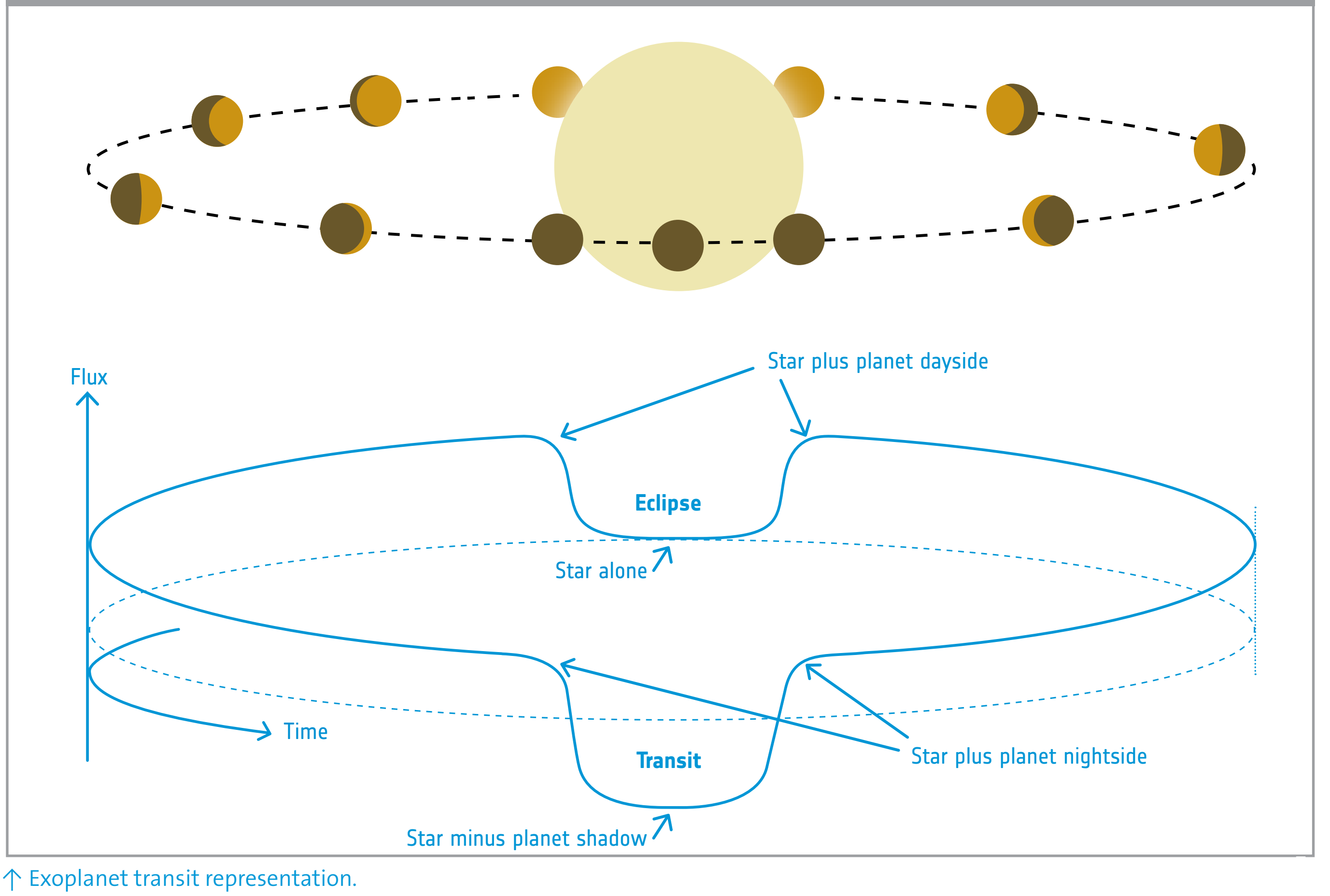
Just as the planets in our Solar System orbit the Sun, there are other celestial objects that orbit around other stars: we call some of them exoplanets. The first confirmed discovery of planets orbiting a Sun-like star outside our own Solar System occurred in 1995. Since then, the hunt has continued using many space and ground-based telescopes. Exoplanetology is the study of the physical and chemical characteristics of exoplanets and their systems. This field is advancing as scientists improve there capabilities of knowing where and when to look for exoplanets. Over 5700 confirmed exoplanets have been discovered to date (2024), and many more candidates are yet to be confirmed.

Exoplanets are difficult to observe because they are smaller than stars and do not emit their own light. They are also obscured by the bright light emitted by the stars they orbit. The main exoplanet detection methods are: transit photometry, radial velocity, gravitational microlensing, astrometry and direct imaging.

Telescopes like ESA's Cheops (Characterising ExOPlanet Satellite) are helping scientists to refine their models of the formation and evolution of planets, with potential implications for our understanding of the evolution of our own Solar System and the origin of life.

The transit method is particularly important because , combined with radial velocity measurements, it allows the determination of the radius and mass of the planet and the study of its atmosphere (Figure 1).

Figure 1



↑ Exoplanet transit representation.

This set of activities aims to introduce students to the topic of exoplanets, and develop their scientific skills by exploring the photometric transit method.

→ Activity 1: Exploring exoplanets

This activity introduces the students to the topic of exoplanets. Following the activity, the students should be able to describe what an exoplanet is, give an estimate of the possible number of exoplanets in our galaxy, and give reasons as to why exoplanets are difficult to detect.

Equipment

- Student worksheet
- Construction guide, Annex 1 (optional)

Exercise

Provide the students with the student worksheets and additional exoplanets background information. This activity can be presented as a classroom discussion, a group discussion or as an independent investigation.

Introduce the students to the concept of exoplanets and discuss the proposed questions with them.

1. Stars are celestial bodies composed primarily of hydrogen and helium, held together by their own gravity. They produce their own light and energy from nuclear fusion that take place within them.
    - Stars are formed from clouds of molecular gas that collapse under the influence of gravity
    - Planets form when the dust and gas that is present in the disc surrounding a star start to condense.

2. When searching for life beyond Earth, scientists have to make assumptions about what is considered finding life (or signature hints of it). One assumption is to focus on finding life forms such as microorganisms, or evidence of their past existence. It is believed that primitive organisms are more likely to exist and persist than advanced species. Another assumption is to focus on water dependent life, as liquid water is considered a fundamental requirement for life as we know it. This condition narrows down the list of possible places that might harbour life to the so called "Habitable Zone" around a star, where water can be present in liquid state (where it is not too hot and not too cold for life as we know it to exist). These are just two examples but there are more criteria that could indicate life such as certain chemical signatures and energy sources.

→ Activity 2: Building your exoplanet in a box

The students will create their own physical model of a transiting exoplanet to understand how variations in observed light of the host star can be used to detect exoplanets (the transit method). During this activity the students will learn how to use data logging applications and interpret graphs of observed light as a function of time.

Equipment

- Student worksheet printed for each group
- Annex 1 printed for each group (optional)
- Cardboard shoebox, or similar with lid
- Torch
- Light meter (e.g. smartphone with app or datalogger)
- Craft knife / scissors
- Semi-circular protractor
- Clothes peg
- Cocktail sticks or wooden BBQ skewer
- White paper
- Sticky tape
- Modelling clay or similar

Health and safety

The construction of the box involves the use of sharp tools

Exercise 1

Explain to the students that they will design and plan the construction of a physical model to study an analogue to an exoplanet photometric transit: an exoplanet in a box. A video demonstration of the activity is available here: https://youtu.be/9ddL-mrHB20). Use the image provided on the student worksheet or complement this information by showing an animation (for example https://www.esa.int/ESA_Multimedia/Videos/2019/12/Detecting_exoplanets_with_the_transit_method). This could also be demonstrated by moving a ball in front of a light source.

Students should work in groups of 3 to 4 students. In their groups, the students should discuss which variable(s) need to be measured, what will change, what will be kept constant, what their set up will be, what equipment they need to take their readings, and how they will present the data.

Exercise 2

After each group has prepared their plan and debated the best way to build their exoplanet in a box model distribute the materials for the groups to create their own designs. Alternatively, the students can follow the construction guide in Annex 1.

To record the data in this activity students can use a light meter. If this tool is not available to you, then there are also many apps available that enable a smartphone to be used as a substitute.

→ Activity 3: Star light analysis

After completing the construction of their exoplanet in a box students should measure the light curve for their "exoplanetary system" transit.

Equipment

- Exoplanet in a box built in Activity 2
- Light meter (e.g. smartphone with app or datalogger)
- Program to analyse graphs

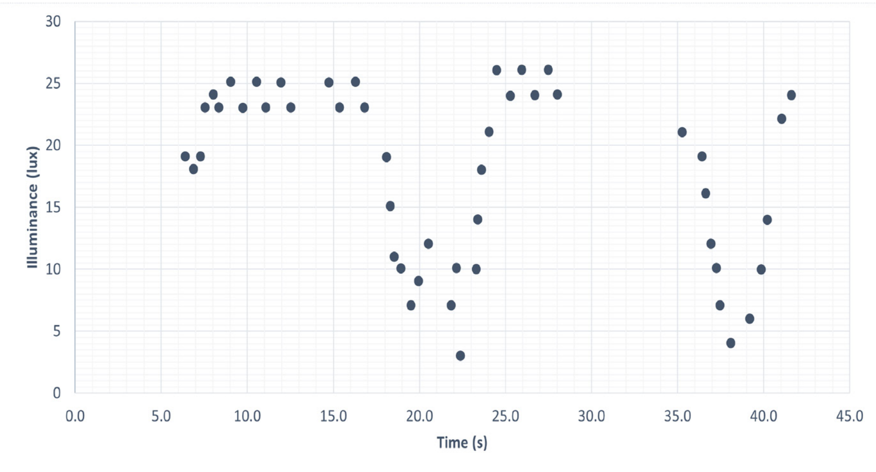
Exercise

Scientists measure star light as a function of time to detect variations on the measurements caused by transiting exoplanets. These graphs are called light curves.

In this exercise students will replicate the construction of a stellar light curve using their exoplanet in a box model. Figure 2 presents an example of a light curve for a setup like the one described in Annex 1

Note: For this example, we have used the free app Physics Toolbox Sensor Suite (vieyrasoftware.net). In this app the available light meter measures illuminance, in units of lux (lx), over time. Most light meters provide a measurement of illuminance. This is not the case for telescopes, which normally provide a measurement of apparent brightness or flux, of a star, so in this activity we will consider illuminance as an approximation to flux, to exemplify the method.

Figure 2



↑ Example of a light curve created using Physics Toolbox app

The light curve we constructed using our model exoplanet system shows two transits. For this example, the illuminance measured before the model exoplanet began transiting is approximately 25 lx, with a maximum change in illuminance of approximately 20 lx.

Multiple graphs can be obtained for analysis by varying the size of the transiting model exoplanet. Students should be able to use their results to demonstrate that a larger model exoplanet will lead to a deeper dip in the illuminance.

The orbital period varies with the distance between the model exoplanet and the detector. A short orbital period means that transits occur frequently because a planet completes more orbits in a given time frame. To dive deeper into this topic it is recommended the check the didactic resource ***Exoplanets in Motion***.

→ Activity 4: How big is an exoplanet?

The dip in the observed flux of the star as the exoplanet transits is a direct measure of the fraction of the disc of the star that the exoplanet blocks. Therefore, the dip in the observed light from the star is directly related to the ratio of the area of the disc of the exoplanet, to the area of the disc of the star.

Students are asked to calculate the radius of their exoplanet, assuming that it is orbiting the star Proxima Centauri. You could ask: "*If we look at this type of graph from Proxima Centauri, what could we discover about this exoplanet?*". The key information they need about the star is its radius (Rs), which is 100 900 km.

From our example light curve in Figure 2, the illuminance measured from the light source measured before, or 'out of', the transit is 25 lx, and during the transit, as the model exoplanet passes between the light source and the detector, is 5 lx. The change is 20 lx. This gives us:

$$\text{change in star light during transit} = \frac{\pi R_p^2}{\pi R_s^2} \quad \text{star light out of transit}$$

$$R_p^2 = \frac{20}{25} \cdot 100900^2$$

$$R_p = 90248\text{km}$$

If this model exoplanet would be orbiting Proxima Centauri, its radius would be 14 times larger than Earth's radius (6378 km) and 1.3 times larger than Jupiter's radius (71492 km).

Discussion

If you wish to take this activity further, ask the students to present their results to the class and to compare the results they obtained in the different groups. The students can also compare their results with real examples of exoplanets such as KELT-3B and TOI-560C.

An interesting extension question to ask is what the mass of the transiting model exoplanet would be if it were to have a similar composition as Jupiter, and if it were to have a similar composition to the Earth? To calculate the masses we need to know what the mean density of Jupiter and the Earth are. Using the relationship between mass, radius and density, the mass of the object can be calculated if it were Jupiter-like or Earth-like in density. You can find a table with the densities of the different planets in the Solar System in the links session.

→ Conclusions

In this set of activities students learned how the transit method can be used to detect and characterise exoplanets. As a plenary discussion, it is useful for students to think about the limitations of the transit method for exoplanet detection and of the model they constructed in particular. Some of these limitations include:

- In their model the size of the light source (star) is fixed. In reality, the size of stars and planets can vary by large factors. What is important is the relative size of the star and the planet.

- In the experiment the measured brightness nearly goes to zero as the exoplanet transits the star. This is not representative of a real-life scenario, where the change in star light during transit is much smaller. In the case of the Earth and the Sun the ratio of the disc areas (equivalent to the ratio of the squares of the radii of the objects) is approximately 10^{-4}.

- A limitation of the transit technique is that it relies on the alignment of the host star, the orbiting planet and the observer – that is, all three being in the same plane. This won't necessarily be the case, and the chances of having this alignment become smaller the more distant the planet is from its host star (longer orbital period). Planets that are closer to the host star are therefore more likely to be detected than planets that are further out, which introduces a so-called bias.

- The period of an exoplanet's orbit could be so long that we would not see a transit for many years, or we could miss it completely if not monitoring the star continuously. In addition, a larger orbit means that there is a lower probability of the planet actually transiting.

- In general, it is easier for instruments to detect the transits of large exoplanets with short orbital periods around relatively small stars. This could give us a skewed impression of the statistics of exoplanets in our galaxy. There could be many more smaller exoplanets, exoplanets with longer orbital periods, or exoplanets around larger stars that have not been detected (yet).

- The limitations of the transit method could lead on to a discussion of other methods of exoplanet detection. As an extension activity students can be asked to research and explain one other method of exoplanet detection. Other exoplanet detection methods include: radial velocity method, direct imaging, gravitational microlensing and astrometry (https://www.esa.int/Science_Exploration/Space_Science/Exoplanets/How_to_find_an_exoplanet).

As a bonus activity if you would like to continue analysing light curves with your students you can complete the activity ***Exoplanets in Transit***, where students can compare model and a real satellite data from ESA's Cheops mission.

→ EXOPLANET IN A BOX

Modelling exoplanet transits

→ Activity 1: Exploring exoplanets

Just as the planets in our Solar System orbit the Sun, there are other celestial objects that orbit around other stars. We call some of these celestial objects exoplanets. Scientists study exoplanets to understand if and how life could have formed outside Earth.

Exercise

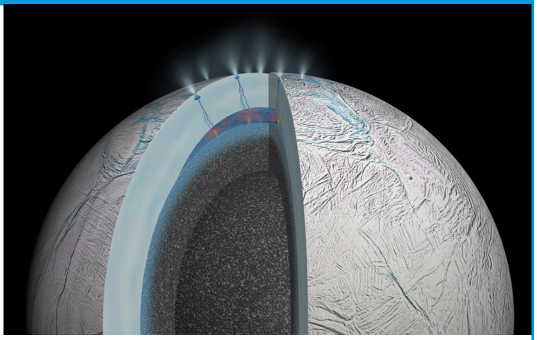
1. What are the differences between stars and planets?

2. Whilst life outside Earth has not been discovered yet, scientists are searching for it in our Solar System and beyond. What conditions do you think life would need to develop?

Did you know?

The Milky Way is estimated to contain a few hundred billion stars. Observations indicate that many stars host exoplanets, so it is likely that there are a few hundreds of billions of planets within our galaxy. Some of these might be located in the star's habitable zone.

Within our Solar System scientists are investigating some of the moons of Saturn and Jupiter as good candidates for finding signs of life, such as Enceladus and Europa.



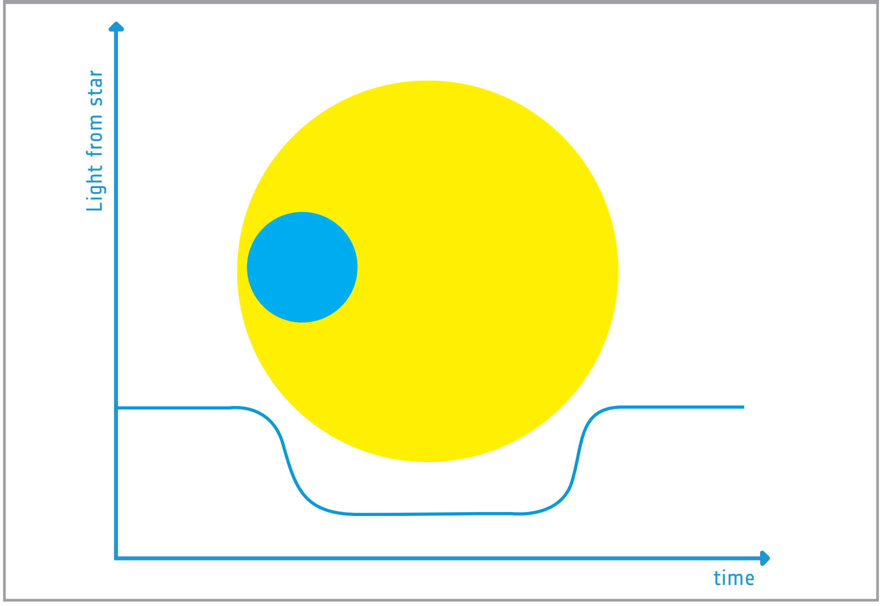
↑ Enceladus

→ STUDENT WORKSHEET

→ Activity 2: Exoplanet in a box

With your group, you will have to plan and construct a physical model to reproduce an exoplanet transit inside a paper box, like the one you see on Figure 1.

Figure 1



↑ Representation of an exoplanet transit. When the planet passes in front of the star the telescope receives less light and there is a dip in the measurement of the light from the star.

Exercise 1

In your group, plan how you would build a model to characterise and reproduce a light curve of an "exoplanet" transit inside a box. Take into consideration the questions below and try to answer them.

- Which variable(s) need(s) to be measured?
- Which variable(s) do you expect will change?
- Which variable(s) should be kept constant?
- What will be your set up?
- What equipment do you need to take readings?
- How will you present the data?

Exercise 2

After presenting your plan to your teacher build your exoplanet in a box and test it.

→ Activity 3: Star light analysis

You are now ready to analyse the light curve for your model exoplanet transit. A light curve shows the measured star light as a function of time. In your model the star light will be represented by the light source used.

Exercise

1. Simulate an orbit of your "exoplanet" around your light source and analyse the data. You should have obtained a graph similar to the one represented on Figure 1, Activity 2.

2. For your "exoplanet" transit model measure and record in the table the:

   a. Illuminance out of transit (exoplanet model not transiting light source)

   b. Maximum change in illuminance that you measured during the model exoplanet transit

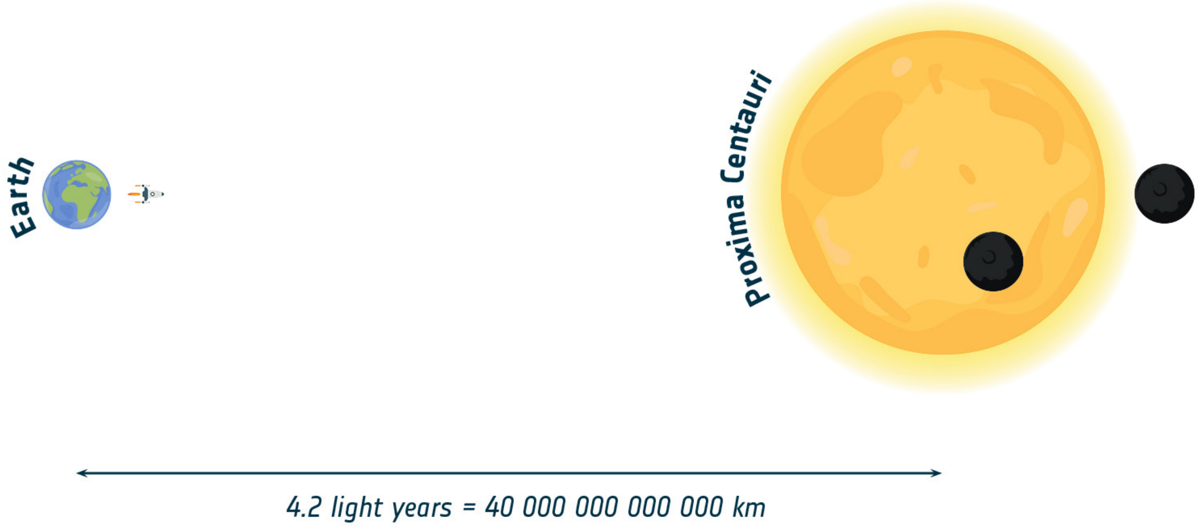
   Change the size of your model exoplanet and repeat.

Star light analysis		
Exoplanet	**Illuminance out of transit (lx)**	**Maximum change in illuminance during transit (lx)**

3. Did you observe any differences in the light curves between the model exoplanets?

→ Activity 4: How big is an exoplanet?

Imagine that your model exoplanet orbits around Proxima Centauri, the closest star to our Sun. Using the image and information below, what could we discover about the exoplanet?



During a transit, the dip in the observed flux is a direct measure of the fraction of the disc of the star that the exoplanet blocks.

$$\text{change in star light during transit} = \frac{\pi R_p^2}{\pi R_s^2}\ \text{star light out of transit}$$

Where R_s is the radius of the star, and R_p is the radius of the exoplanet. πR_p^2 is the surface area of the disk of the planet and πR_s^2 is the surface area of the disk of the star. Telescopes normally measure the star's flux or apparent brightness. In this activity we will consider the illuminance of the light source in your model as an approximation of the star light to exemplify the method.

Exercise

Rearrange the equation above to calculate the radius of your exoplanet (R_p), as if it was orbiting Proxima Centauri. Proxima Centauri has a radius of 100 900 km.

→ Links

ESA resources

Video demonstration of the activity “Exoplanets in a Box”
https://youtu.be/9ddL-mrHB2o

ESA classroom resources:
esa.int/Education/Classroom_resources

Teach with Exoplanets
esa.int/Education/Teach_with_Exoplanets

Hack an Exoplanet
hackanexoplanet.esa.int

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

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

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

ESA space projects

ESA’s exoplanet missions timeline
esa.int/ESA_Multimedia/Images/2018/08/Exoplanet_mission_timeline

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

Gaia - ESA's billion star surveyor
esa.int/Science_Exploration/Space_Science/Gaia

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

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

Solar System planet factsheet
nssdc.gsfc.nasa.gov/planetary/factsheet

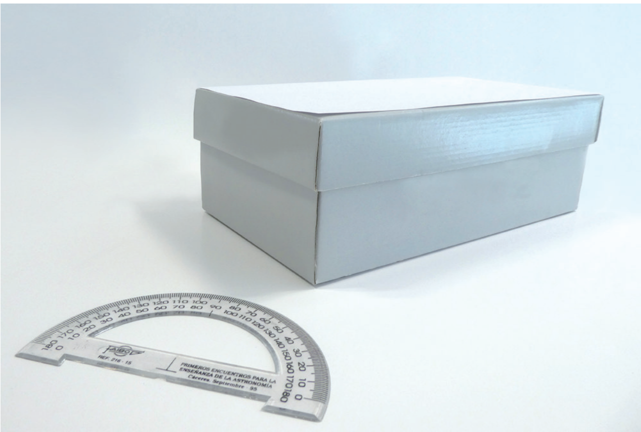
→ Annex 1 - Build an exoplanet in a box

Equipment

- Cardboard shoebox, or similar with lid
- Torch
- Light meter (e.g. smart phone with app or datalogger)
- Craft knife / scissors
- Semi-circular protractor
- Clothes peg
- Cocktail sticks or wooden BBQ skewer
- Plane white paper
- Sticky tape
- Modelling clay or similar

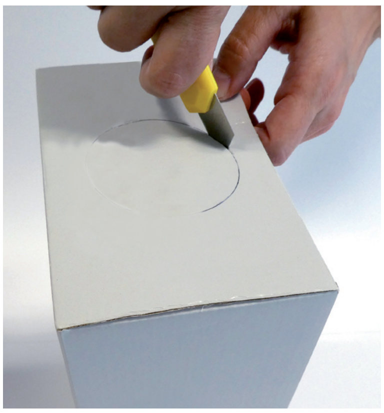
Instructions to construct an exoplanet in a box model

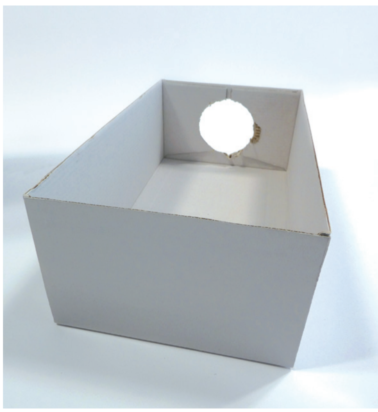
1. If the outside of your box lid has a dark surface then you may want to attach a blank sheet of paper on to it this will make it easier to read measurements once you start to do the experiment.



2. Use sticky tape to attach your protractor on to the lid of the box, across the straight side only.

3. Use a knife to carefully cut around the edge of the protractor. You can adjust the orbit of the exoplanet by cutting a semi-circle further away from the light source. An orbital path further from the light source may produce a more focused shadow. Move a cocktail stick around in the gap to make it easier to move whilst taking readings.

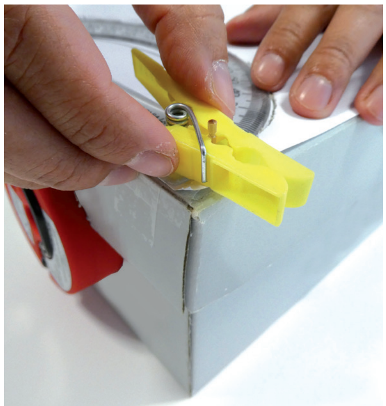




4. Cut a hole in the end of the box (the side end as the protractor) that is large enough for your torch to poke through. Tape your torch firmly into the hole.

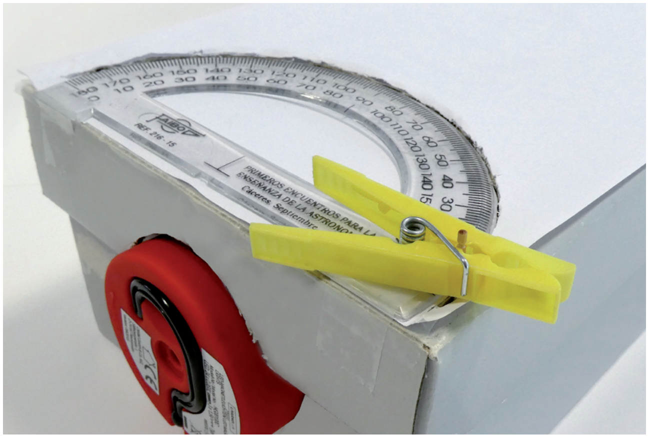
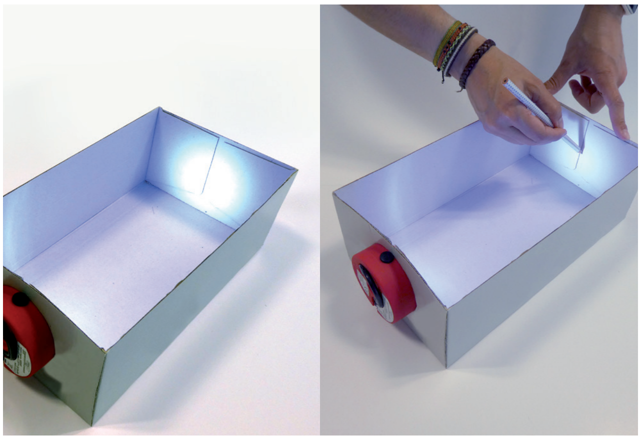
5. Using a cocktail stick measure the depth to centre of the torch lamp and mark the stick and attach the peg on that mark. Tape the end of the peg to secure it in place.



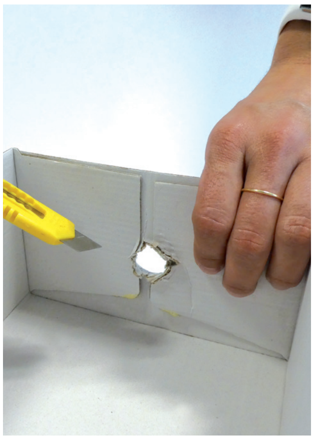
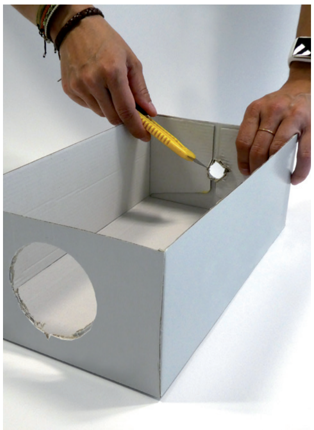


6. Insert the cocktail stick into the gap around the protractor. Check that you can move the peg around the full 180° of the semi-circle. You may need to use the knife again to free up movement.

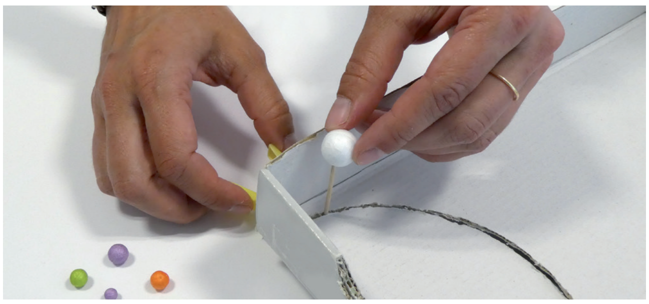
7. Turn on your torch and make a mark on the other end of the box at the centre of the beam.

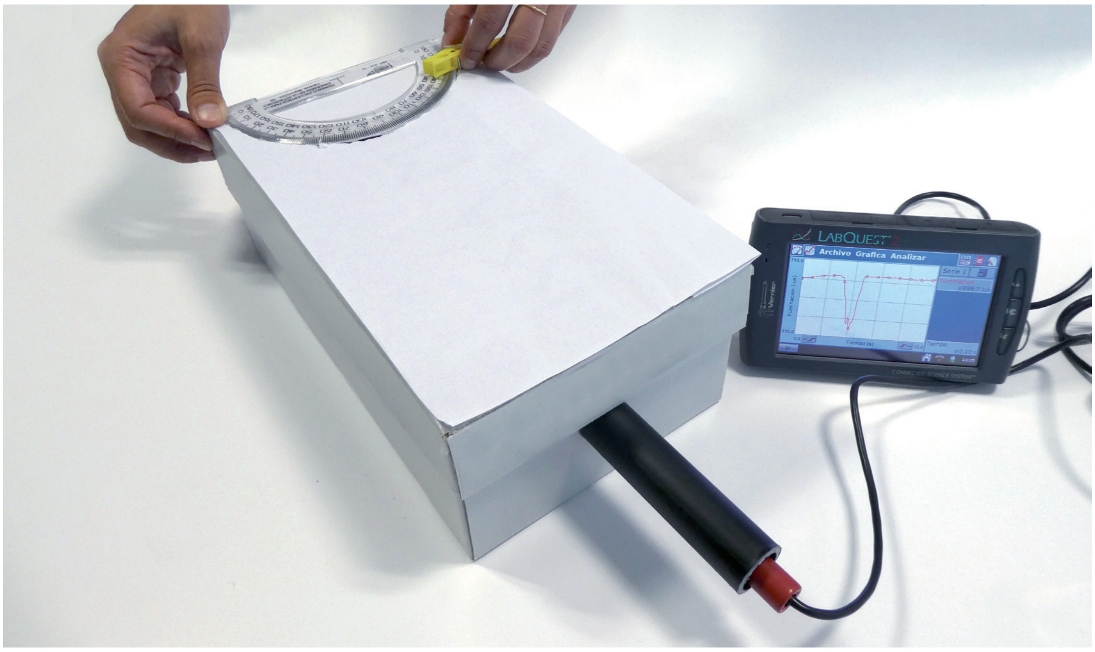
8. On the mark you made in the previous step, cut a hole large enough for your smartphone camera or datalogger to see through.

9. Make your exoplanet and push on to the end of the cocktail stick. Be careful of the sharp end. Close the box lid.

10. Start your light meter and point through the viewing hole to take readings.Alternatively, the datalogger can be placed inside the box and propped up with a flap of cardboard taped to the side.



11. Move the peg past the light source to check that the light meter is showing a dip in light level. You may need to adjust the position of your exoplanet and/or your light meter.