Secondary | P39

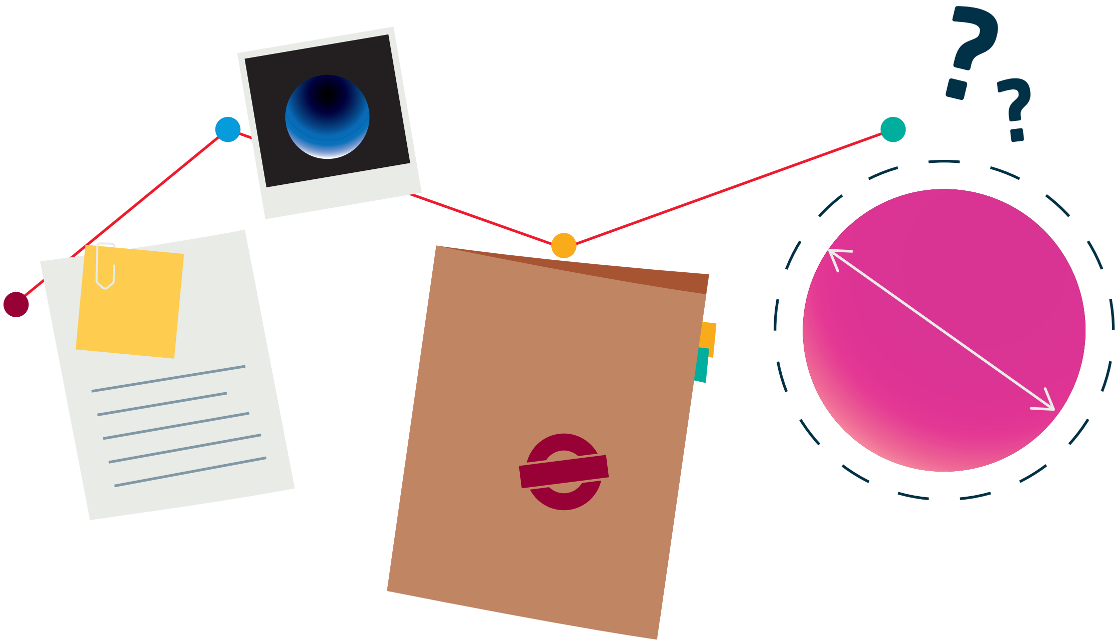
teach with space

→ HACK AN EXOPLANET

Becoming a Space Detective

teacher guide

European Space Agency



TEACHER GUIDE

teach with space – hack an exoplanet | P39
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→ HACK AN EXOPLANET

Becoming a space detective

Fast facts

Subject: Physics, Mathematics, Astronomy
Age range: 14 - 19 years old
Type: student activity and / or hackathon
Complexity: medium
Teacher preparation time: 1 hour
Lesson time required: 90 minutes per challenge (3 hours total)
Cost: low (0-10 euros)
Location: classroom
Makes use of: computer (if not possible an alternative is suggested)
Keywords: Physics, Mathematics, Astronomy Exoplanet, Transit

Brief description

In this activity, students will characterise two exoplanets by analysing data acquired by ESA's Cheops satellite. Students will work as real scientists and fit a model to the data to retrieve the best fit parameters.

The activity can be completed using a guided format or in a project-based learning format, for example in a hackathon. The teacher guide presents both options.

The activities are complemented with video explanations prepared by exoplanet experts.

Learning objectives

- Work scientifically with real satellite data.
- Apply mathematical data analysis techniques by fitting a model to real data.
- Learn about Kepler's Third Law and orbital mechanics.
- Understand what an exoplanet transit is.
- Build teamworking skills under a time constraint.

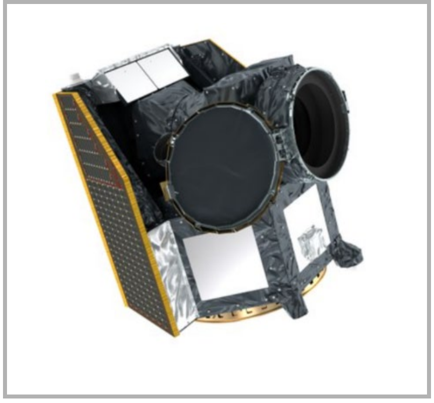
You also need

Supporting video materials. See Links section.

- Introduction to Hack an Exoplanet – become an exoplanet detective
- *Allesfitter* mini tutorial – step-by-step guide on how to fit the best model to the data
- How to determine the size of an exoplanet
- The orbital period and distance of an exoplanet, using Kepler's Third Law
- Could exoplanets be habitable?
- What are exoplanets made of?

→ Introduction

Figure 1



↑ Artist's impression of Cheops.

This educational activity has been developed in the context of the first ever ESA Education hackathon for secondary students: "**Hack an Exoplanet**". These challenges allow students to use real satellite data to investigate alien worlds and become exoplanet detectives for a day.

In January 2023, ESA's Cheops (CHaracterising ExOPlanet Satellite) observed two exoplanets, KELT-3b and TOI–560c, specifically for this activity. By analysing the Cheops data, students can join the ESA scientists in the search for answers and help them understand these two mysterious alien worlds.

The challenges are hands-on activities where the students are expected to analyse the data provided from ESA's Cheops satellite. The students will have to characterise the main properties of the exoplanets, making use of the supporting materials and the educational version of the fitting tool, *allesfitter,* prepared specifically for these data sets. The activities are accompanied with both written and video explanations and examples, prepared by exoplanet experts.

The activities can be presented using a guided format or in a project-based learning format, for example in a hackathon. The teacher guide presents both options.

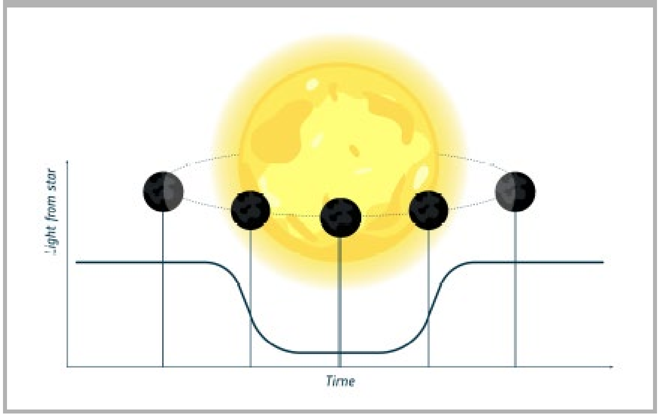
What is an exoplanet?

Exoplanets, or extrasolar planets, are planets outside our own Solar System orbiting a star other than our Sun.

How do we study exoplanets?

There are currently over 5000 confirmed exoplanets, in approximately 4000 stellar systems, but exoplanets are difficult to detect. The signal that we receive from an exoplanet is very small in comparison to the much larger signal coming from their bigger, brighter host stars, typically much less than 1%.

Figure 2



↑ Representation of the transit photometry method.

There are different methods to detect and characterise exoplanets, in this activity we will use the **transit photometry method.** This is the most common method to find exoplanets.

Photometry – the word photometry comes from the Greek: photo "light" and metry "measure". It is a technique used in astronomy to measure the light from stars in a quantitative way.

Transit – the exoplanet is detected by measuring a dimming in the light coming from the star.

→ Activity

The *Hack an Exoplanet* activity is composed of two challenges. The first challenge is the analysis of the transit light curve of the giant exoplanet KELT-3b. By following the instructions in the supporting material and/or following the information in the instructional videos, the students will be able to derive the properties of KELT-3b.

The second challenge is the analysis of the transit light curve of the mini-Neptune exoplanet TOI-560c. After completing the process for KELT-3b, the students should be able to complete the data analysis of TOI-560c autonomously by following a similar process.

Equipment

- Computer with access to the internet to access the browser software tool *allesfitter*. If this step is not possible the teams can use the best fit parameters provided in **Annex 1 –** Transit light curve of the exoplanet KELT-3b and **Annex 2** - Transit light curve of the exoplanet TOI-560c
- Student worksheet printed for each group, it includes:
  - Exoplanet investigation map
  - KELT-3b and TOI-560c case files
  - Information about the Solar System planets
  - Step-by-step *allesfitter* guide
- Calculator (optional)
- This activity also has six supporting videos to guide the teams (see Links section):
  - Introduction to Hack an Exoplanet – become an exoplanet detective
  - *Allesfitter* mini tutorial – step-by-step guide on how to fit the best model to the data
  - How to determine the size of an exoplanet
  - The orbital period and distance of an exoplanet, using Kepler's Third Law
  - Could exoplanets be habitable?
  - What are exoplanets made of?

  The information provided in the videos is also presented in this teacher guide.

Exercise:

The data sets for the two targets were obtained by ESA's Cheops satellite on 22 and 23 January 2023, specifically for this educational activity. The data has been processed by ESA experts and it is ready to be used by the students.

This activity can be presented using a guided format or in a project-based learning format, for example in a hackathon. The teacher guide presents both options.

We recommend the completion of this activity in teams of 3 to 4 students. This will allow the students to debate the best approach to complete each challenge and discuss the results.

Note: if the analysis of the data is too complex, teams can also complete the case file by searching online for the information.

Guided format

- Start by introducing the topic of exoplanets to the class. We suggest the use of this introductory video: *Introduction to Hack an Exoplanet*.
- Divide the class into teams of 3 to 4 students.
- Present the challenge to the students. Each team will have to characterise the main properties of the exoplanet KELT-3b by completing the case file available in their student worksheets. Teams will have to determine the size, orbital period, orbital distance, temperature, and composition of KELT-3b, and compare its properties to the planets in our Solar System. The exoplanet investigation map provides more information for each property mentioned.
- Distribute the supporting documentation to the teams and give them a few minutes to analyse them.
- Set a time for the teams to determine each exoplanet property. ***Before*** the teams start their work to determine each characteristic, present to them the respective supporting video. The supporting videos include information on how to determine each property and the solution for KELT-3b.
- Make sure the teams understand how to determine each parameter before moving to the next one.
- After determining all the parameters, the teams should present and discuss their conclusions with the class.
- As the next step you can propose to complete Challenge 2 and determine the characteristics of the exoplanet TOI-560c.

Project based format – hackathon

- Divide the class into teams of 3 to 4 students.
- Start by introducing the hackathon concept to the students by using this introductory video: *Introduction to Hack an Exoplanet*
- You can let the teams perform the challenges autonomously (for example as homework or as a classroom project) or do it in a joint classroom or school event.
- If needed, reinforce the concept of the challenge to the students. Each team will have to characterise the main properties of the exoplanet KELT-3b by completing the case file available in their student worksheets. Teams will have to determine the size, orbital period, orbital distance, temperature, and composition of KELT-3b, and compare its properties to the planets in our Solar System. The exoplanet investigation map provides more information for each property mentioned.
- Distribute the supporting documentation to the teams and give them a time frame to complete the full challenge, we suggest around 90 minutes for the analysis of KELT-3b.
- To make sure the teams have a steady progress, you can set a time frame for the determination of each characteristic or show the relevant supporting video and provide tips at specific moments. The supporting videos include information on how to determine each property and the solution for KELT-3b.
- After determining all the parameters, the teams should present and discuss their conclusions with the whole group.
- As the next step you can propose to complete Challenge 2 and determine the characteristics of the exoplanet TOI-560c.

➔ Challenge 1 – Analysis of KELT-3b data

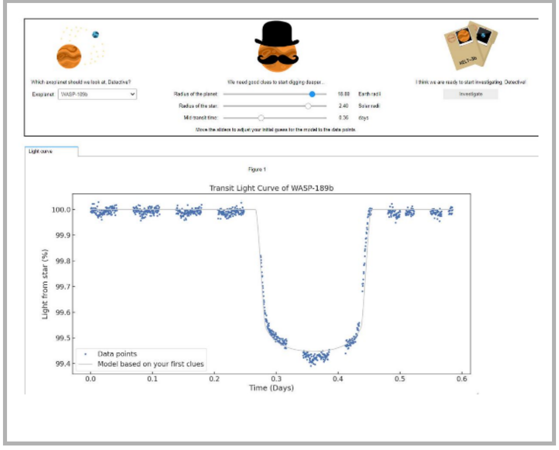
Access and fitting the satellite data

The data can be accessed following this link: hackanexoplanet.esa.int/allesfitter

This version of *allesfitter* is an online application that provides easy and free access to Cheops satellite data, allowing multiple exoplanets to be modelled from transit measurements. It can be accessed from a desktop browser.

To retrieve the best fit parameters of the data, students should follow the *allesfitter* step-by-step guide in the student worksheet or follow the video tutorial. This guide will provide instructions on how to use the browser based educational version of the *allesfitter* tool. This version of the tool already has the data sets uploaded, and it only allows the exploration of specific parameters: planet radius, star radius and mid-transit time.

Figure 3



↑ *Allesfitter* interface.

Note: If this step is not possible, the teams can use the best fit parameters provided in **Annex 1** – Transit light curve of the exoplanet KELT-3b and **Annex 2** - Transit light curve of the exoplanet TOI-560c.

How to determine the size of an exoplanet?

When using the transit photometry method, the telescope measures the amount of star light over a time period. Scientists fit models to the data to attempt to detect variations on the star light that could be caused by an exoplanet.

When using the transit photometry method, we do not directly detect the exoplanet (except for very specific cases). We instead measure the amount of star light that the exoplanet is blocking when it passes between the star and the telescope.

The amount of star light that the exoplanet blocks is normally referred to as the transit's depth. And this value is proportional to the exoplanet's projected area.

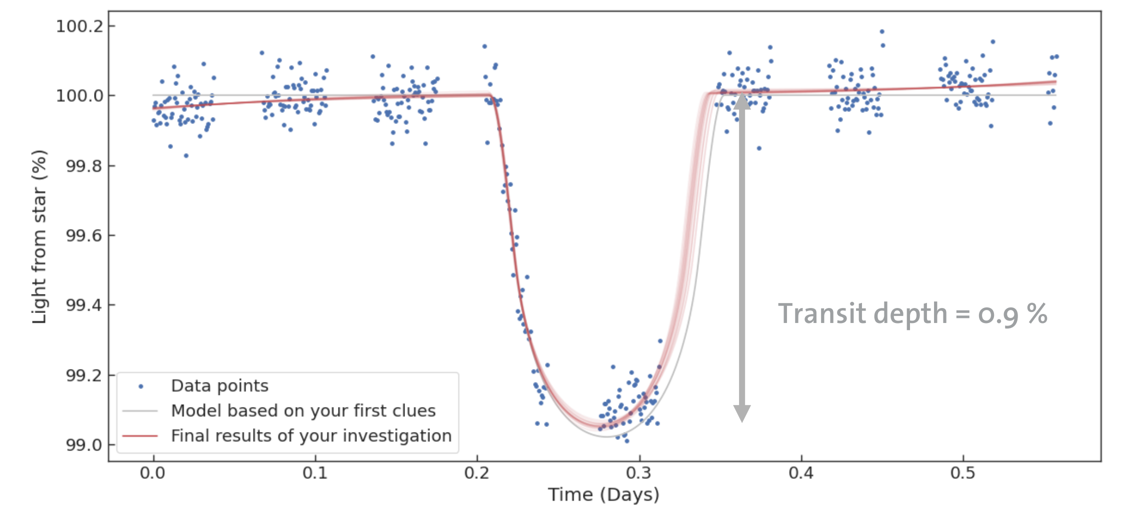
It is possible to determine the exoplanet's radius (R_p) if you know the star's radius (R_s) and the transit depth:

$$\text{transit depth (\%)} \sim \frac{\pi . R_p^2}{\pi . R_s^2} \text{ x 100}$$

KELT-3b example:

Let's now analyse KELT-3b data as an example.

Figure 4



↑ KELT-3b data from Cheops with the transit light curve best fit model from *allesfitter*.

The radius of the star KELT-3 is known and provided in the case file: $R_s = 1.70\ R_{Sun}$

By analysing the Cheops data we can measure the transit depth to be approximately 0.9 % (Figure 4).

Using the equation above: $R_p = \sqrt{R_s^2 \times \frac{transit\ depth}{100}} = \sqrt{1.70^2 \times \frac{0.9}{100}} = 0.161\ R_{Sun}$

Converting to Earth radii units: $R_p = 0.161 \times 109 = \mathbf{17.5\ R_{Earth}}$

When students run the *allesfitter* software they will retrieve a best fit value for the radius. This value can differ significantly from this simple estimation. On the interface students can only vary three parameters, but the *allesfitter* software fits the data with a complex model with several more hidden parameters that can provide a more complete fit to the data.

How to determine the orbital period and distance, using Kepler's Third Law

The orbital period, *T*, 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 mid-transit time (the centre of the transit) of two consecutive transits of the same exoplanet and measuring the time interval between them.

For these observations we only have one transit, but we can extrapolate the orbital period by comparing the current observational data with previous observational data found in the data archive.

After knowing the orbital period of the exoplanet, we can use Kepler's Third Law to derive the mean orbital distance, *d*, between the planet and the star.

$$T^2 = \left(\frac{4\pi^2}{GM_s}\right)d^3$$

Where *G* is the gravitational constant and M_s is the mass of the star.

KELT-3b example:

Let's now analyse KELT-3b data as an example. In this exercise students should pay close attention to the units.

- The gravitational constant in SI units is $G = 6.67430 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$
- The mass of the star KELT-3 is known: $M_s = 1.96\ M_{Sun}$
- We need to convert its mass to SI units: $M_s = 3.90 \times 10^{30}\ kg$
- From the model fit we have learned that the orbital period, *T = 2.70339 days*. Converting the orbital period to seconds: $T = 233573$ s

We now have all the information needed to determine the distance between the star and exoplanet.

$$d = \sqrt[3]{\frac{GM_s}{4\pi^2}T^2} = \sqrt[3]{\frac{6.67430 \times 10^{-11} \times 3.90 \times 10^{30}}{4\pi^2}233573^2} = 7.112 \times 10^9\ m = \mathbf{0.048\ au}$$

Let's now compare KELT-3b's period and mean orbital distance to the planets in our Solar System:

Planet	Period *(days)*	Mean orbital distance *(au)*
KELT-3b	2.70339	0.048
Mercury	87.97	0.4
Earth	365.25	1
Neptune	60266.25	30

Table 1

↑ Comparison of the period and mean orbital distance for KELT-3b and planets in the Solar System

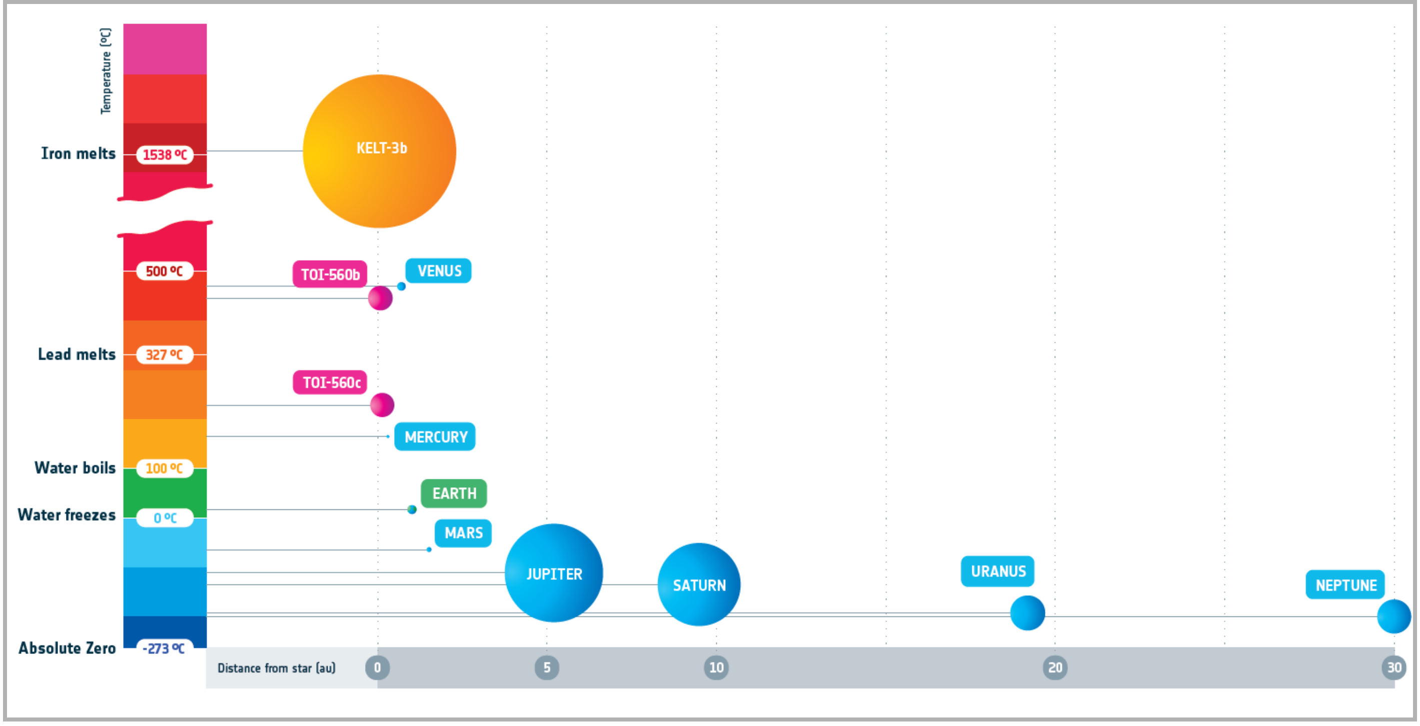
KELT-3b has a much shorter orbital period than Mercury, the closest planet to the Sun in our Solar System, due to the exoplanet's small distance to its host star. The transit photometry method identifies planets in these types of orbits more easily than it identifies planets like the ones in our Solar System.

How do we know if an exoplanet could be habitable?

To this day, Earth is the only place in the universe that is known to host life. It is also unknown if life could develop and exist in conditions very dissimilar to the ones that exist on our planet. When examining exoplanets and defining the possible conditions for habitability, scientists try to identify similar conditions to Earth, like temperature.

An important factor to be considered for habitability is temperature. The temperature of a planet is mostly defined by its distance to its host star. When a planet orbits a star at a distance where **liquid water** can be present on its surface, the planet is in the **habitable zone** of its host star.

Figure 5



↑ Diagram presenting the planets size and temperature versus the distance to its host star. The planets' size and distance are represented with two different scales.

Venus: the exception in the Solar System

The temperature measured at the surface of a planet is also impacted by its atmosphere. In the Solar System, Venus is an extreme example. Its thick atmosphere acts as a greenhouse and heats the surface to above the melting point of lead, making it a warmer planet than Mercury, despite being further away from the Sun.

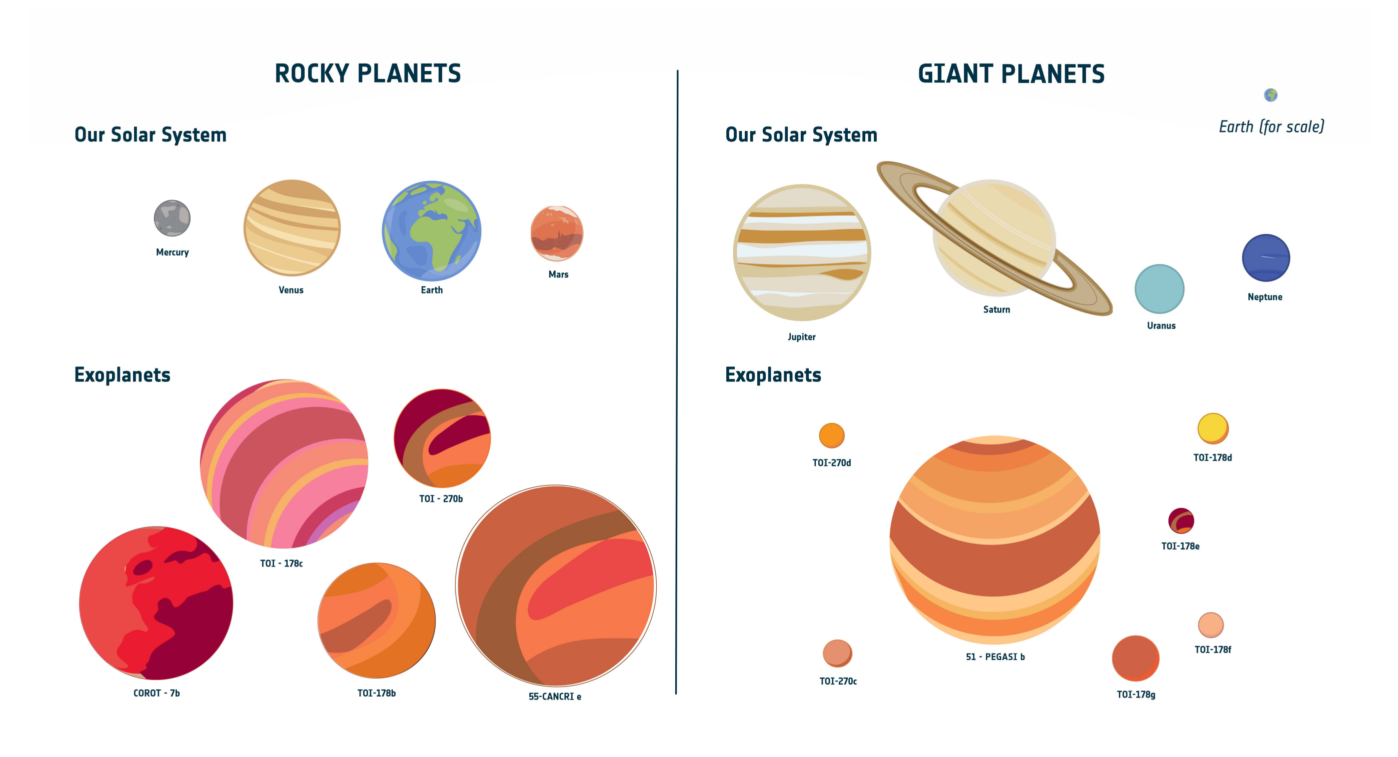
KELT-3b example:

Let's now discuss KELT-3b as an example. KELT-3b is unlikely to host life because it is too close to its host star, making its surface temperature very high, above the melting point of iron. Most amino acids, the building blocks of life, would not survive such extreme temperatures. The planet is also bombarded by high levels of radiation because of its very close distance to its host star.

What are exoplanets made of?

In our Solar System, planets are usually divided into two categories: rocky and gaseous. However, exoplanets can be very different from the neighbouring planets we are used to.

Figure 6



↑ Examples of artists' impressions of real exoplanets that have already been discovered orbiting nearby stars.

By calculating an exoplanet's mean **density**, $\boldsymbol{\rho}$, it is possible to have an idea about the composition of the exoplanet.

$$\rho = \frac{M}{V}$$

Where M is the mass of the exoplanet and V is the volume of the exoplanet.

The mass and volume of the exoplanet are normally determined with a large error associated to the values. These errors are then propagated to the calculation of the exoplanet's density, creating an uncertainty in the density value in the range of 10% to 30%.

A different technique used to study exoplanets is called spectroscopy. With this technique the light received from the star or exoplanet is split into different wavelengths, allowing for the determination of the exoplanet's **atmospheric composition** or cloud coverage.

KELT-3b example:

Let's now analyse the KELT-3b data as an example. KELT-3b's mass is 617 M_{Earth}. This value is not possible to determine from transit photometry. It was determined from previous observations using a different technique called radial velocity.

In the first exercise we already determined the radius of KELT-3b. By knowing the radius, we can calculate the volume of the exoplanet, assuming it is a perfect sphere: $V = \frac{4}{3}\,\pi\, R^3$.

M_p = 617 M_{Earth} = 3.685 x 10^{30} g

R_p *= 17.5 R_{Earth} = 1.116 x 10^{10} cm

* This radius value was estimated from the transit depth calculation, students can also use the *allesfitter* best fit model value.

$$\rho = \frac{M}{V} = 0.63\ g\ cm^{-3}$$

This value is much smaller than the mean density of Jupiter, and closer to the density of WASP-189b (a known hot Jupiter exoplanet). The small distance to its host star and its high temperature makes the exoplanet 'puffy'.

KELT-3b summary

KELT-3b is a hot Jupiter orbiting a Sun like star, KELT-3, approximately 690 light years away from Earth.

KELT-3b orbits very close to its host star, more than 10 times closer than Earth orbits the Sun. The exoplanet only needs 2.7 days to complete a full orbit around KELT-3.

Due to its proximity to its host star, the exoplanet's mean temperature is very high, above the melting temperature of iron, making it completely inhabitable.

KELT-3b is composed of mostly hydrogen and helium, similar to Jupiter. Because of the exoplanet's high temperature and proximity to the star, its atmosphere is very extended (puffy) and its mean density is very low.

Table 2

Exoplanet	**KELT-3b**
Type of planet	Hot Jupiter
Radius *(R_{Earth})*	16.81 (from allesfitter)
	17.5 (from transit depth)
Mass *(M_{Earth})*	617 ± 105
Orbital period *(days)*	2.70339
Mean orbital distance *(au)*	~0.048
Density *(g/cm³)*	~0.63
Mean Temperature *(°C)*	~1543

↑ Summary of an estimation of KELT-3b properties

Submit your project

Teams can submit their team's hack an exoplanet project on the Hack an Exoplanet platform to receive a participation certificate. To submit your project visit hackanexoplanet.esa.int/submit-your-project .

→ Challenge 2 – Analysis of TOI-560c data

After completing the analysis of KELT-3b the teams should be able to follow the same analysis process for the TOI-560c data.

All the information needed is available in the case file in the student worksheet, and at hackanexoplanet.esa.int/challenges.

Teams can submit their hack an exoplanet project on the Hack an Exoplanet platform to receive a participation certificate. To submit your team's project visit hackanexoplanet.esa.int/submit-your-project .

Best Project Prize:

For a chance to win the Best Project Prize teams should submit their investigative journal about TOI-560c, following the template available in the platform.

Your team's submission should include your analysis of the Cheops data for TOI-560c, and it should follow the format of a scientific paper including an abstract, analysis and results, and conclusions.

The winning teams will receive ESA goodies, as well as the opportunity to participate in a webinar with Physics Nobel Laureate Didier Queloz, on 17 July 2023. Deadline for submissions is 14 June 2023.

To submit your project visit hackanexoplanet.esa.int/submit-your-project .

→ LINKS

Supporting resources

Hack an exoplanet:
hackanexoplanet.esa.int

Hack an exoplanet educators' guide to the activity
hackanexoplanet.esa.int/educators-guide

AllesFitter educational version of the software:
hackanexoplanet.esa.int/allesfitter

Introduction to Hack an Exoplanet – become an exoplanet detective
hackanexoplanet.esa.int/challenges

Allesfitter mini tutorial – step-by-step guide on how to fit the best model to the data
hackanexoplanet.esa.int/allesfitter-guide

How to determine the size of an exoplanet
hackanexoplanet.esa.int/challenges-size

The orbital period and distance of an exoplanet, using Kepler's Third Law
hackanexoplanet.esa.int/challenges-orbital-period-and-distance

Could exoplanets be habitable?
hackanexoplanet.esa.int/challenges-temperature-and-habitability

What are exoplanets made of?
hackanexoplanet.esa.int/challenges-composition

Scientific references for KELT-3b
exoplanetarchive.ipac.caltech.edu/overview/KELT-3

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

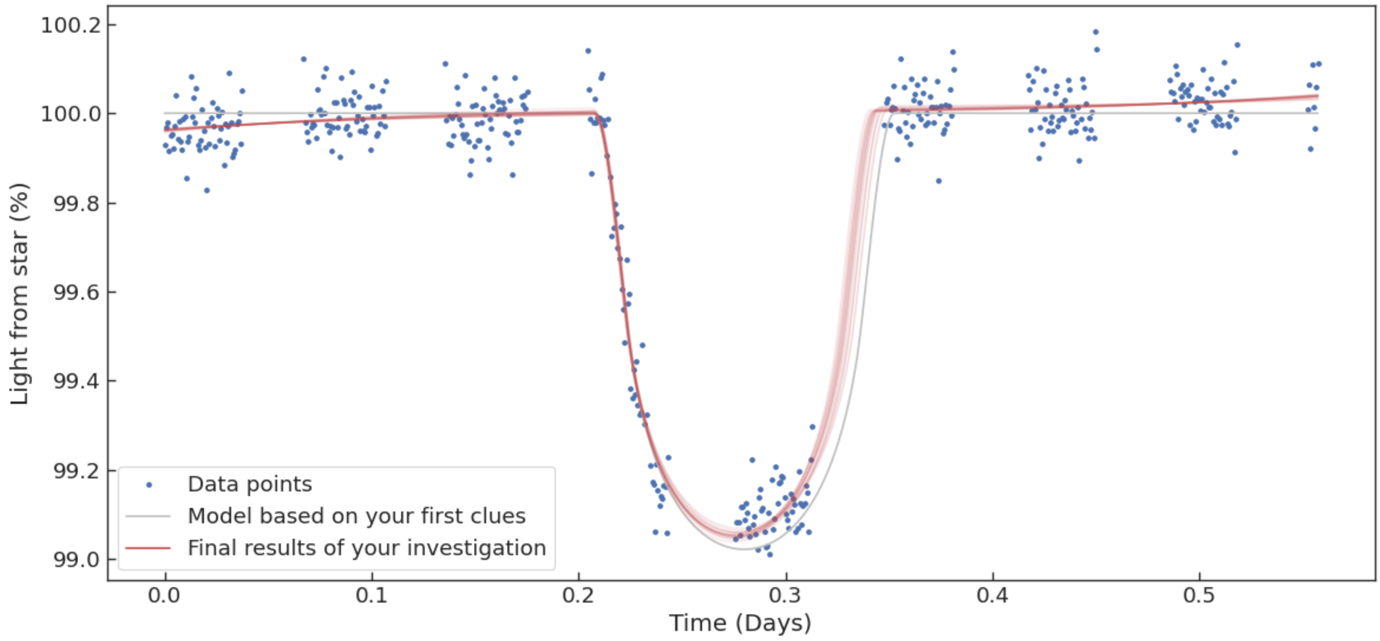
ESA space projects

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

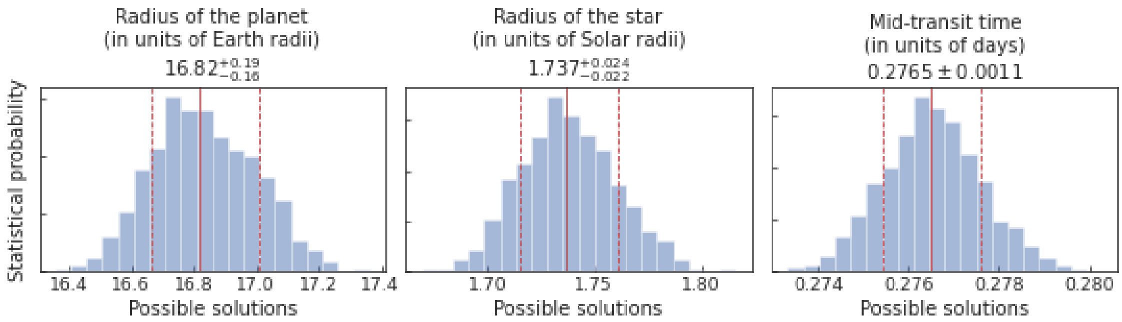
→ Annex 1

Transit light curve of the exoplanet KELT-3b

KELT-3b best model fit results from *allesfitter*



↑ Transit light curve best fit model.



- The histograms show the probability of each parameter having a certain value.
- The central, solid line shows the median value of each parameter.
- The dashed lines to the left and right of it indicate the lower and upper bounds, respectively.
- These are called the 1-sigma uncertainties. That means, statistically we can be 68% sure that the true value lies within them.
- Note that this means it is possible that the true value of a parameters lies outside of these bounds; they are only statistical uncertainties, not definite limits.

↑ Histogram of the statistical probability of all parameter values of KELT-3b

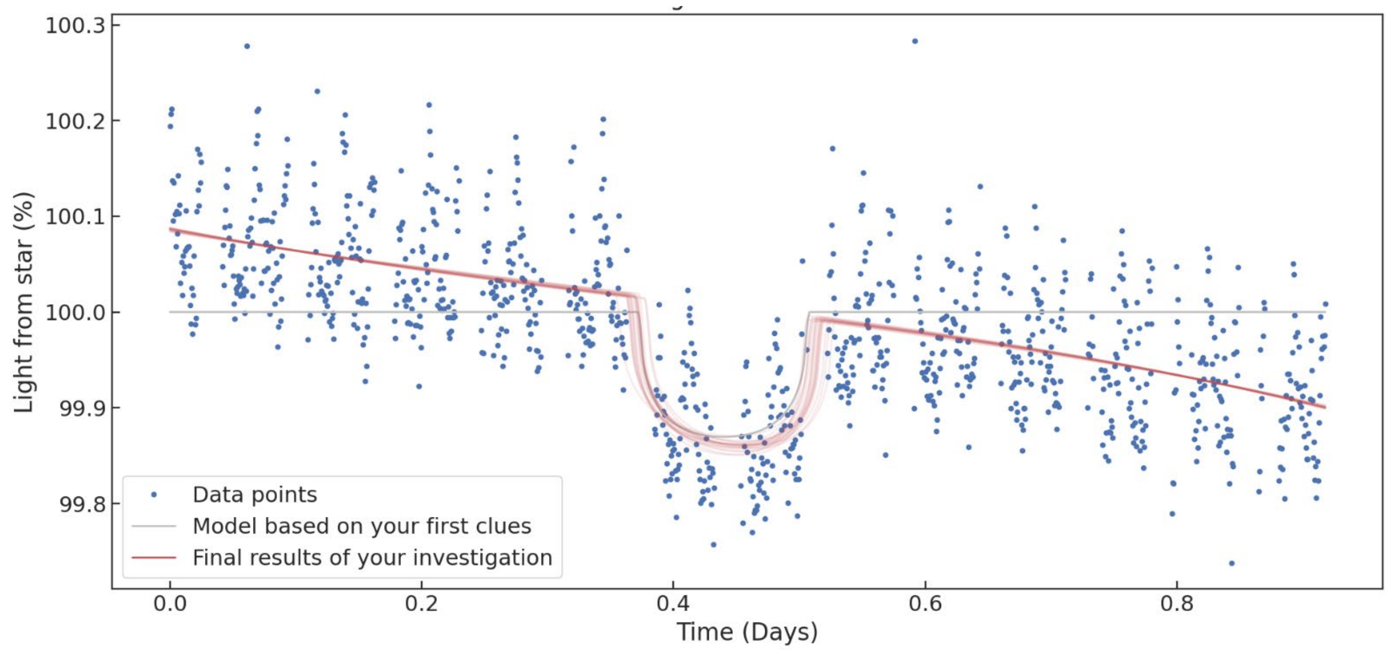
Name	Median value	Lower error	Upper error	Case note
Radius of the planet (in units of Earth radii)	16.82	0.16	0.19	Cheops observations
Radius of the star (in units of Solar radii)	1.737	0.022	0.024	Cheops observations
Mid-transit time (in units of days)	0.2765	0.0011	0.0011	Cheops observations
Orbital period (in units of days)	2.70339			Other observations from the archive

↑ Table with the best fit model parameters.

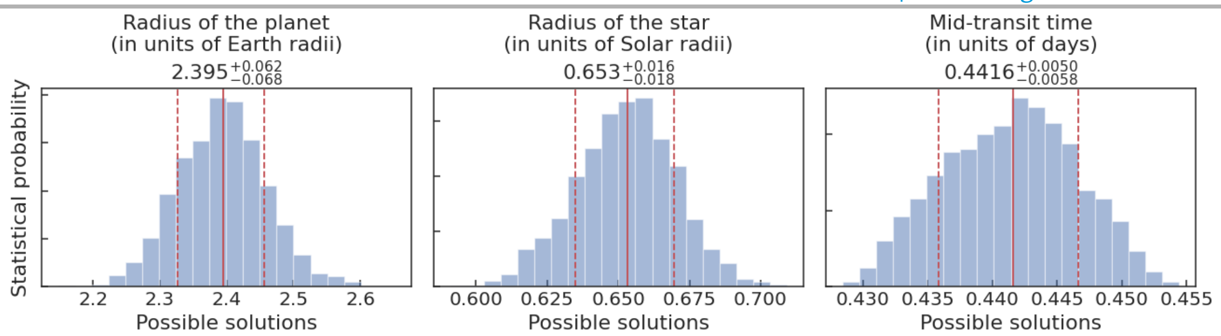
➔ Annex 2

Transit light curve of the exoplanet TOI-560c

TOI-560c best model fit results from *allesfitter*



↑ Transit light curve best fit model.



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- Note that this means it is possible that the true value of a parameters lies outside of these bounds; they are only statistical uncertainties, not definite limits.

↑ Histogram of the statistical probability of all parameter values of TOI-560c

Name	Median value	Lower error	Upper error	Case note
Radius of the planet (in units of Earth radii)	2.395	0.068	0.062	Cheops observations
Radius of the star (in units of Solar radii)	0.653	0.018	0.016	Cheops observations
Mid-transit time (in units of days)	0.4416	0.0058	0.0050	Cheops observations
Orbital period (in units of days)	18.8797			Other observations from the archive

↑ Table with the best fit model parameters.