Secondary | P39

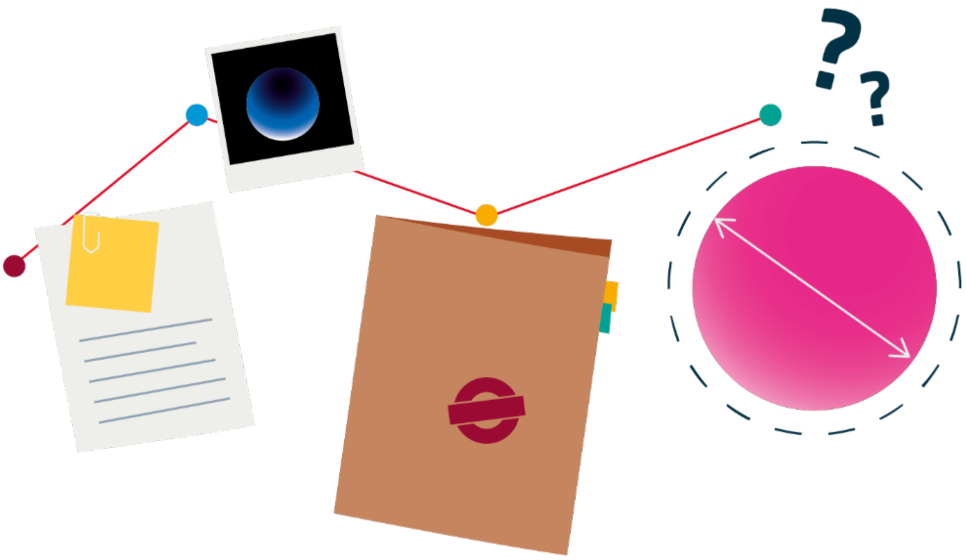
teach with space

→ 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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The ESA Education Office welcomes feedback and comments
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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 investigation (4.5 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 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.

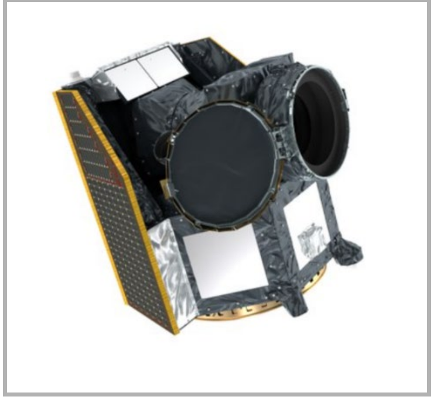
- Introduction to Hack an Exoplanet – become an exoplanet detective
- *Allesfitter* mini tutorial – step-by-step guide on how to fit the best model to the data
- How to determine the size of an exoplanet
- The orbital period and distance of an exoplanet, using Kepler's Third Law
- Could exoplanets be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

➜ Introduction

"**Hack an Exoplanet**" is an activity that invites students to use real satellite data to profile mysterious exoplanets and become exoplanet detectives for a day, by investigating their casefiles.

In January 2023, ESA's CHEOPS (CHaracterising ExOPlanet Satellite) observed two exoplanets, KELT-3b and TOI–560c, specifically for this activity. Later that year, in September 2023, CHEOPS observed two more exoplanets for this activity, K2-141b and K2-141c, which are orbiting the same star. By analysing the CHEOPS data, students can join the ESA scientists in the search for answers and help them understand these mysterious alien worlds.

Figure 1



↑ Artist's impression of CHEOPS.

This is a hands-on activity where students are expected to analyse the data provided from ESA's CHEOPS satellite. The students will characterise the main properties of the exoplanets, making use of the supporting materials (the casefiles) 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.

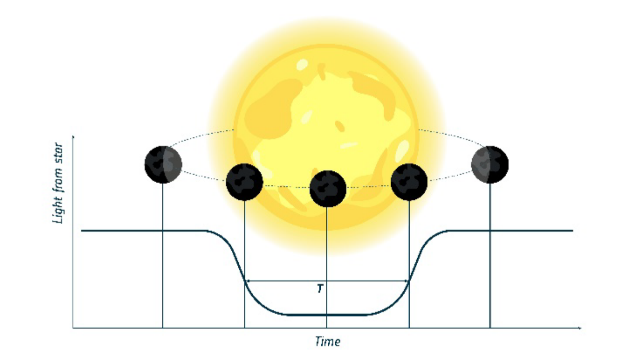
What is an exoplanet?

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 three investigations, each with information to derive the properties of the respective exoplanet: 1) KELT-3b, 2) TOI-560c and 3) exoplanet system K2-141b and K2-141c. By following the instructions in the supporting material and/or following the information in the instructional videos, the students will be able to complete the missing information in the casefiles.

It is recommended to start with KELT-3b, followed by TOI-560c and finally exoplanet system K2-141b and K2-141c.

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 **Appendix 1 –** Transit light curve of the exoplanet KELT-3b, **Appendix 2** - Transit light curve of the exoplanet TOI-560c, and **Appdendix 3** – Transit light curve of the exoplanet K2-141b
- Student worksheet printed for each group, it includes:
  - Exoplanet investigation map
  - KELT-3b, TOI-560c and K2-141b & c case files
  - Information about the Solar System planets
  - Step-by-step *allesfitter* guide printed for each group
- Calculator (optional)
- This activity also has six supporting videos to guide the teams (see Links section):
  1. Introduction to Hack an Exoplanet – become an exoplanet detective
  2. *Allesfitter* mini tutorial – step-by-step guide on how to fit the best model to the data
  3. How to determine the size of an exoplanet
  4. The orbital period and distance of an exoplanet, using Kepler's Third Law
  5. Could exoplanets be habitable?
  6. What are exoplanets made of?

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

Exercise:

The data sets for the targets were obtained by ESA's CHEOPS satellite in January and September 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 casefile and discuss the results.

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* (see Links section).
- Divide the class into teams of 3 to 4 students.
- Present the activity to the students. Each team will characterise the main properties of the exoplanet (recommended to start with KELT-3b) by completing the case file available in their student worksheets. Teams will determine the size, orbital period, orbital distance, habitability, and composition of the exoplanet, 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 (see Links section). 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 investigations 2 and 3, to determine the characteristics of the exoplanet TOI-560c and exoplanet system K2-141b and c.

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* (see Links section)
- You can let the teams complete the investigation 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 activity to the students. Each team will have to characterise the main properties of the exoplanet (recommended to start with KELT-3b) by completing the case file available in their student worksheets. Teams will have to determine the size, orbital period, orbital distance, habitability, and composition, 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 casefile of one exoplanet. We suggest around 90 minutes for the investigation of one exoplanet.
- 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 investigation 2 and 3, to determine the characteristics of the exoplanet TOI-560c and exoplanet system K2-141b and c.

→ Investigation 1 – Analysis of KELT-3b data

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

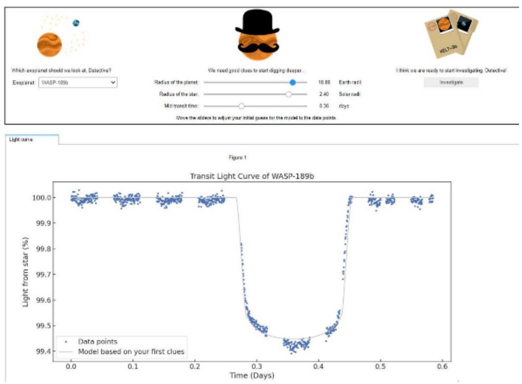
Access and fitting the satellite data

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.

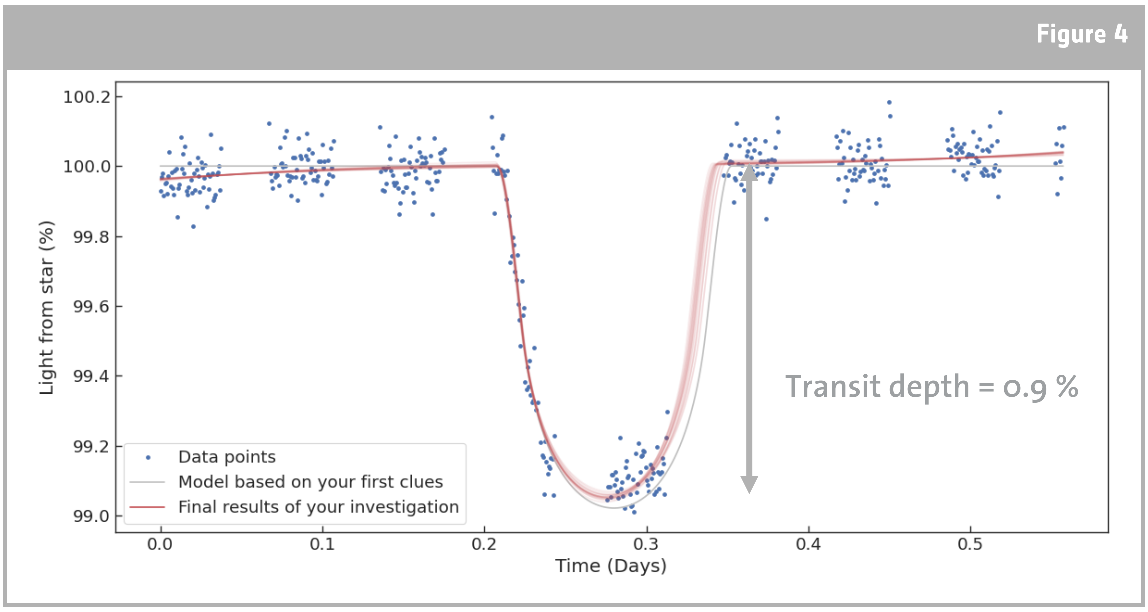
Note: If this step is not possible, the teams can use the best fit parameters provided in **Appendix 1** – Transit light curve of the exoplanet KELT-3b.

How to determine the size of an exoplanet?

When using the transit photometry method, the telescope measures the amount of star light over a specific period of time. 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 depth**. 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:

$$transit\ depth\ (\%) \approx \frac{\pi \cdot R_p^2}{\pi \cdot R_s^2} \times 100$$



↑ 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: $R_p = \sqrt{R_S^2 \times \frac{transit\ depth}{star\ light\ out\ of\ transit}} = \sqrt{(1.70 R_{Sun})^2 \times \frac{0.9}{100}} = 0.161\ R_{Sun}$

Converting to Earth radii units using: $1\ R_{sun} = 109\ R_{Earth}$

This results in: $R_p = 0.161 \times 109 = \mathbf{17.5\ R_{Earth}}$

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.

Let's analyse KELT-3b data. 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 in *allesfitter* or from the datasheet we have learned that the orbital period is 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.

$$d = \sqrt[3]{\frac{GM_s}{4\pi^2}T^2} = \sqrt[3]{\frac{6.67430 \times 10^{-11} \times 3.90 \times 10^{30}}{4\pi^2}233573^2} = 7.11 \times 10^9\ m = \mathbf{0.048\ au}$$

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

Table 1

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

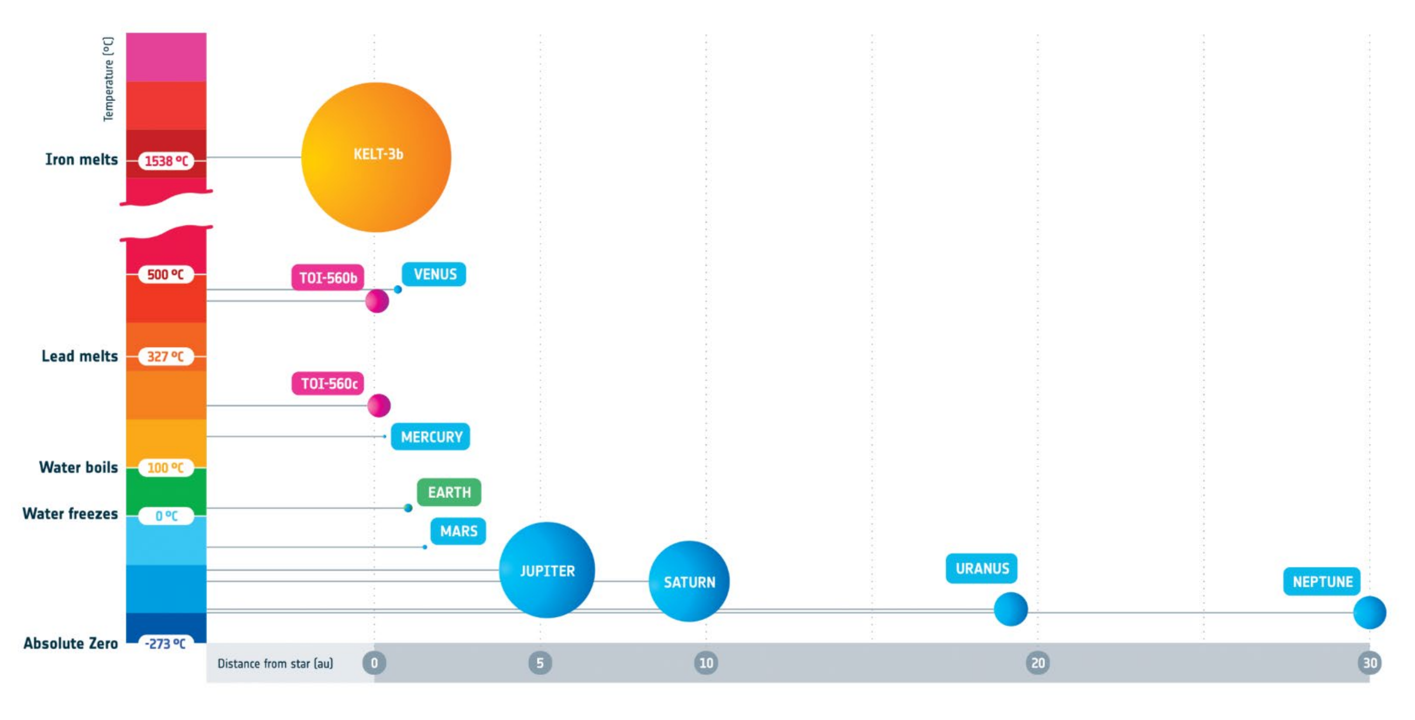
↑ Comparison of the period and mean orbital distance for KELT-3b and planets in the Solar System

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 finds planets in orbits close to their host star more easily than planets that are further away from their host star, in longer orbital period and therefore wider orbits.

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 different 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. 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.

Determining the temperature of an exoplanet is difficult. Exoplanet scientists use a quantity known as the 'equilibrium temperature'. This is calculated by assuming that the energy absorbed by the exoplanet from its host star (starlight) is equal to the energy that the exoplanet emits, and makes use of the host star's size, temperature and distance to the exoplanet.

Earth

The actual average surface temperature of a planet can vary wildly from the equilibrium temperature. For example, the equilibrium temperature of the Earth is –18°C, whilst the mean surface temperature of the Earth is 15°C. This is largely due to the greenhouse effect, with greenhouse gases in the atmosphere absorbing and emitting infrared radiation back to the surface. If you want to find out more about the greenhouse effect on Earth and climate change, check out the school project Climate Detectives and the resources there.

Venus: the exception in the Solar System

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.

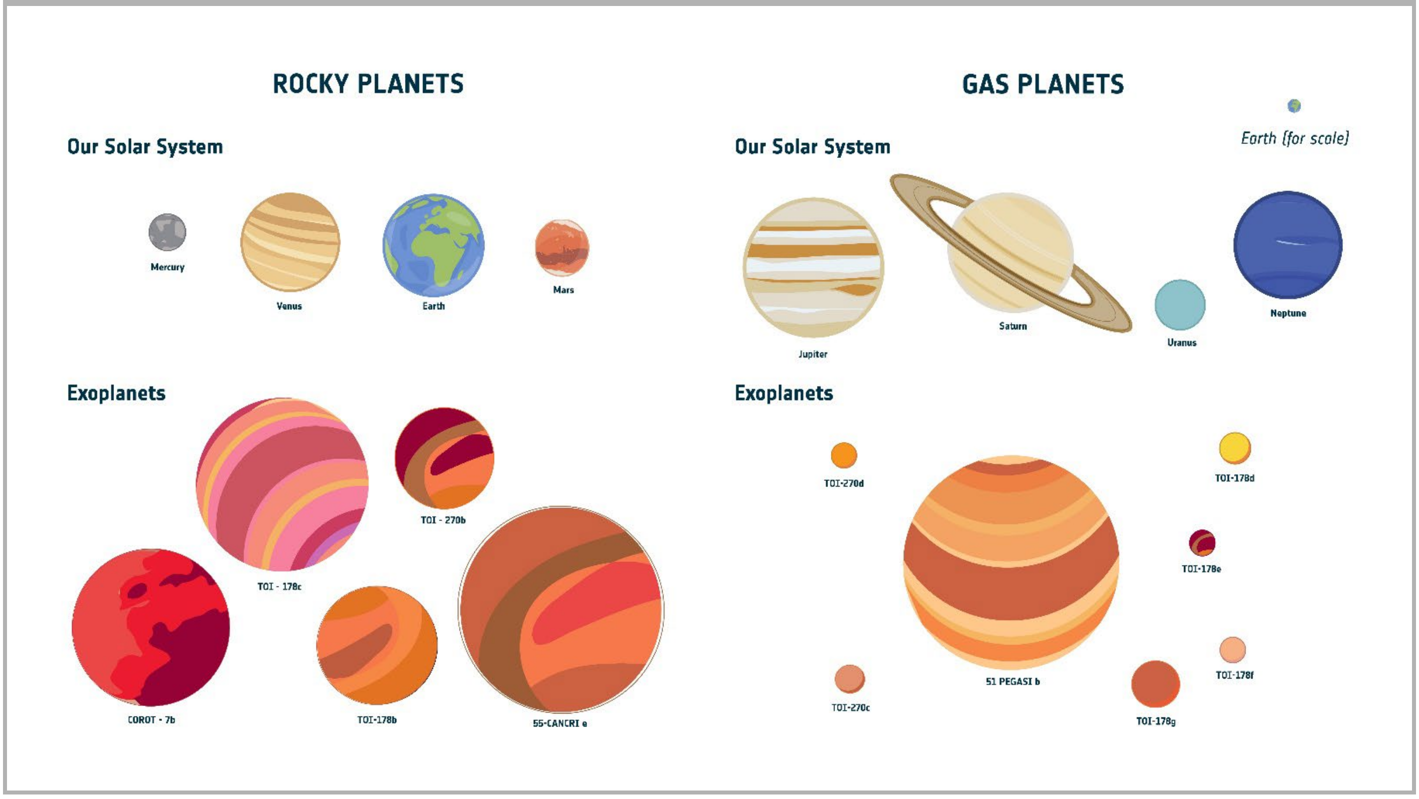
KELT-3b:

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 **bulk density**, ρ, it is possible to have an idea about the composition of the exoplanet.

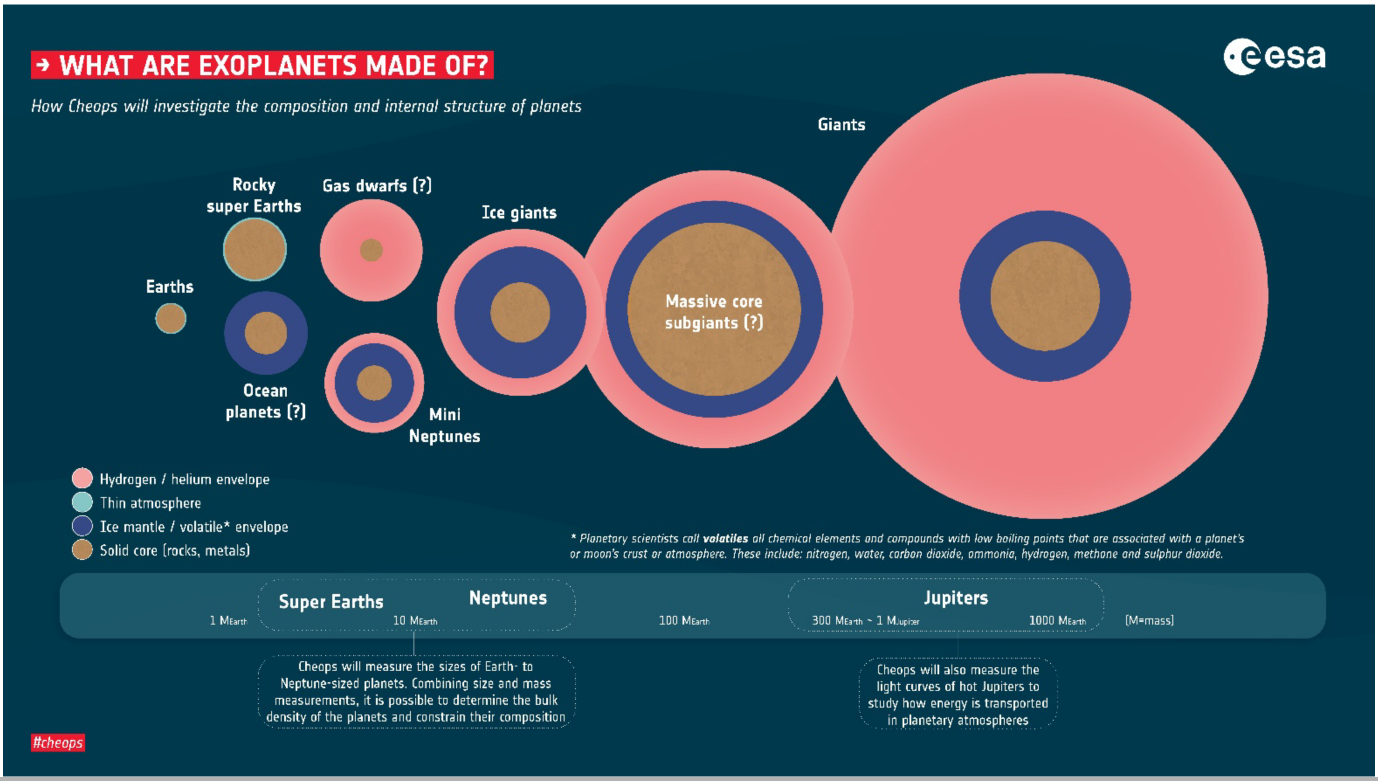
$$\rho = \frac{M}{V}$$

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 bulk density, creating an uncertainty in the bulk density value in the range of 10% to 30%.

Bulk density is an average, therefore different parts of the exoplanet can have different density values. For example, the bulk density of the Earth is 5.5 g/cm^3, but the inner core of the Earth is far denser than the mantle. Figure 7 shows that each planet can have regions with different densities.

Figure 7



↑ How CHEOPS will investigate the composition and internal structure of exoplanets.

While bulk density gives insights into the internal composition of an exoplanet, other techniques such as spectroscopy are used to study atmospheric properties of exoplanets. 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:

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. More information about radial velocity can be found in the classroom resource Exoplanets in Motion.

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: $V = \frac{4}{3}\,\pi\,R^3$.

$M_p^* = 617 M_{Earth} = 3.685 \times 10^{30}\ g$

$R_p^{**} = 17.5 R_{Earth} = 1.116 \times 10^{10}\ cm$

$V_p = \frac{4}{3}\ \pi\ {R_p}^3 = 5.822 \times 10^{30}\ cm^3$

*Students can look up the mass of Earth online.

** This radius value was estimated from the transit depth calculation, students can also use the *allesfitter* best fit model value. The radius of the Earth can be found online.

Inserting these values into the equation results in:

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

This value is much smaller than the bulk density of Jupiter, and closer to the bulk density of WASP-189b (a known hot Jupiter exoplanet). The small distance to its host star and its high equilibrium 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 equilibrium temperature is very high, above the melting temperature of iron, making it completely uninhabitable.

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 bulk density is very low.

Table 2

Exoplanet	**KELT-3b**
Type of planet	Hot Jupiter
Radius *(R_{Earth})*	16.8 (from allesfitter)
	17.5 (from transit depth)
Mass *(M_{Earth})*	617
Orbital period *(days)*	2.70
Mean orbital distance *(au)*	~0.048
Bulk density *(g/cm³)*	~0.63
Equilibrium Temperature *(°C)*	~1543

↑ Summary of an estimation of KELT-3b properties

➜ Investigation 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/start-investigation.

Access and fitting the satellite data

The data can be accessed following this link: hackanexoplanet.esa.int/allesfitter-guide. If you don't have access to a computer with internet access, you can use the datasheet in Appendix 2. More information about accessing and fitting the data can be found in section *Investigation 1 – Analysis of KELT-3b data*.

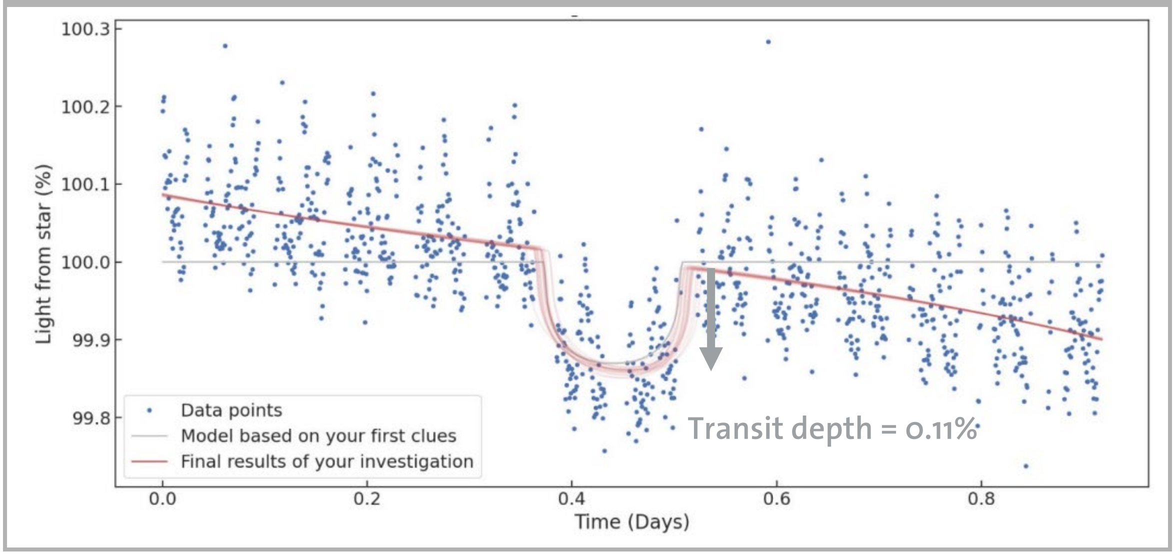
How to determine the size of an exoplanet?

More information about determining the size of an exoplanet can be found in section *Investigation 1 – Analysis of KELT-3b data*.

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

$$transit\ depth\ (\%) \approx \frac{\pi \cdot R_p^2}{\pi \cdot R_s^2} \times 100$$

Figure 8



↑ TOI-560c data fromCHEOPS with the transit light curve best fit model from *allesfitter*.

The radius of the star TOI-560 is known and provided in the casefile: $R_s = 0.65\ R_{Sun}$ By analysing the CHEOPS data we can measure the transit depth to be approximately 0.11% (Figure 7).

Using the equation above: $R_p = \sqrt{R_s^2 \times \frac{transit\ depth}{star\ light\ out\ of\ transit}} = \sqrt{(0.65 R_{Sun})^2 \times \frac{0.11}{100}} = 0.0216\ R_{Sun}$

Converting to Earth radii units using: $1\ R_{sun} = 109\ R_{Earth}$

This results in: $R_p = 0.0216 \times 109 = \mathbf{2.4}\ \boldsymbol{R_{Earth}}$

The radius of TOI-560c has been rounded to two significant figures due to the difficulty in determining the transit depth from the transit light curve with a precision of more than two significant figures. Exoplanet scientists use computers to measure the transit depth and can therefore make more accurate measurements of the depth than can be made from hand-measurements from a graph. Scientists have used transit observations made with other telescopes to determine that TOI-560c has a radius of $2.39\ R_{Earth}$, with an uncertainty of $\pm 0.1\ R_{Earth}$. The calculated radius falls within the uncertainty range, indicating that the calculation was done correctly.

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

More information about determining the orbital period and distance of an exoplanet can be found in section *Investigation 1 – Analysis of KELT-3b data*.

Let's analyse TOI-560c data. 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 TOI-560 is known: $M_s = 0.73\ M_{Sun}$
- We need to convert its mass to SI units: $M_s = 1.5 \times 10^{30}\ kg$
- From the model fit in *allesfitter* or from the datasheet we have learned that the orbital period is T = 18.8797 days. Converting the orbital period to seconds: $T = 1631210$ s

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

$$d = \sqrt[3]{\frac{GM_s}{4\pi^2}T^2} = \sqrt[3]{\frac{6.67430 \times 10^{-11} \times 1.5 \times 10^{30}}{4\pi^2} 1631210^2} = 1.89 \times 10^{10}\ m = \mathbf{0.13}\ \boldsymbol{au}$$

The orbital distance of the Earth is 1 au, so the orbital distance of TOI-560c is about 8 times smaller than the orbital distance of the Earth and 2.7 times larger than the orbital distance of KELT-3b. Have a look at Table 1 for more comparisons.

How do we know if an exoplanet could be habitable?

More information about determining the habitability of an exoplanet can be found in section *Investigation 1 – Analysis of KELT-3b data*.

The equilibrium temperature of TOI-560c is 225°C at an orbital distance of 0.13 au, compared to Earth's equilibrium temperature of –18°C at an orbital distance of 1 au. Therefore, TOI-560c is too hot for liquid water to form and the exoplanet is not in the habitable zone of its host star. Earth has a greenhouse effect, which makes the average surface temperature 15°C (instead of –18°C). Therefore, if TOI-560c has an atmosphere that produces a greenhouse effect, the exoplanet could have an even greater surface temperature.

The mass of a star and its temperature are closely related. The mass of the host star is only 79% of the mass of the Sun, which means that the star is cooler than the Sun. However, TOI-560c is in an orbit that is relatively close to its host star and therefore, the equilibrium temperature of the exoplanet is high (225°C). TOI-560c orbits far too close for liquid water to form because of its high temperature, so it is also unlikely for TOI-560c to be habitable for life to exist, unless the form of life is exceptionally different to life on Earth.

What are exoplanets made of?

More information about the composition of an exoplanet can be found in section *Investigation 1 – Analysis of KELT-3b data*.

$M_p^* = 9.70 M_{Earth} = 5.79 \times 10^{28}\ g$

$R_p^{**} = 2.39 R_{Earth} = 1.52 \times 10^{9}\ cm$

$V_p = \frac{4}{3}\,\pi\, {R_p}^3 = 1.47 \times 10^{28}\ cm^3$

*Students can look up the mass of Earth online.

** This radius value was estimated from the transit depth calculation, students can also use the *allesfitter* best fit model value. The radius of the Earth can be found online.

Inserting these values into the equation results in:

$$\rho = \frac{M}{V} = 3.9\ g/cm^3$$

Hence, TOI-560c has a bulk density just over 5 times that of KELT-3B (at 0.69 g/cm^3) and just over half of the density of the Earth (at 5.5 g/cm^3).

As explained in the example of KELT-3b, the bulk density can be used to develop an understanding of the composition of the exoplanet. For example, is the exoplanet a rocky planet, a gas giant, or an ice giant? Using a different technique – known as spectroscopy – also helps to build an understanding of the exoplanet's atmosphere. With a density of 3.9 g/cm^3, TOI-560c is likely to be a rocky planet. Mercury, Venus, Earth and Mars are the rocky planets in our own solar system.

TOI-560c summary

TOI-560c is a Mini Neptune orbiting a small orange-red star called TOI-560, also known as HD 73583, in the Hydra constellation, approximately 100 light years away from Earth. TOI-560 is smaller and cooler than our Sun. Besides TOI-560c, there is a second planet orbiting this star, TOI-560b.

TOI-560c is in an orbit that is closer to its host star (0.13 au) than the orbit of Mercury around our own Sun (0.387 au), but not as close as KELT-3b orbits its host star (0.048 au).

The exoplanet takes 18.9 days to complete a full orbit around its host star, TOI-560, compared to Mercury's orbital period of 88 days around the Sun, and KELT-3b's orbital period of 2.7 days around its host star. Don't forget, Earth's orbital period is roughly 365 days!

Due to its proximity to its host star, the exoplanet's equilibrium temperature is high, far above the boiling point of water, making it completely uninhabitable for humans and Earth-based life.

Table 3

Exoplanet	TOI-560c
Type of planet	Mini Neptune
Radius *(R_{Earth})*	2.4 (from allesfitter)
	2.4 (from transit depth)
Mass *(M_{Earth})*	9.70
Orbital period *(days)*	18.9
Mean orbital distance *(au)*	~0.13
Bulk density *(g/cm^3)*	~3.9
Equilibrium Temperature *(°C)*	~225

↑ Summary of an estimation of TOI-560c properties

However, due to the star being smaller and cooler than our Sun – even though TOI-560c is closer to its host star than Mercury is to the Sun – the exoplanet has an equilibrium temperature of 225°C, which is only about 60°C hotter than Mercury.

The bulk density of TOI-560c is 3.9 g/cm^3, which is over half the average density of the Earth. This implies that TOI-560c is a rocky planet, just like Mercury, Venus, Earth and Mars.

→ Investigation 3 – Analysis of K2-141b and K2-141c data

After completing the analysis of KELT-3b and TOI-560c, the teams should be able to follow the same analysis process for the data from two exoplanets in the K2-141 system. This is slightly more advanced because there are two target exoplanets in the same planetary system.

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

The K2-141 planetary system is approximately 200 light years away from Earth. This means that light takes approximately 200 years to travel from K2-141 to Earth. As a comparison, the Sun's light takes approximately 8 minutes to reach Earth.

The fastest man-made object to-date is NASA's Parker Solar Probe spacecraft, which had a maximum recorded speed of 191 km/s – which is 0.064% of the speed of light. It would take the Parker Solar Probe more than 310000 years to reach K2-141 at its fastest speed, which is approximately how long our species (*Homo sapiens*) has existed. All of human history and every human life on Earth has been contained in this span of time.

To date, exoplanet scientists have discovered two exoplanets in the K2-141 planetary system. K2-141b is known as a 'Super Earth' – due to its size – and K2-141c is a Neptune-like planet. Both exoplanets were discovered by NASA's Kepler satellite in 2018, during the second phase of its mission – hence the prefix K2. CHEOPS observed the exoplanetary system in September 2023.

Access and fitting the satellite data

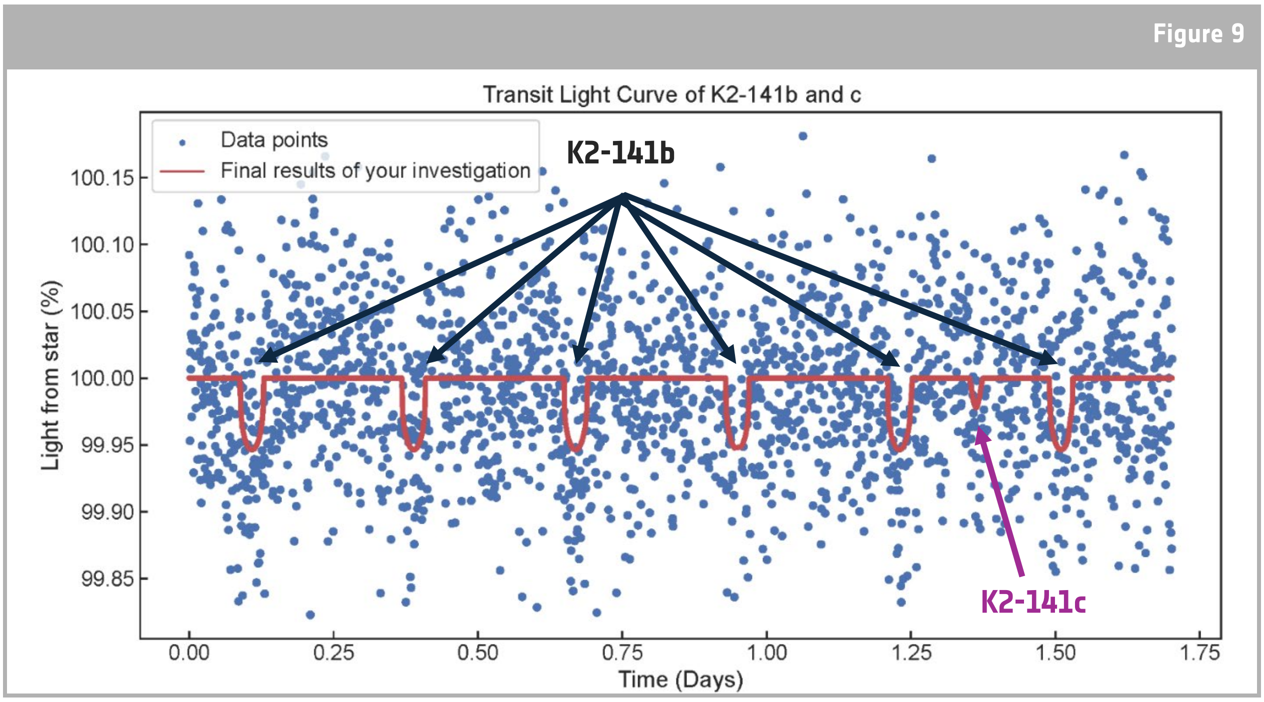
The data can be accessed following this link: hackanexoplanet.esa.int/allesfitter-guide. If you don't have access to a computer with internet access, you can use the datasheet in Appendix 3. More information about accessing and fitting the data can be found in section *Investigation 1 – Analysis of KELT-3b data*.

How to determine the size of an exoplanet?

More information about determining the size of an exoplanet can be found in section *Investigation 1 – Analysis of KELT-3b data*.

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

$$transit\ depth\ (\%) \approx \frac{\pi \cdot R_p^2}{\pi \cdot R_s^2} \times 100$$

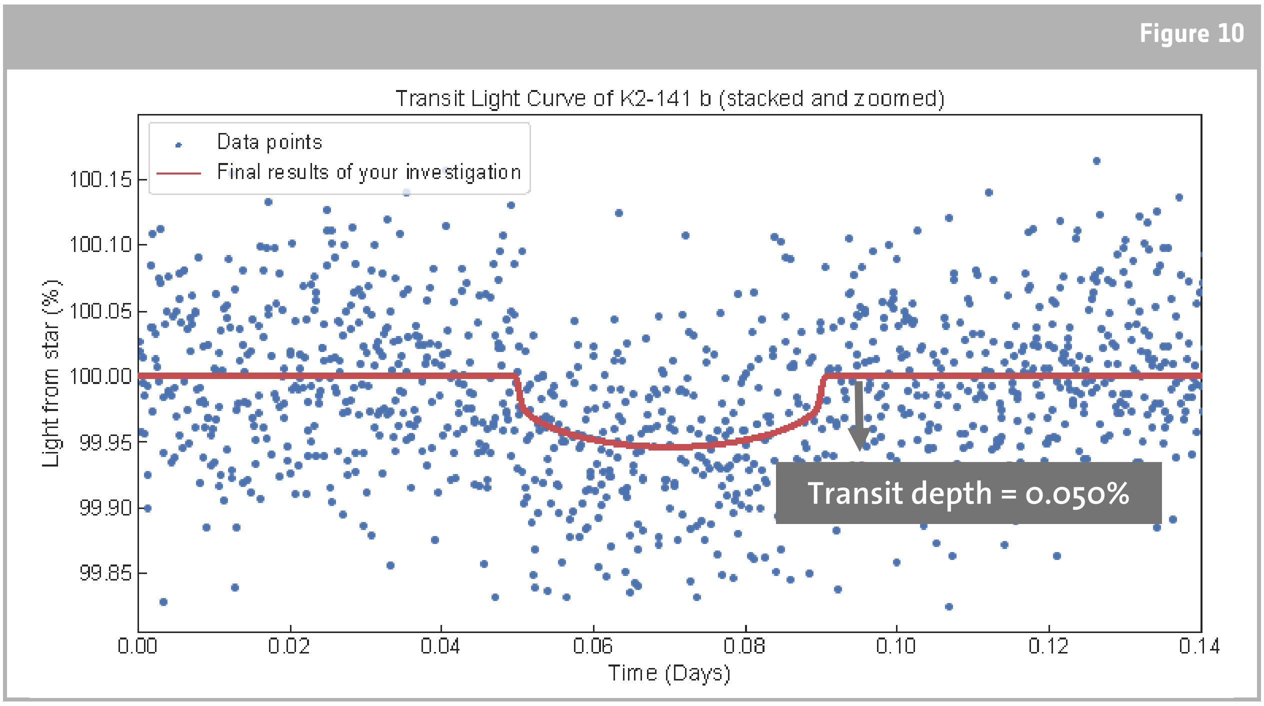


↑ K2-141b and c data from CHEOPS with the transit light curve best fit model from *allesfitter*.

Figure 9 is the light curve of the star K2-141. Here we see several dips at regular intervals as well as a single, more shallow dip. The multiple dips are the transits of K2-141b and the single shallow dip is the transit of K2-141c. Using the depth of a single transit and the interval between transits we can calculate the radius of the planet and its orbital period respectively.

K2-141b

In Figure 9, we can see six individual transits of K2-141b. These transits light curves can be 'stacked' on top of each other to produce one, more precise, transit light curve, as seen in Figure 10.



↑ K2-141b data from CHEOPS 'stacked' on top of each other with the transit light curve best fit model from *allesfitter*.

The radius of the star K2-141 is known and provided in the casefile: $R_s = 0.681 R_{Sun}$ By analysing the CHEOPS data we can measure the transit depth to be approximately 0.050% (Figure 10). Using the equation above:

$$R_p = \sqrt{R_s^2 \times \frac{transit\ depth}{star\ light\ out\ of\ transit}} = \sqrt{(0.681 R_{Sun})^2 \times \frac{0.050}{100}} = 0.015\ R_{Sun}$$

Converting to Earth radii units using: $1\ R_{sun} = 109\ R_{Earth}$

This results in: $R_p = 0.015 \times 109 = \mathbf{1.6\ R_{Earth}}$

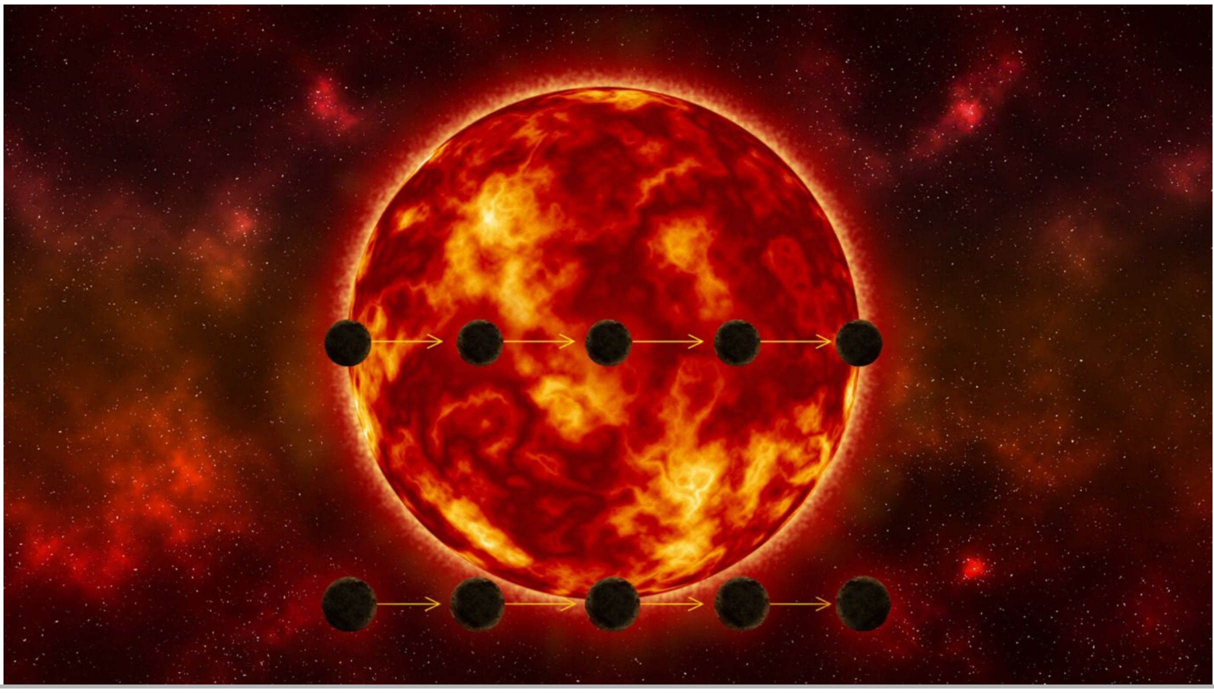
The radius of K2-141b has been rounded to two significant figures due to the difficulty in determining the transit depth from the transit light curve with a precision of more than two significant figures.

Exoplanet scientists use computers to measure the transit depth and so can make more accurate measurements of the depth than can be made from hand-measurements made from a graph. Exoplanet scientists have used transit observations made with other telescopes to determine that K2-141b has a radius of 1.51 R_{Earth}, with an uncertainty of ±0.05 R_{Earth}. The calculated radius falls slightly outside the uncertainty range, which can be related to small rounding and measurement errors. Given the minimal error, we can reasonably assume that the calculation was done correctly.

K2-141c

The single, shallow dip (Figure 9) is due to the transit of exoplanet K2-141c. The transit is 'grazing', which means that – as seen from Earth (or from a telescope close to Earth, such as CHEOPS) – only a part of the exoplanet appears to cover its host star as it transits and blocks the light from the star.

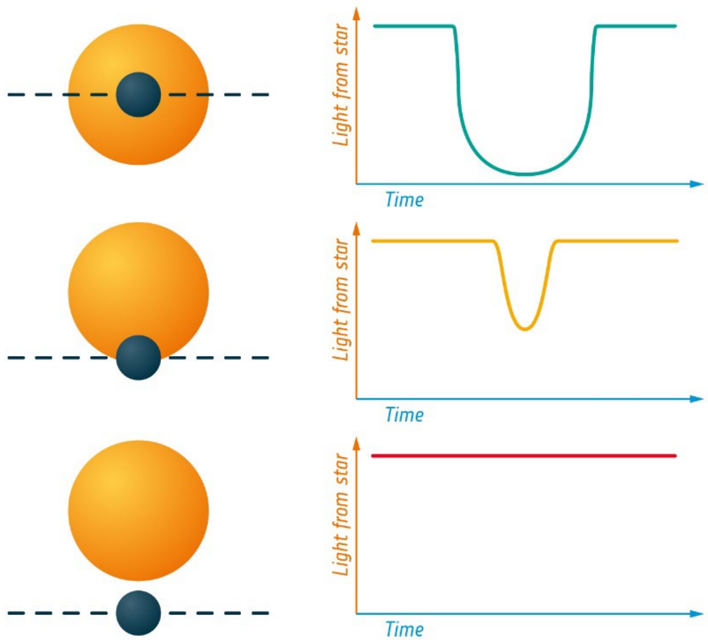
Figure 11



↑ Comparison of transit paths. The top path shows a planet transiting the full disk of the star. The bottom path shows the planet just grazing the star (credit: NASA, ESA, E. Wheatley (STScI)).

The dip in the light curve is therefore shallower than would be expected for a planet of its size and has a very distinctive V-shape. This means that we cannot use just the depth of the transit to determine the radius of the planet because it would appear smaller than it really is. Figure 12 is a visual representation of why a grazing transit cannot be used to calculate the radius of an exoplanet.

Figure 12



Exoplanet transiting directly between the host star and the satellite. The dip in the light curve is U-shaped and is proportional to the radius of the exoplanet.

Exoplanet with a 'grazing' transit between the host star and the satellite. The dip in the light curve is more V-shaped and is less deep than a full transit.

Exoplanet with no transit between the host star and the satellite. There is no dip in the light curve because the exoplanet does not cross between the line of sight of the host star and the satellite, so no starlight is blocked.

↑ A representation of light curves of exoplanets transiting the host star differently.

The fitting of grazing transit light curves is complex and can result in estimates of the exoplanet radius which can have large uncertainties, particularly in cases where the transit light curve that we are using is very shallow and the data is very noisy as is the case here for K2-141c. Calculation of this type are too complex for the scope of this student activity. Therefore, the estimated value of the radius of K2-141c is given in the casefile. This value can be used by the students to compute the bulk density.

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

More information about determining the orbital period and distance of an exoplanet can be found in section *Investigation 1 – Analysis of KELT-3b data*.

Both planets are in orbits that are close to the host star. K2-141b is the closest-in of the two, with an orbital period of less than 7 hours. This is one of the shortest orbital periods of any planet discovered to date; in fact, it is known as a USP – or ultra-short period – planet. Don't forget that the orbital period of the Earth is approximately 365 days!

Figure 9 shows six transits of exoplanet K2-141b. One can estimate the orbital period by measuring the time interval between two transits. If more than two transits are visible, you can measure the time between the first and the last transit and divide by the number of transits to determine the average time interval, hence decreasing the measurement error.

Exoplanet scientists use computers to measure the transits and can therefore make more accurate measurements of the orbital period than can be made from hand-measurements from a graph. Students can retrieve an accurate value for the orbital period in *allesfitter* or from the datasheet.

K2-141b

Let's analyse K2-141b data. 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 K2-141b is known: $M_s = 0.708\ M_{Sun}$
- We need to convert its mass to SI units: $M_s = 1.41 \times 10^{30}\ kg$
- From the model fit in *allesfitter* or from the datasheet we have learned that the orbital period is T = 0.280325 days. Converting the orbital period to seconds: $T = 24220.08$ s .

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

$$d = \sqrt[3]{\frac{GM_s}{4\pi^2}T^2} = \sqrt[3]{\frac{6.67430 \times 10^{-11} \times 1.41 \times 10^{30}}{4\pi^2}24220.08^2} = 1.12 \times 10^{10}\ m = \mathbf{0.0075\ au}$$

The orbital distance of the Earth is 1 au, so the orbital distance of K2-141b is approximately 130 times smaller than the orbital distance of the Earth! Its orbital distance is also approximately 17 times smaller than that of TOI-560c (at 0.13 au) and approximately 6 times smaller than that of KELT-3b (at 0.048 au). Have a look at Table 1 for more comparisons.

K2-141c

Let's analyse K2-141c data. 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 K2-141b is known: $M_s = 0.708\ M_{Sun}$
- We need to convert its mass to SI units: $M_s = 1.41 \times 10^{30}\ kg$
- In the student casefile it is stated that the orbital period is T = 7.74850 days. Converting the orbital period to seconds: $T = 669470.4$ s .

$$d = \sqrt[3]{\frac{GM_s}{4\pi^2}T^2} = \sqrt[3]{\frac{6.67430 \times 10^{-11} \times 1.41 \times 10^{30}}{4\pi^2} \times 669470.4^2} = 1.02 \times 10^{10}\ m = \mathbf{0.068\ au}$$

The orbital distance of the Earth is 1 au, so the orbital distance of K2-141c is almost 15 times smaller than the orbital distance of the Earth! Its orbital distance is also approximately half that of TOI-560c (at 0.13 au) and approximately 1.5 times larger than that of KELT-3b (at 0.048 au). Compared to K2-141b, the orbital period of K2-141c is approximately 9 times larger. Have a look at Table 1 for more comparisons.

How do we know if an exoplanet could be habitable?

More information about determining the habitability of an exoplanet can be found in section *Investigation 1 – Analysis of KELT-3b data*.

The host star, K2-141, is smaller than our own Sun, with just ~71% of the mass of our Sun. As a result, K2-141 is cooler than the Sun and – due to the difference in temperature – it appears to be orange, rather than the yellow of our Sun.

K2-141b

K2-141b orbits closer to its host star than KELT-3b or TOI-560c, or its neighbour K2-141c, with K2-141b orbiting at only 0.0075 au. Thus, the orbit of K2-141b is too close to be in its host star's habitable zone, so the planet is too hot for liquid water to exist.

Therefore, even though the exoplanet is known as a 'Super Earth' with some similar characteristics, K2-141b is far too hot for life as we know it to survive there, even for extremophile organisms. Its temperature is so hot that iron would melt on its surface!

K2-141c

K2-141c orbits closer to its host star than the Earth does to the Sun or TOI-560c does to its host star, but further away from the host star than its neighbouring exoplanet of K2-141b and further away from its host star than KELT-3b. Hence, K2-141c is also too hot for life as we know it to survive there.

What are exoplanets made of?

More information about the composition of an exoplanet can be found in section *Investigation 1 – Analysis of KELT-3b data*.

K2-141b

$$M_p^* = 4.97 M_{Earth} = 2.97 \times 10^{28}\ g$$

$$R_p^{**} = 1.51 R_{Earth} = 9.63 \times 10^{8}\ cm$$

$$V_p = \frac{4}{3}\ \pi\ {R_p}^3 = 3.74 \times 10^{27}\ cm^3$$

*Students can look up the mass of Earth online.

** This radius value was estimated from the transit depth calculation, students can also use the *allesfitter* best fit model value. The radius of the Earth can be found online.

Inserting these values into the equation results in:

$$\rho = \frac{M}{V} = 7.9\ g/cm^3$$

The Earth's average density is approximately 5.5 g/cm^3, which is close to the bulk composition of K2-141b– thus another reason why it is known as a 'Super Earth'.

Exoplanet scientists calculated the density of K2-141b to be 8.2 g/cm^3, with an uncertainty of ±1.1 g/cm^3. Hence, the value that we calculated is well within this value.

K2-141c

As discussed previously, the transit of exoplanet K2-141c is 'grazing'. This means that only part of the exoplanet crosses the disk of its host star as it transits. The size of the planet we determine from the transit depth alone is therefore a fraction of the true value. Hence, we will use the data for the radius from other observations made by exoplanet scientists (see casefile). Take note of the large uncertainties in the value of the radius observed by exoplanet scientists, which are due to the difficulty of fitting shallow and noisy transit light curves. Therefore, the bulk density will have a large uncertainty.

This is a good opportunity to explain to students that scientists sometimes do not have all the information necessary to come up with a conclusion or that, sometimes, scientists use data that other scientists discovered and that the sharing of information is key for scientific advancement.

Exoplanet scientists determined that the mass of K2-141c is $< 8.0\ M_{Earth}$. Therefore, the bulk density of K2-141c will be a maximum value and this calculation will use inequalities, which will provide an interesting challenge for your students as they may have not worked with inequalities yet.

$M_p^* < 8.0\ M_{Earth} \rightarrow\ M_p < 4.8 \times 10^{28}\ g$

$R_p^{**} = 7.0\ R_{Earth} = 4.5 \times 10^9\ cm$

$V_p = \frac{4}{3}\ \pi\ {R_p}^3 = 3.8 \times 10^{29}\ cm^3$

*Students can look up the mass of Earth online.
** The radius value is given in the casefile.

Inserting these values into the equation results in:

$$\rho = \frac{M}{V} \rightarrow \rho < 0.13\ g/cm^3$$

Therefore, the bulk density of K2-141c (because the mass is a maximum bound) is less than 0.13 g/cm^3. Even though the bulk density is less than 0.13 g/cm^3, the density of specific parts of the planet can be larger than this value. Bulk density is an average, therefore different parts of the exoplanet can have different density values (see Figure 7).

K2-141b and K2-141c summary

K2-141b is a 'Super Earth' and K2-141c is a Neptune-like exoplanet, both orbiting a small orange star called K2-141, approximately 200 light years away from Earth. K2-141 is smaller and cooler than our Sun.

K2-141b orbits very close to its host star, closer than Mercury orbits our own Sun, and even closer than KELT-3b and TOI-560c orbit their host stars. The exoplanet only needs approximately 7 hours to complete a full orbit around K2-141. K2-141c also orbits close to the host star, but 9 times further out than its neighbour K2-141b, so it takes approximately 7.7 days to complete a full orbit around the host star.

Due to its proximity to the host star, K2-141b's equilibrium temperature is high, far above the melting point of iron, making it completely uninhabitable for humans and Earth-based life. Neighbouring K2-141c is cooler – orbiting 9 times further away – but still too hot for humans or Earth-based life.

The bulk density or average density of K2-141b is the same order of magnitude to that of the bulk density of the Earth, which suggests that it is a rocky planet.

Table 4

Exoplanet	**K2-141b**	**K2-141c**
Type of planet	Super Earth	Neptune-like
Radius *(R_{Earth})*	1.5 (from allesfitter)	Not available in allesfitter
	1.6 (from transit depth)	7.0 (from literature)
Mass *(M_{Earth})*	4.97	< 8.0
Orbital period *(days)*	0.280	7.75
Mean orbital distance *(au)*	~0.0075	~0.068
Bulk density *(g/cm^3)*	~7.9	< 0.13
Equilibrium Temperature *(°C)*	~ 1830	~ 422

→ LINKS

Supporting resources

Hack an exoplanet:
hackanexoplanet.esa.int

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

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

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-3, TOI-560 and K2-141
exoplanetarchive.ipac.caltech.edu/overview/KELT-3
exoplanetarchive.ipac.caltech.edu/overview/TOI-560
exoplanetarchive.ipac.caltech.edu/overview/K2-141

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
hackanexoplanet.esa.int/meet-cheops

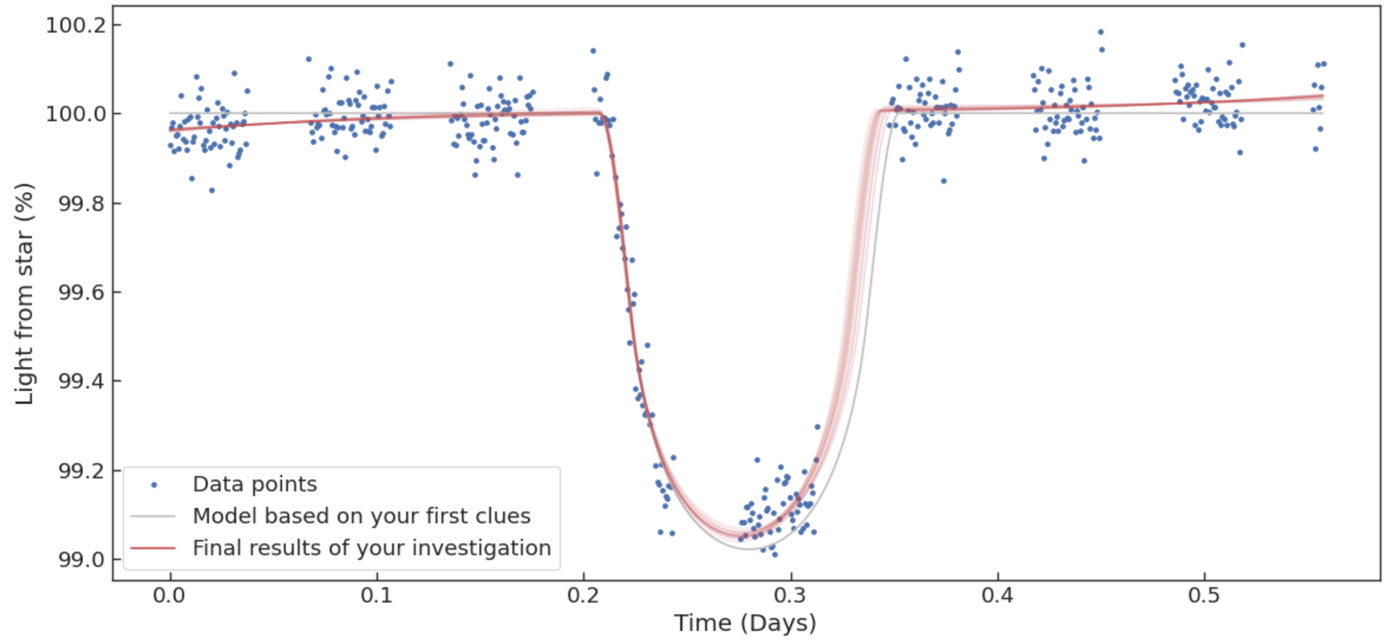
ESA space projects

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

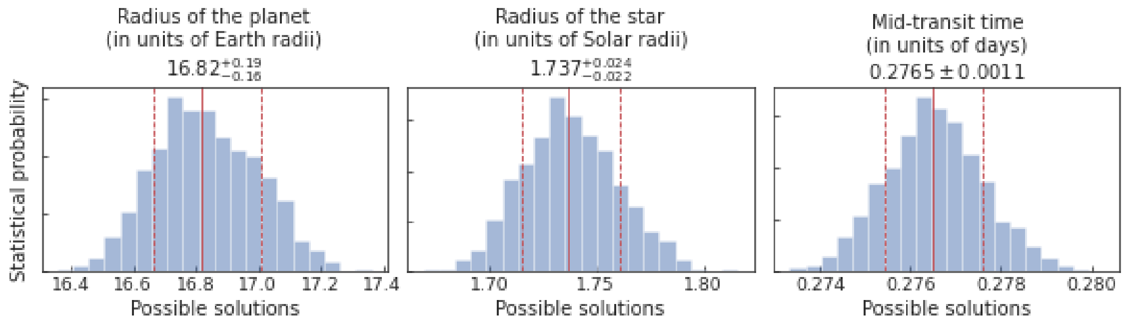
→ Appendix 1

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

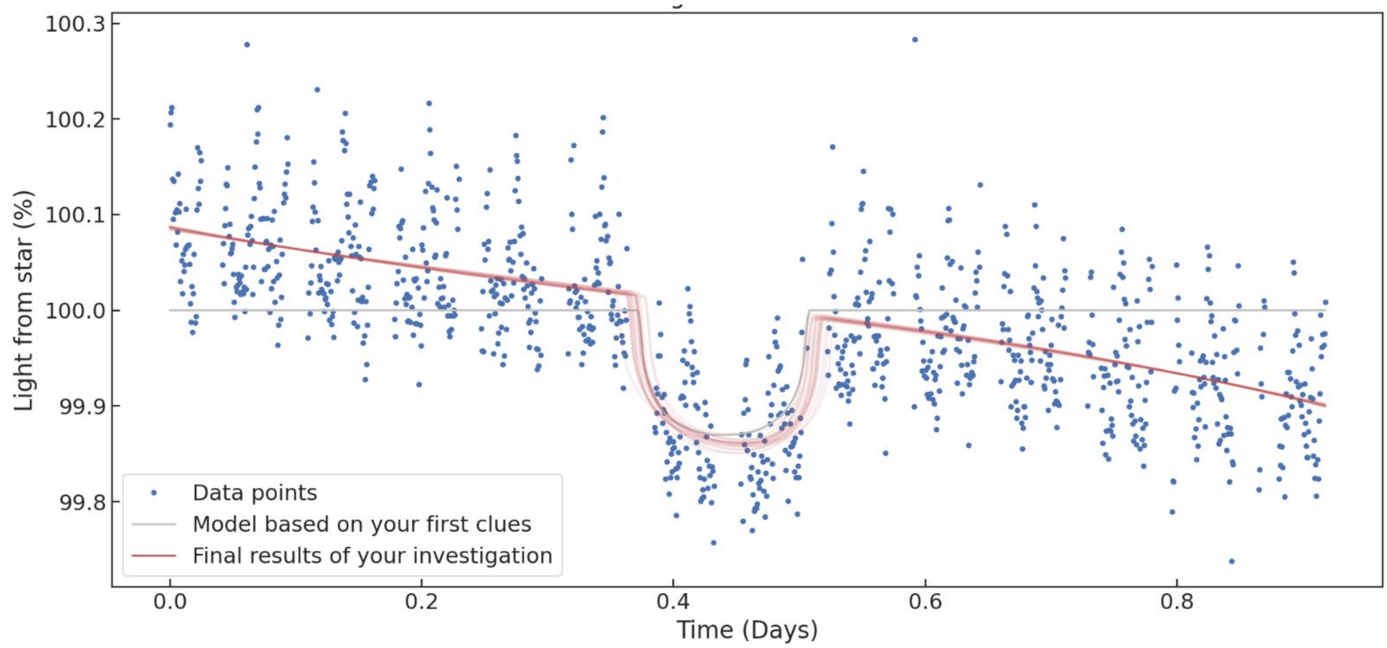
Name	Median value	Lower error	Upper error	Case note
Radius of the planet (in units of Earth radii)	16.82	0.16	0.19	Cheops observations
Radius of the star (in units of Solar radii)	1.737	0.022	0.024	Cheops observations
Mid-transit time (in units of days)	0.2765	0.0011	0.0011	Cheops observations
Orbital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

↑ Table with the best fit model parameters.

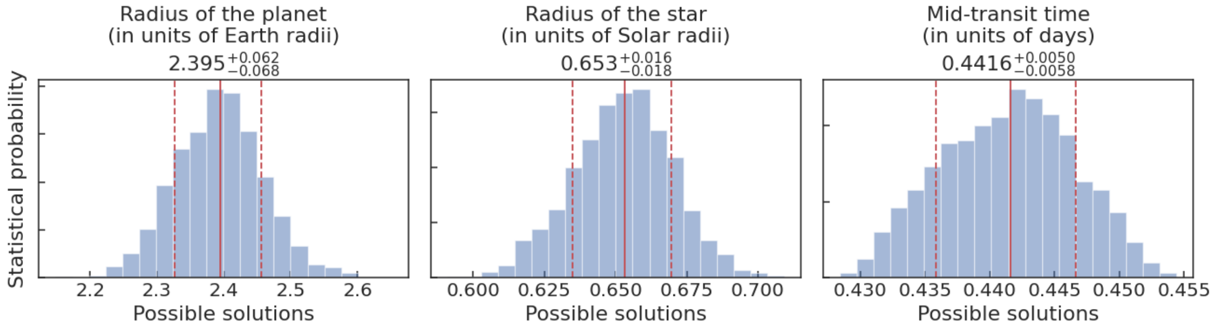
➔ Appendix 2

Transit light curve of the exoplanet TOI-560c

TOI-560c 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 TOI-560c

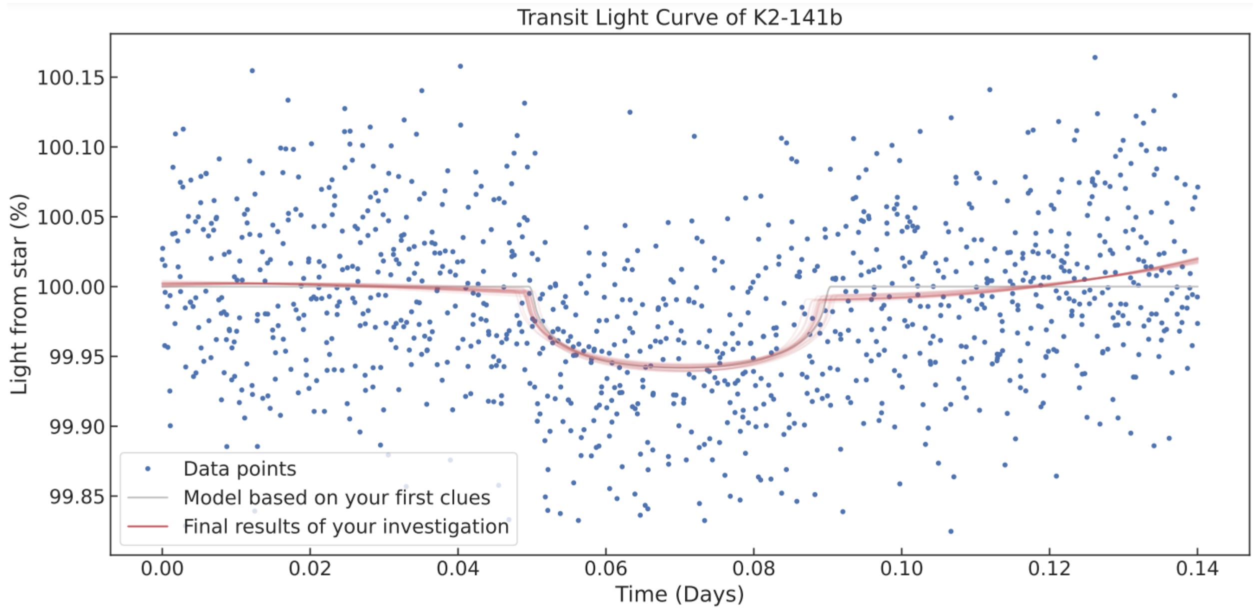
Name	Median value	Lower error	Upper error	Case note
Radius of the planet (in units of Earth radii)	2.395	0.068	0.062	Cheops observations
Radius of the star (in units of Solar radii)	0.653	0.018	0.016	Cheops observations
Mid-transit time (in units of days)	0.4416	0.0058	0.0050	Cheops observations
Orbital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

↑ Table with the best fit model parameters.

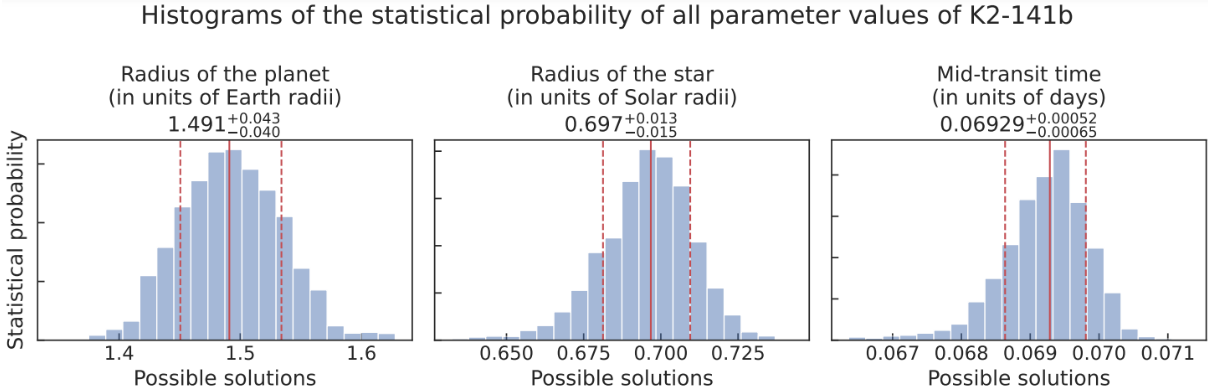
→ Appendix 3

Transit light curve of the exoplanet K2-141b

K2-141b 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 K2-141b

Name	Median value	Lower error	Upper error	Case note
Radius of the planet (in units of Earth radii)	1.491	0.040	0.043	Cheops observations
Radius of the star (in units of Solar radii)	0.697	0.015	0.013	Cheops observations
Mid-transit time (in units of days)	0.06929	0.00065	0.00052	Cheops observations
Orbital period (in units of days)	0.280325			Other observations from the archive
Distance (au)				

↑ Table with the best fit model parameters.

→ Appendix 4: Solar System planets information sheet

	Planet	Radius (R_{Earth})	Mass (M_{Earth})	Mean Orbital Distance (au)	Orbital Period (days)	Density (g/cm^3)	Mean Surface Temperature (°C)
Rocky	Mercury	0.383	0.055	0.39	88	5.43	167
	Venus	0.949	0.815	0.72	224.7	5.24	464
	Earth	1	1	1	365.25	5.51	15
	Mars	0.532	0.107	1.5	687	3.93	-65
Gas giant	Jupiter	11.21	317.8	5.2	4331	1.33	-110
	Saturn	9.45	95.2	9.6	10747	0.69	-140
	Uranus	4.01	14.5	19.2	30589	1.27	-195
	Neptune	3.88	17.1	30.2	59800	1.64	-200

→ Appendix 5: Overview of exoplanet data

Exoplanet	KELT-3b	TOI-560c	K2-141b	K2-141c
Type of planet	Hot Jupiter	Mini Neptune	Super Earth	Neptune-like
Radius (R_{Earth})	16.8 (from allesfitter)	2.4 (from allesfitter)	1.5 (from allesfitter)	Not available in allesfitter
	17.5 (from transit depth)	2.4 (from transit depth)	1.6 (from transit depth)	7.0 (Malavolta et al. 2018)
Mass (M_{Earth})	617	9.70	4.97	< 8.0
Orbital period *(days)*	2.70	18.9	0.280	7.75
Mean orbital distance *(au)*	0.048	0.13	0.0075	0.068
Bulk density *(g/cm³)*	0.63	3.9	7.9	< 0.13
Equilibrium Temperature *(°C)*	1543 (Pepper et al. 2013)	225 (Barragán et al. 2021)	~1830 (Bonomo et al. 2023)	~422 (Bonomo et al. 2023)