Discovering Alien Worlds

The discovery of an exoplanet

Orientation Phase

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

Exoplanets

You certainly know that our planet orbits a star, the Sun, and that there are other planets revolving around the Sun in our Solar System.

The Sun is a small star formed 4.5 billion years ago from the gravitational collapse of a molecular cloud. The leftovers formed a disc-shaped cloud of gas and dust surrounding the Sun, out of which the planets and other smaller bodies of the solar system were formed. How they formed is still not clear and we find different theories to explain how it happened.

In this short video, Professor Stephen Hawking explains how the Earth and solar system were formed:

https://www.youtube.com/watch?v=Uhy1fucSRQI

For a long time, scientists wondered if there were more planets around other stars. Would those stellar systems look like our solar system? Could there be life in planets outside the solar system? And how to find them? They are tiny objects too far away to capture with an image!

A major break-through came in 1992: the first exoplanet - a planet that orbits a star that is not our sun - was discovered around a very unexpected place: a neutron star. Aleksander Wolszczan and Dale Frail were the discoverers. Although the discovery was scientifically amazing, there was little hope of finding life in this system, so different from ours.

Finally, in 1995, the first exoplanet orbiting a star similar to our Sun was discovered!

The 2019 Nobel Prize of Physics was awarded to the scientists Michel Mayor and Didier Queloz for this discovery.

https://youtu.be/VC7Q2aSQktw

The first exoplanet, 51 Pegasi b, was a Jupiter-like gas giant orbiting its star closer than Mercury circles our sun. It made scientists review their theories about planet formation and migration - how could a gaseous planet survive so close to its star?

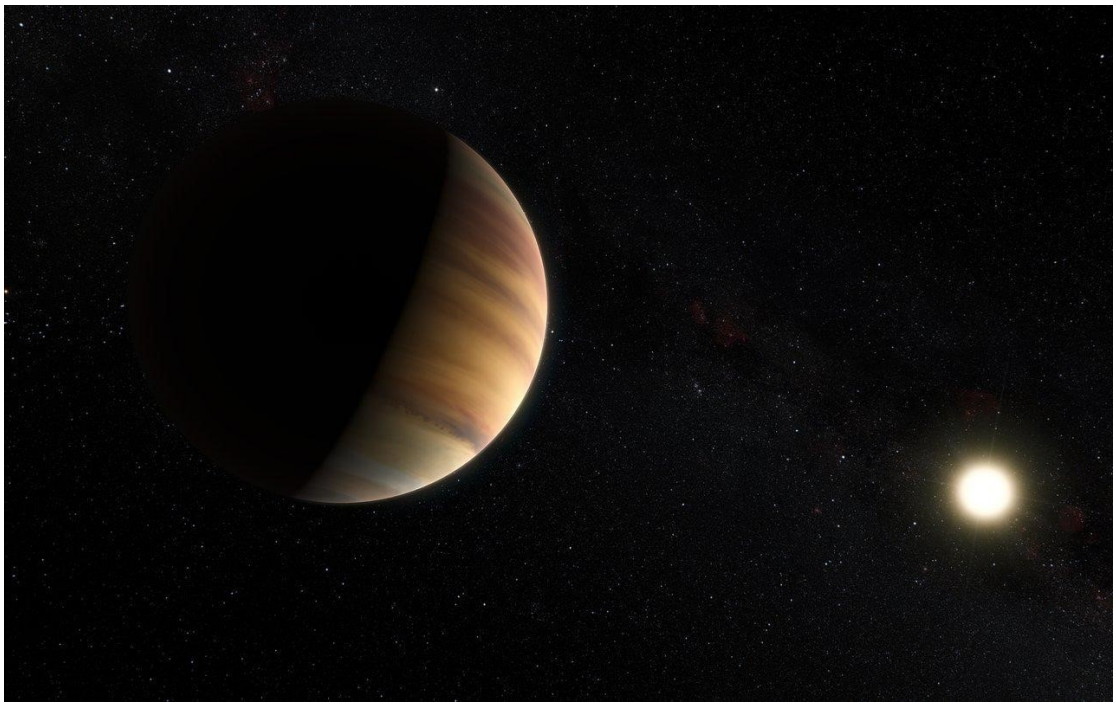


Fig. 1 This artist's view shows the hot Jupiter exoplanet 51 Pegasi b orbiting its star. Credits: ESO/M. Kornmesser/Nick Risinger (skysurvey.org).

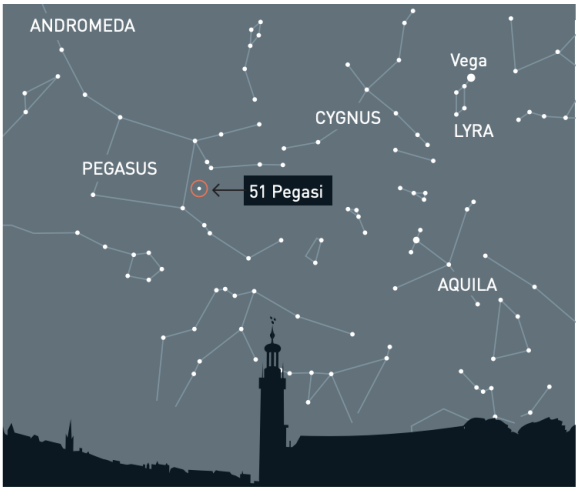


Fig. 2 The exoplanet 51 Pegasi b lies in the Pegasus constellation (The Winged Horse). Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences.

The hunt for more planets and eventually the discovery of life in the Universe beyond our planet got a whole new strength!

After the discovery of 51 Pegasi b, a series of new missions were launched trying to find more exoplanets similar to this one or preferably smaller. The discovery became a normal daily experience and presently, as of 2020, we know more than 4 000 planets orbiting other stars!

You can find updated information here: https://exoplanets.nasa.gov/ and http://www.exoplanet.eu/

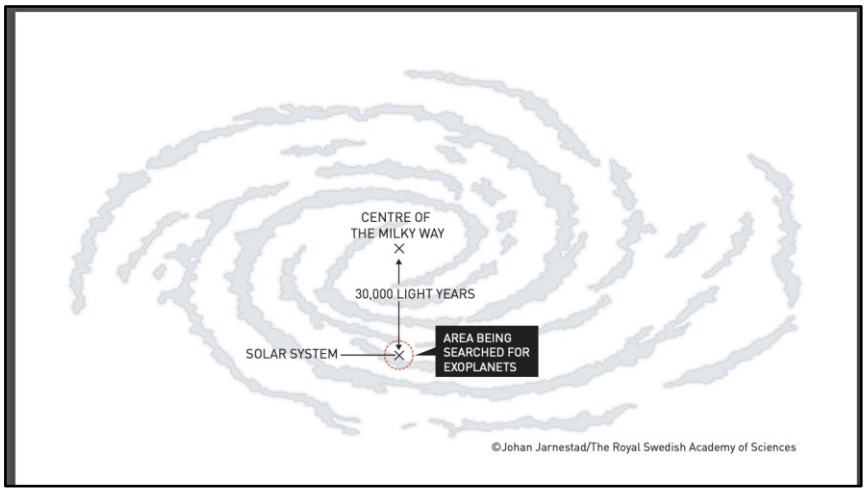


Fig. 3 The Sun is one of several hundred billion stars in our home galaxy, the Milky Way.

There should be planets orbiting most of those stars!

Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences.

The quest now is to find a planet with the conditions to harbor life and eventually some evidence of the existence of life like our own (so far, we have only discovered life on planet Earth!).

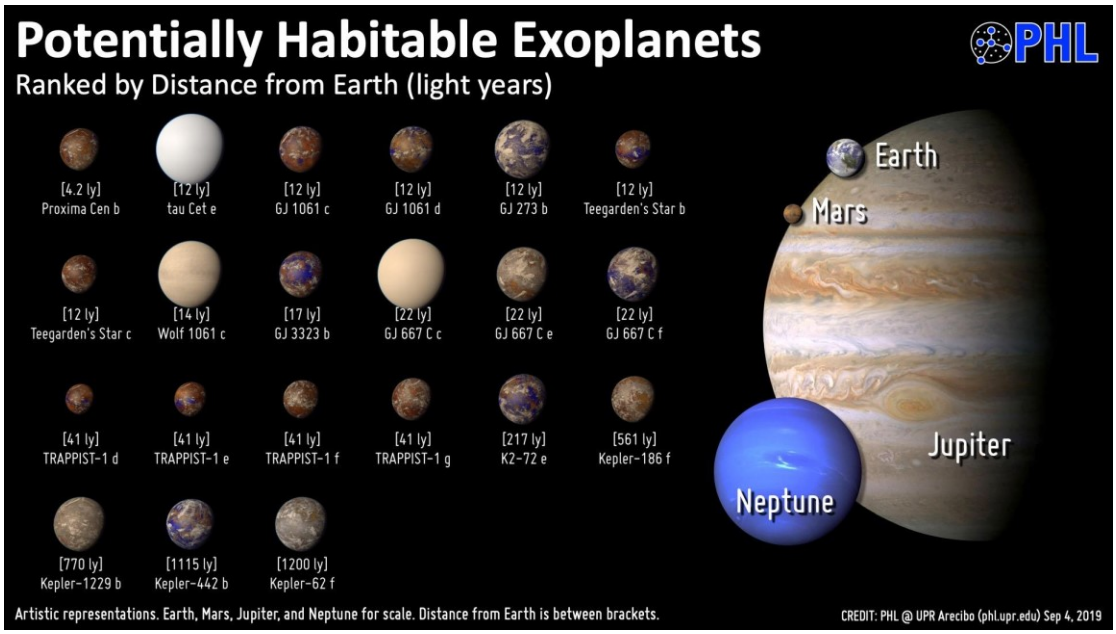


Fig. 4 This is a list of the exoplanets that are more likely to have a rocky composition and maintain surface liquid water

(i.e. 0.5 < Planet Radius ≤ 1.5 Earth radii or 0.1 < Planet Minimum Mass ≤ 5 Earth masses).

They are represented artistically in the above image.

Exploratory Phase

Question or Statement

Define goals and/or questions from current knowledge

How do we find exoplanets?

Exoplanets cannot be detected on images because they are very tiny and dim compared to their star. Astronomers need to be very creative to come up with different methods to find exoplanets. Their detection ends up relying on the effect exoplanets have on their parent star.

Watch this short video to get an idea of the different methods scientists have come up to discover exoplanets:

https://www.youtube.com/watch?v=EUU0-ZpFoK4

The first exoplanet was discovered by the radial velocity method. This method favours giant planets orbiting near the star, the so-called hot Jupiters (Jupiter because of their large masses, hot because of the close proximity to their parent star).

The most popular method is the transit method, but only applies to planets whose orbit takes them to pass in front of their star.

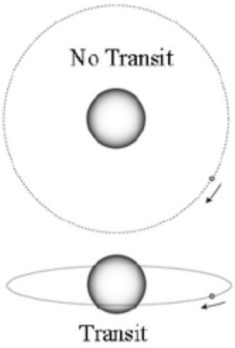


Fig. 5 Illustration of a planet not transiting and transiting its star.

It just depends on the line-of-sight of the observer.

Would you like to hunt an exoplanet?

In this lesson, you will have the opportunity to work with real observations of a portion of sky that contains an exoplanet that is transiting its star - HD 189733 b, discovered in 2007. You will study the system and learn how scientists handle data to discover exoplanets. And you will be able to estimate the diameter of the planet!

Curiosity: have you noticed that all exoplanets have a name and then a letter? Well, that is because their name is formed by taking the name of its parent star and adding a lowercase letter. The first planet discovered in a system is given the designation "b" (the parent star is considered to be "a") and later planets are given subsequent letters. If several planets in the same system are discovered at the same time, the closest one to the star gets the next letter, followed by the other planets in order of orbital size.

What can you say about the exoplanet that you are going to study, called HD 189733 b?

Generation of Hypothesis or Preliminary Explanations

Have you looked at the sky at night and noticed that not all stars shine equally? Well, astronomers measure the brightness of celestial bodies to learn about them.

Imagine a star on its own, and a star that has a transiting planet, like the pictures below.

Fig. 6 A star on its own.

Fig. 7 A star with a transiting planet.

Now imagine that you are an astronomer and you can measure the brightness of the stars in each situation. What would you expect to be the behaviour of the brightness as time passes?

With your colleagues, discuss:

- how would a graph of brightness vs. time look like in each situation?

The graph that depicts the variation of brightness with time, i.e. brightness vs. time, is called a **light curve.** And as you will see, it can be very useful!

Design/Model

Let's try to model the situation.

With your colleagues, think about:

- why does the light curve have this shape?
- if there were no planet transiting, what shape would the light curve have?
- how can scientists detect a transiting body?

Plan Investigation

Now that you understand planetary transits, let's study a real object. You will work with images taken with the NASA Spitzer Space Telescope. It is an infrared observatory launched to space in 2003.

The images show lots of stars. There are 3 brighter stars in the field and you will gather evidence to identify one of them that might have a transiting body. Remember that the planet is not visible, so you have to build light curves and analyse them to look for characteristics of the light curve of a star with a planet transiting.

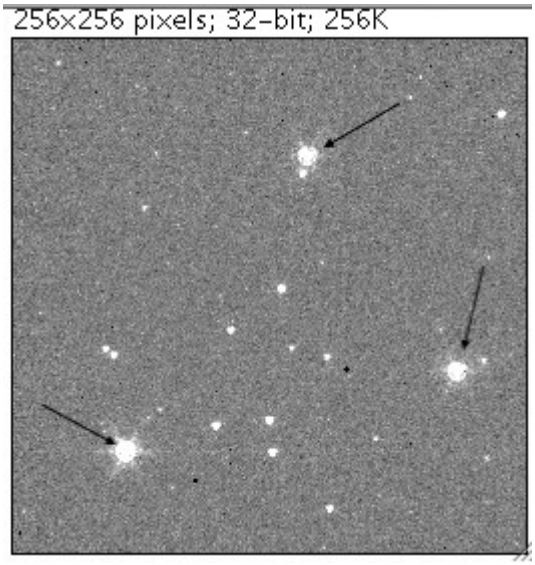


Fig. 7 Identification of the 3 stars you will study.

Download the different images you will analyse here. (link)

Let's get you familiarized with a software called Salsa J, an image processing software that will enable you to reproduce the light curve of this object.

Image Analysis - SalsaJ software

You can find SalsaJ here. Install it on your computer.

Measuring Brightness

The technique of measuring the brightness of objects is called photometry. It encompasses much more than just measuring the number of photons that reaches us from a certain object. If you want to know more, have a look at:

- **An introduction to photometry (link)**

Let's start our photometry!

- **Open SalsaJ**
- Use **(Open) to open an image, e.g.** ***SPITZER_I2_24538368_0000_0000_1_bcd.fits***
- **You can use** **and play with the brightness and contrast to be able to see better the image**
- The image can be zoomed in using the (**Magnifying glass**)
- Use (**Scrolling tool**) to select the region where the stars are. In general, they are at the centre of the image.

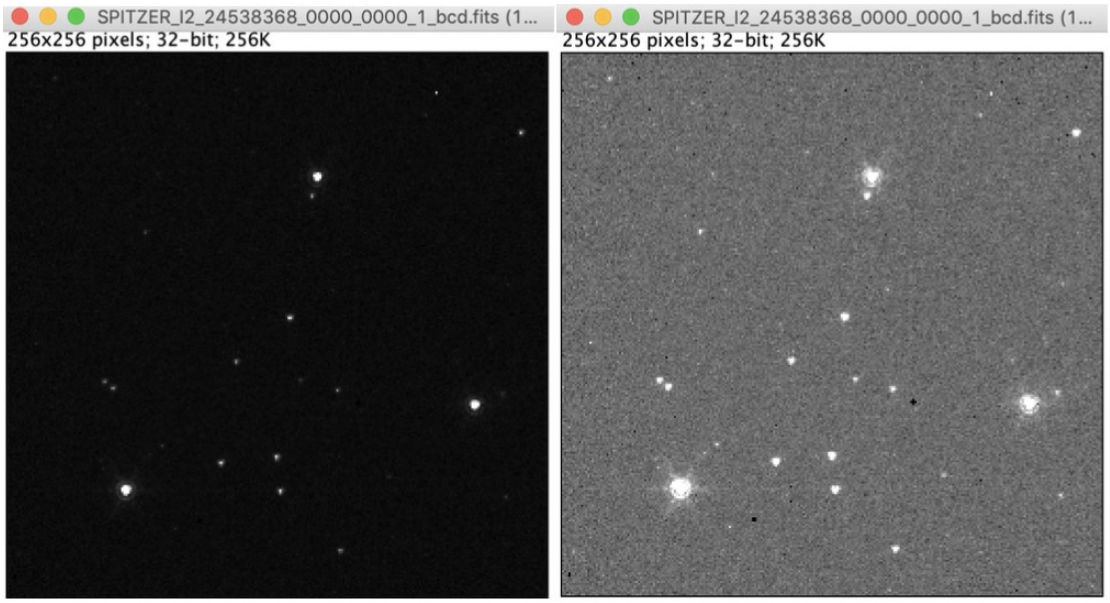
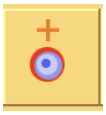
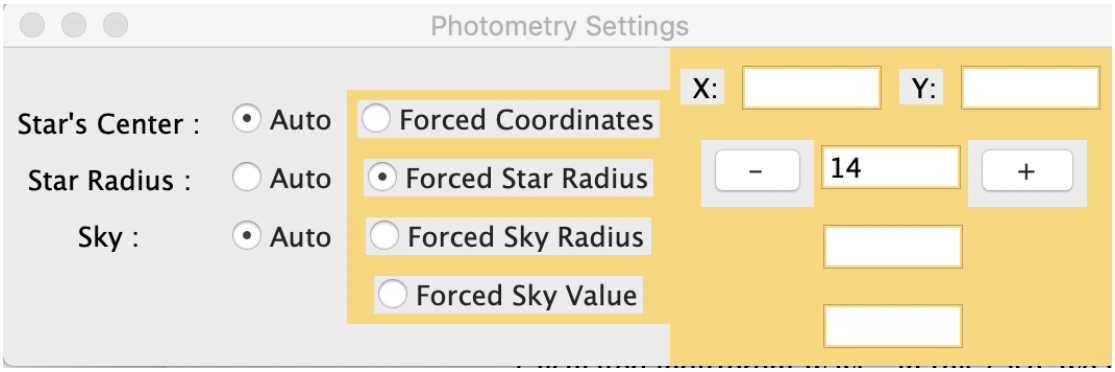


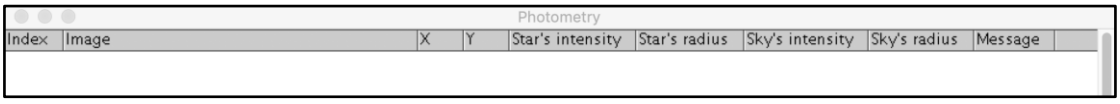
Fig 8 - One of the Spitzer images, showing the 3 bright stars you will study. On the left, the image when it was opened by SalsaJ, on the left, the same image after we used the Contrast/Brightness tool to better see the stars.

PHOTOMETRY All the stars, except our Sun, are very far away from us, thus they behave like light point sources. When their light hits the ccd, there is a characteristic response to the photons that arrived, and the light point source appears as a "blob" in the image: stars will occupy several pixels in the image. We can consider that the stars occupy a circle with a certain radius and it's the same radius for all stars in an image. The brightness of the star will be the sum of all the light in the pixels that are inside the circle of this radius, subtracting the contribution of the sky brightness. The sky brightness can be calculated in different ways - in this case, we will let the auto mode (it averages the sky value in an annulus with a radius 1.5 times the star radius).

- You need to define the photometry parameters. More specifically, the radius of the aperture that contains the light of each star.
- Open  (**Photometry Settings**) and force star radius to 14. This value has already been tested and works well for our purpose.



- You can now proceed to measure the brightness of each star by selecting (**Photometry**) and then clicking in each star.
- When you click for the first time, a box will appear.



- When you click on a star, a small yellow circle will appear around it as you can see below and the value of the measurement will appear in the box.
- You will be able to see all your measurements in the box. This will be very useful as you will need to copy these values to the spreadsheet given in this lesson.
- For one of the stars, these are the results you should obtain:

Index	Image	X	Y	Star's intensity	Star's radius	Sky's intensity	Sky's radius
5	SPITZER_I2_24538368_0400_0000_1_bcd.fits	146	58	33114	14	1	21
6	SPITZER_I2_24538368_0500_0000_1_bcd.fits	146	57	32976	14	1	21
7	SPITZER_I2_24538368_0600_0000_1_bcd.fits	146	58	33352	14	1	21
8	SPITZER_I2_24538368_0700_0000_1_bcd.fits	146	58	33572	14	1	21
9	SPITZER_I2_24538368_1100_0000_1_bcd.fits	146	57	32580	14	1	21
10	SPITZER_I2_24538368_1200_0000_1_bcd.fits	146	58	32549	14	0	21
11	SPITZER_I2_24538368_1300_0000_1_bcd.fits	146	57	32853	14	0	21

Perform Investigation

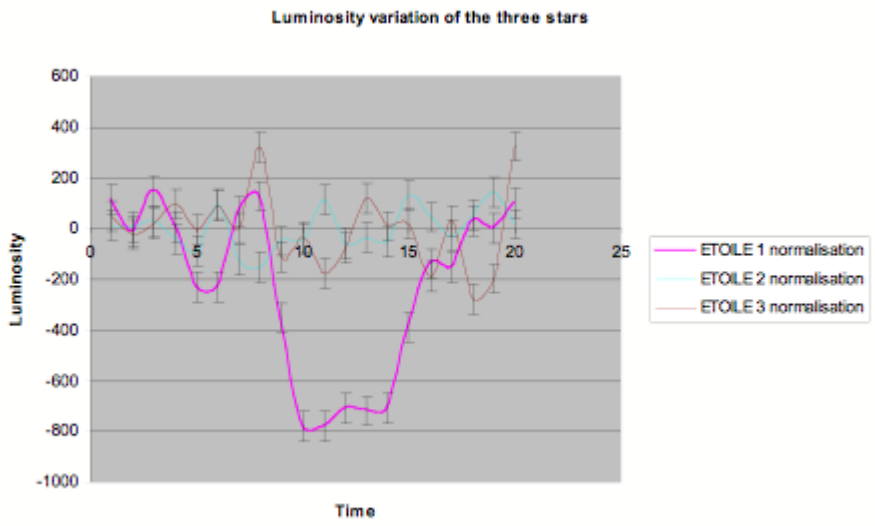
Now go ahead, do the photometry of the 3 bright stars on the 20 images!

Download this spreadsheet (link) and copy the photometry values of each star to the appropriate place. It is already prepared to build the light curves of the 3 stars!

Evidence

Finished doing the photometry? Look at the light curves of the 3 stars.

You should have a result similar to this one:



Analysis and Explanation

Analysis: Analyse evidence to discover a possible answer

With your colleagues, analyse the light curves and think about:

- of the three light curves, which one might have a transiting body? Write down your arguments.

During a transit we can define several "contacts", when the circumference of the planet coincides with the circumference of the star :

1) First contact: the planet is entirely outside the star, moving inward.

2) Second contact: the planet is partially inside the star, moving further inward.

3) Third contact: the planet is entirely inside the star, moving outward.

4) Fourth contact: the planet is entirely outside the star, moving outward.

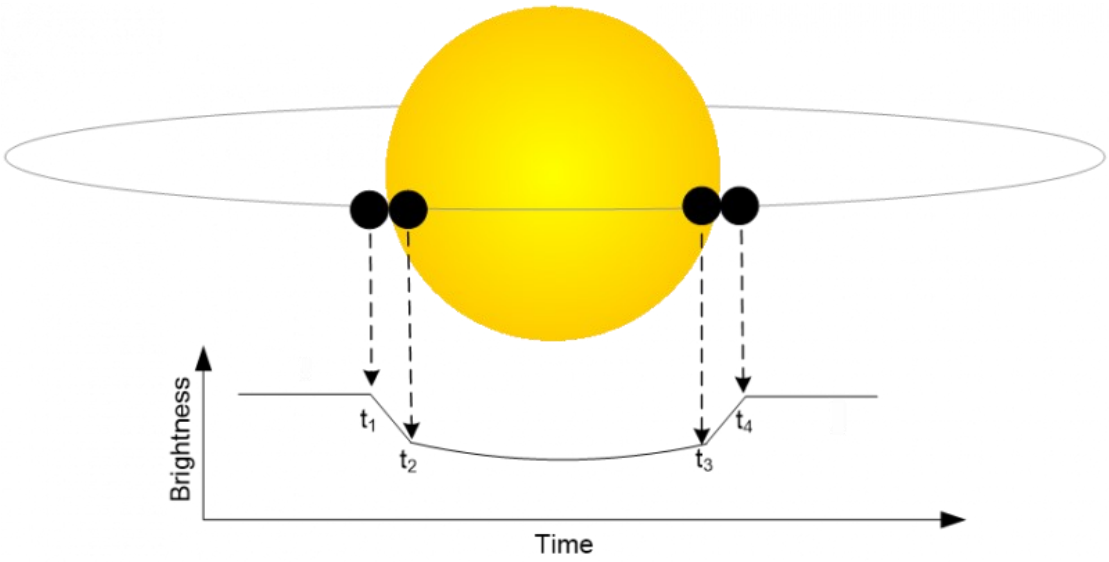


Fig 6 - Diagram of the four contacts that occur during a transit.

Looking at your data, let's deepen the analysis taking into account the "meaning" of the different instants of contact.

With your colleagues, <u>think about</u>:

- can you extract from your data the different t_i?
- what happens, physically, between instants t_1 and t_2?
- and between instants t_2 and t_4?
- what parameter does $(t_1 - t_2)/(t_2 - t_4)$ represent, assuming the transiting body has a constant speed?
- can you estimate the diameter of the transiting body with respect to the star's diameter?
- since the star is well known, you can find in the literature that its diameter has been calculated to be 0.788 (+/- 0.051) R_{sun}; can you estimate the diameter of the transiting body with respect to the Sun's diameter?
- compare the diameter of the transiting body with the Earth's diameter and speculate the nature of the transiting body;

- what relation would you expect between (t_1 - t_3) and (t_2 - t_4)?

Explanation: Formulate an explanation based on the analysis of your evidence

From the discussion with your colleagues, write about your findings:

- Do you think you detected a transiting body?
- Is it feasible that it is a planet?
- What other kind of object could it be?

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

As you know, this exoplanet has already been studied by astrophysicists. You can find the most reliable scientific data on The Extrasolar Planets Encyclopaedia (http://exoplanet.eu/).

With your colleagues, think about:

- How do your results compare with the ones published?
- Why do you think there are differences?
- What would you suggest that could be done to improve your knowledge of the planetary system?

Let's explore a simulation of a light curve during a planetary transit and how the different parameters influence the data you collect. The simulator lets you play with the parameters of the planet, of the star and the observing conditions. You can find it here:

https://astro.unl.edu/naap/esp/animations/transitSimulator.html

With your colleagues, use the simulator and think about:

- how does your findings compare with the data of this exoplanet?

- can you estimate the noise of your observations?
- what can you say about the system orientation?

Communicate

Communicate and justify your explanation

You can now gather all the data, analysis and results in a full report with all the steps of your investigation. Present and discuss your report with the rest of the classroom.

Well done! You are now an exoplanet hunter!

Reflect

Reflect on what you have learned from the learning process

Review your learning process while studying HD 189733 b:

- What are the main concepts that you have learned?
- Which competencies did you improve or acquire?
- How do you feel about the activity?
- What would you do differently?
- What would you like to know more about exoplanets?