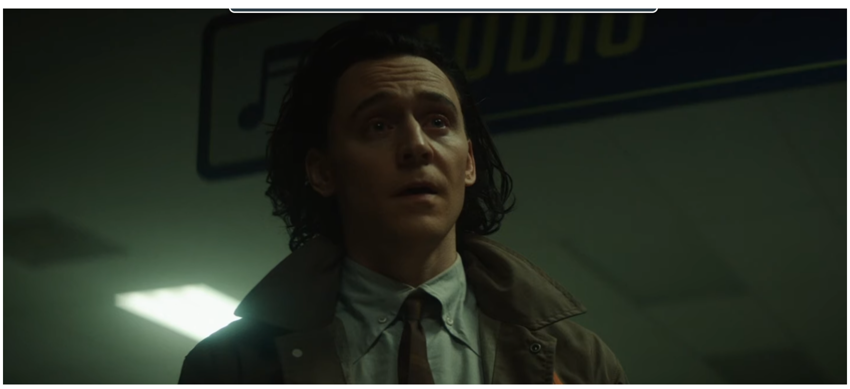
Exoplanets:
Detection methods and examples

Loki

Abstract

Assignment about exoplanets and detection methods, with examples.



1 Introduction

Planets that do not orbit the Sun but rather distant stars are called “extrasolar planets” or “exoplanets”. Although it has long been suspected that there must be numerous planetary systems other than our solar system, the first evidence of these celestial bodies was not found until 1995. In fact, the search for exoplanets poses enormous challenges for observational astronomy, mainly due to the enormous distances of these celestial bodies. The following tasks illustrate this.

1.1 Task 1

Distances and lengths in astronomy are often not given in meters but in light years (ly) or parsecs (pc). A parsec means: $1pc = 3.08568 \cdot 10^{13} km$.
a) Describe in words: What is a light year?
b) Calculate:
b1. How many kilometers is a light year?
(Usage: Speed of light c = 299792458 s , 1 year = 365.25 days)
b2. How many light years is a parsec? Explain the concept of parallax seconds, and find the equivalence between arcseconds, meters, and parsecs.
c) Below are some typical values for exoplanets.
Convert the data to parsecs, light years, and kilometers:
1. The distance of exoplanet HD-17156 b from Earth is 255 light years.
2. The distance of exoplanet Corot-10 b from Earth is 345 pc.
3. The distance of exoplanet Kepler-5 b from Earth is $3 \cdot 10^{16} km$.

1.2 Task 2

a) Suppose we observe the planet Jupiter from Earth when it is 600 million km away.
Calculate: How many times farther away from us is the exoplanet HD-17156 b than Jupiter?
b) Suppose further that we have reduced the scale of our solar system in a model so that Jupiter would be exactly one metre from Earth in the situation described above. Calculate: How far from Earth would the exoplanet HD-17156 b be in this model?
d) State the distance of the Voyager 1 and Voyager 2 probes from Earth currently in light-years. State the references used.

2 The transit method

If the orbit of an exoplanet is oriented in such a way that from Earth we look at the edge of the orbital plane, the total brightness of the central star will periodically decrease by a small amount. The planet will then move regularly in front of the star disk and darken it somewhat. From these brightness fluctuations, various conclusions can be drawn about the physical properties of the planet.

2.1 Task 3: Part 1

Fluctuations in the brightness of the star’s light can be recorded with the help of extremely sensitive telescopes and sensors if the star is observed for long enough. However, measurements with ground-based telescopes have the disadvantage that air movements in the atmosphere worsen the results. Therefore, most of the ”transit planets” were detected with the help of special satellites. Find out about the COROT, KEPLER and TESS satellites on the Internet and summarize their main features in your own words.

2.2 Simulating brightness curves

a) The online computer program `https://astro.unl.edu/naap/eng/animations/transitSimulator.html` will help you understand the origin and shape of typical brightness curves (transit curves). Go to the website https://astro.unl.edu/naap/eng/animations/transitSimulator.html and familiarize yourself with its functions.

b) Describe in words and drawings (or use clipboard diagrams) what influence the size of the exoplanet and its position relative to the star have on the brightness curve. Then investigate and explain to what extent the appearance of the planets is influenced by the brightness curve. of the star disk (darkening of the edges) changes the brightness curve.

c) The brightness curve of the star TrES-1 has a special feature. The drop in the curve occurred because, apparently, the planet passed through a sunspot (starspot) during its transit in front of the star disk. What other causes could cause this bump or peak in the valley of the decrease in the brightness curve?

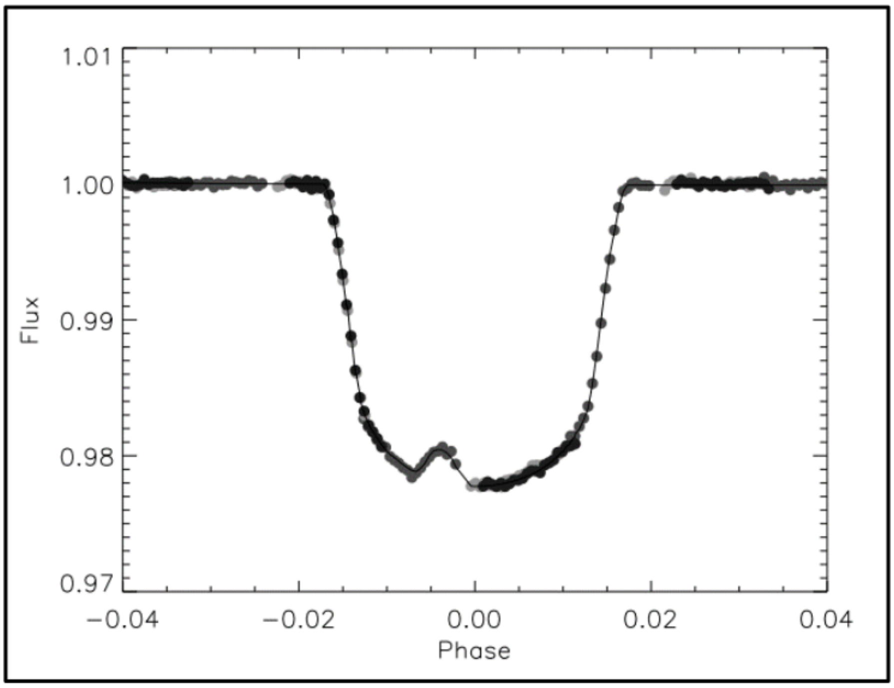


Fig. 1: Brightness curve of the star TrES-1.
Source https://arxiv.org/abs/0812.1799v1

Figure 1: Figure of a transit.

d) The depth of the brightness drop during a transit provides information about the diameter (or radius) of the exoplanet. The following applies: The loss of brightness corresponds to the ratio of the area of the planetary disk to the area of the stellar disk. That is,

$$\Delta H = \frac{A(planet)}{A(star)}$$

Using this and the formula for the area of a circle, derive the following formula for the radius of the exoplanet $r_P = r_* \cdot \sqrt{\Delta H}$. Remark: As can be seen from the formula, knowledge of the brightness drop-off alone is not enough. You also need the radius of the star. However, this is usually known from other research (e.g. the stellar spectrum).

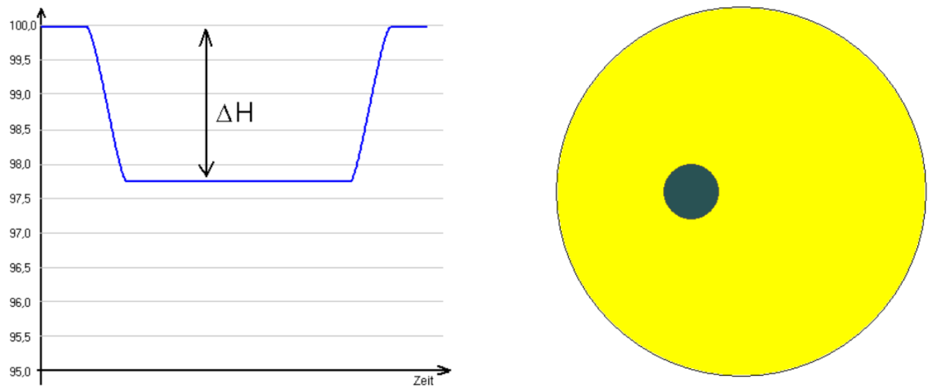


Fig. 2. Source: M. Borchardt

Figure 2: Figure 2. Source: M. Borchardt.

2.3 Task 3: Brightness curves of real exoplanets

In the appendix you will find the brightness curves of two exoplanets. With the help of these curves, determine the radii (or diameters) of these exoplanets. To help you, a step-by-step example is provided below. This is the light curve of the exoplanet Corot-1 b (Fig. 3):

Example:

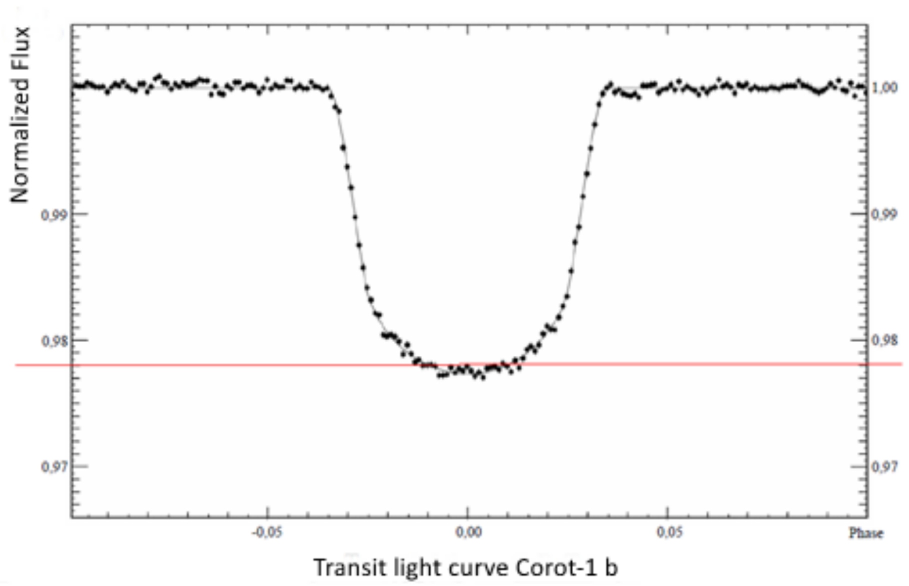


Fig. 3: Light curve of the exoplanet Corot-1b. Source: https://arxiv.org/pdf/0803.3202.pdf

Figure 3: Corot-1b: brightness curve. Reference: `https://arxiv.org/pdf/0803.3202.pdf`

First, a comment on the notation: in the natural sciences it is customary to indicate differences or discrepancies of a quantity with the Greek letter Δ. ΔH stands for the difference in brightness. The minimum of the curve is located at a brightness of approximately 0.978 (in percentage: 97.8%). The potential drop is therefore: $\Delta H = 1 - 0.978 = 0.022$ (corresponds to 2.2 %). From the spectral study of the star, it is known that it has a radius of $R(star) = 732267$ km. This gives the radius of the exoplanet:

$$r_P = r_* \sqrt{\Delta H} = 732267\ km \cdot \sqrt{0.022} = 108613\ km$$

It is common to compare the radius of an exoplanet with the radius of the planet Jupiter. We calculate

$$\frac{R_P}{R_J} = \frac{108613}{71492} = 1.52$$

The result is: $r_p/r_J = 1.52$. Our exoplanet is therefore approximately one and a half times the size of the planet Jupiter. Now determine, as shown above, the sizes of the exoplanets Kepler-5 b and Kepler-17 b (see material in the appendix). Find an appropriate simulator or a reference that shows such brightness curves, and capture the result of the simulations or the reference, indicating the program and/or reference used.

3 The radial velocity method

If the orbit of an exoplanet is oriented in such a way that we look from Earth at the edge or somewhat obliquely on the surface of the orbital plane, the planet sometimes moves towards us and sometimes away from us. However, we CANNOT observe this directly because we cannot see the planet due to the enormous distance. Look at the following figure (figure 4). Source: M. Borchardt:

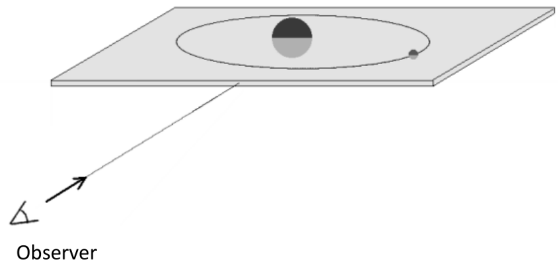


Figure 4: Doppler effect and radial velocity. Credits: M. Borchardt.

However, the motion of the planet produces a mirror motion of the star. Then, as the planet moves away from us, the star moves a little closer, and as the planet moves closer to us, the star moves away. Both bodies rotate around their common centre of gravity. To understand this, it is useful to imagine a bar with balls: The system will rotate around the centre of gravity of the two balls.

The speed at which the star approaches us and moves away from us is the so-called radial velocity. The radial velocity can be determined by spectrally splitting the light from the stars (for example, by sending it through a prism or a grating) and by closely observing the position of certain colours (spectral lines). The “Doppler effect” produces a shift in the colours of the light that we see according to figure 5 below: And depending on the star’s speed, we see some changes in the radial component of the speed. It is thus possible that we can perceive the presence of the planet indirectly without seeing it ourselves. The wobbling of light due to the Doppler effect marks the existence of an exoplanet. This technique was once also used with binary systems. Now we use it to see planets (smaller than stars in general).

3.1 Task 4

Research on the Internet what the Doppler effect does to sound and light, and summarize what we have seen in class. Highlight the essential aspects in your own words. It was already mentioned that the star’s speed is sometimes oriented towards us (negative), and sometimes away from us (positive). But how does it develop more precisely during a transit? The orbit around the center of gravity over time must be calculated with the help of the following task.

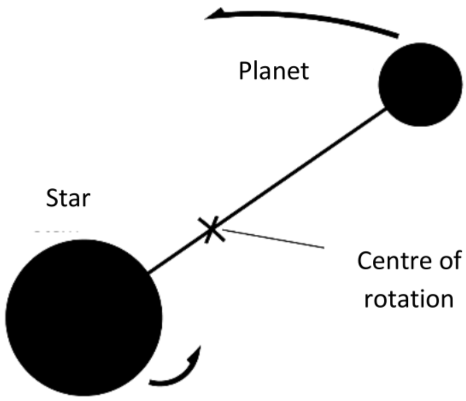
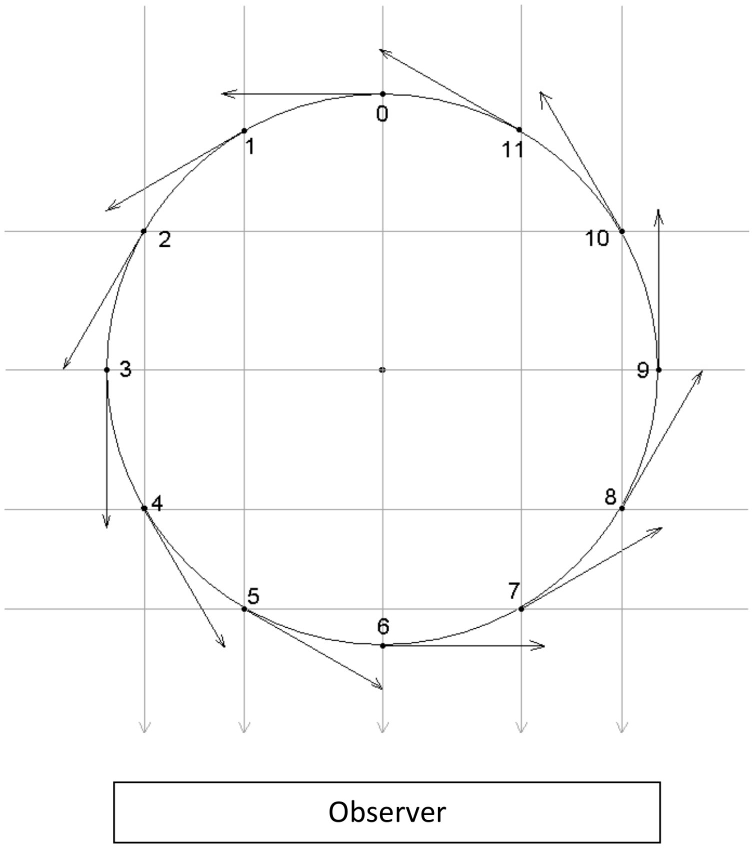


Fig. 2. Source: M. Borchardt

Figure 5: Doppler effect and radial velocity (II). Credits: M. Borchardt.

3.2 Task 5

Look at the illustration on the next page. We assume that the star moves in a perfectly circular orbit around its own centre of gravity. In doing so, it has the same orbital velocity at every point. In the drawing this is represented by arrows of equal length. We are interested in the radial and perpendicular components of each of these arrows in the direction of the observer. To do this, resolve the velocity into two perpendicular components. Plot each arrow into two components: one in the direction towards the observer and perpendicular to him. Measure the length of the first component with a set square, transfer the value to the table, and enter the values from the table in the diagram below. Draw a curve (not a straight line) through the points by eye. This gives you a typical curve of the star's radial velocities. You must print out the sheet and include the data that comes out of the printout, by hand-drawing the data, and the points in the attached graph (figures 6 and 7 below)



Time	Radial velocity (length of the arrow component to the observer)
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	

Figure 6: Origin of the radial velocity curve (I).

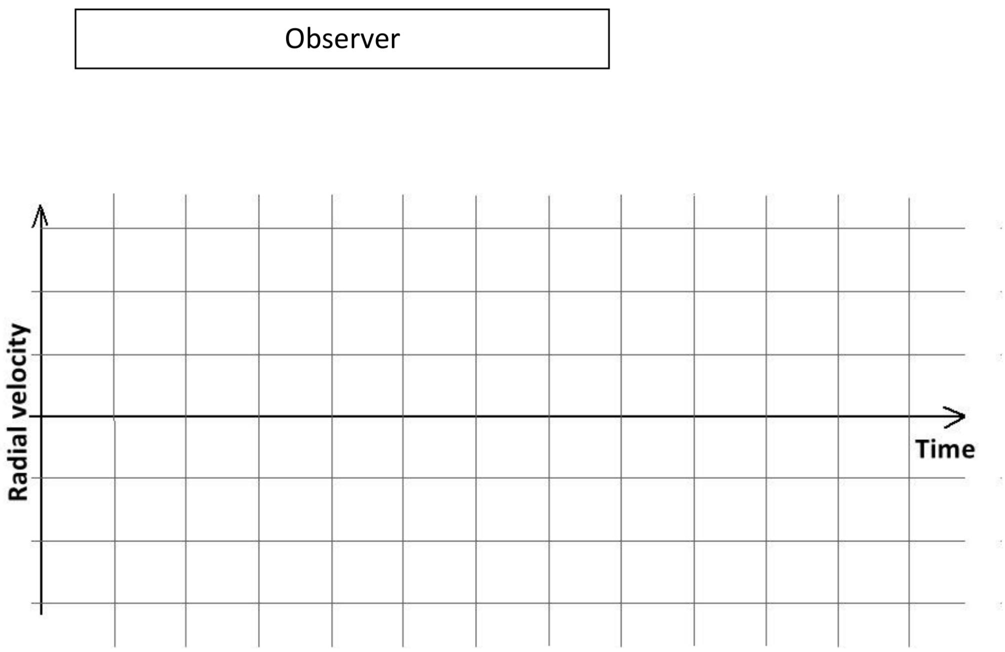


Figure 7: Origin of the radial velocity curve (II).

3.3 Task 6

Valuable information about the (invisible) exoplanet can be obtained from the radial velocity curve of the star. For example, it is easy to determine the orbital period of the planet. The shape of the planet's orbit (circular or elliptical) and the position of the ellipse relative to the observer can also be determined. Unfortunately, you cannot calculate the mass of the planet directly from the curve because the amplitude of the curve depends not only on the masses of the star and the planet, but also on the inclination of the orbital plane relative to the observer. With the help of the small computer program at the following URL: `https://astro.unl.edu/classaction/animations/extrasolarplanets/radialvelocitysimulator.html`

Open the program on the page with an internet browser, and let the exoplanet orbit around you. The simulation draws the radial velocity curve. Test the effects of different mass ratios on the amplitude of the curve. If you now change the inclination of the orbital plane, you should see that the amplitude changes as well. For this reason, you can usually only set a lower limit for the given mass. This would be the result if you were to look at the edge of the orbital plane (i.e. sideways in the rotating frame). For all other inclinations of the orbital plane, a higher mass must be assumed. By the way: If you choose an elliptical path instead of a circular one, you will notice that depending on the eccentricity and position of the ellipse, the radial velocity curve changes significantly. Actually, these curves provide important information about the shape and orientation of the elliptical path.

6A) Represent some exoplanet radial velocities available in the simulator. And highlight the mentioned effects. Include screenshots of each observation you make.

6B) Find the mathematical equation that relates radial velocity to phase or time, and indicate which variables it depends on in the general case. At least for one of the simulator examples, show that it is consistent with the simulated data and its real values.

4 51Peg-b

Discovery: In November 1995, the two Swiss astronomers Michel Mayor and Didier Queloz published measurement data they had made using the radial velocity method on a Sun-like star "51 Pegasi" about 50 light-years away. The assessment revealed that the star is orbited in an extremely narrow path by a planet that should be about the mass of Jupiter. This was the first exoplanet discovered around a solar-type star; many hundreds would follow in later years. For the first time, this was the detection of an exoplanet and the subsequent investigation of an exoplanet around a solar-type star, for which Mayor and Queloz were jointly awarded the 2019 Nobel Prize in Physics. The bottom diagram in the two scientists' publication shows the measured radial velocity. locations of the star "51 Pegasi" (51 Peg) and its exoplanet 51 Peg-b. The curve represents the best fit of the model to the stored data.

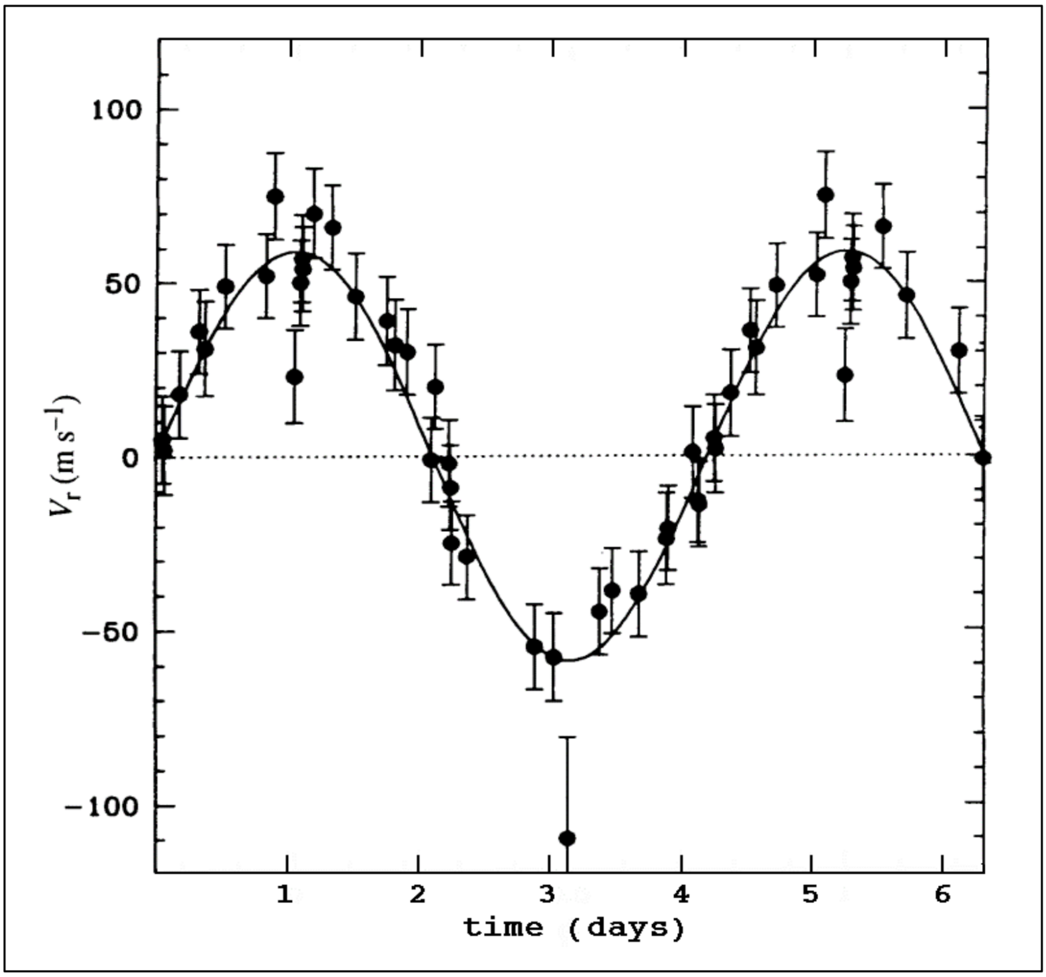


Figure 1. Radial velocities of the star "51 Pegasi". Source: https://web.pa.msu.edu/courses/2011spring/AST208/mayorQueloz.pdf

Figure 8: 51 Peg-b. Radial velocity curve. `https://web.pa.msu.edu/courses/2011spring/AST208/mayorQueloz.pdf`

4.1 Assignment 7

a) Determine the period of the exoplanet 51 Peg-b from the given radial velocity curve. (Alternatively, find the data and explain how to obtain the period from the raw data.)

4.2 Task 8

b) For circular orbits, the following formula gives the mass of the exoplanet:

$$m_P = \sqrt[3]{\frac{T_P \cdot M_s^2}{2\pi G}} v_r$$

The formula applies to the situation where the observer is looking at the edge of the plane of planetary motion. Explain where this formula is obtained from, and how to determine the minimum value for the mass of the planet. Why can we not infer the exact value but only a minimum bound on the mass of the exoplanet?

The mass of the central star can be determined by spectroscopic measurements, and for 51 Peg it is $M_S = 2.21 \cdot 10^{30} kg$. The universal gravitational constant is $G = 6.674 \cdot 10^{-11} m^3/(s^2 \cdot kg)$. T is the orbital period from part a). Use the value 4.23 days. Determine the value of the radial velocity v_r from the diagram, and calculate the mass of the exoplanet from your period, mass of 51 Peg (star), and value of the radial velocity. State the sources of error for your estimate of the mass of the exoplanet.

4.3 Task 9

Exoplanet masses are occasionally given in multiples of the mass of Earth or the mass of Jupiter. Note that $M_T = M_\oplus = 5.97 \cdot 10^{24} kg$ and $M_J = 1.898 \cdot 10^{27} kg$. Give the value of the mass of 51 Peg-b in terms of the mass of Jupiter and the mass of Earth, obtained from YOUR DATA (the data for this lab). State the calculations you have performed.

4.4 Task 10

A) The extremely short orbital period of the planet (4.26 days) indicates a small distance from the exoplanet to the star. Calculate the distance and express it in meters, km and astronomical units. Use Kepler's third law:

$$R^3 = \frac{G(M_S + m_P)}{4\pi^2} T^2$$

B) Comment on the conditions that would allow life as we know it to exist on the exoplanet 51 Peg b. Indicate whether these conditions would be possible in the examples of Kepler-5b and Kepler-17b, the other examples of this practice or learning situation. What would happen with these conditions in the recently studied system `https://en.wikipedia.org/wiki/82_G._Eridani`? And with Gliese 12-b and Kepler 62-f?

A Brightness curves of two exoplanets

Below are the figures of the light curves or brightness of Kepler-5 and Kepler 17:

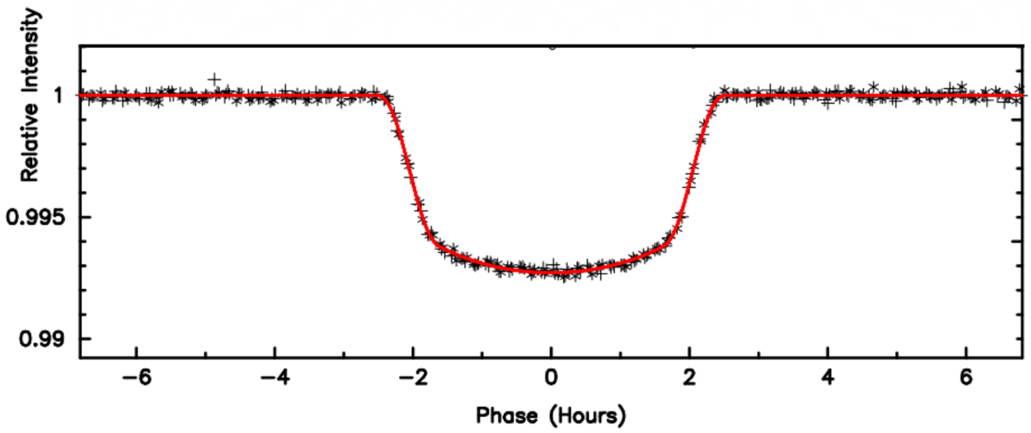


Fig. 4: Light curve of the star Kepler-5. Source: https://arxiv.org/abs/1001.0913v1

Radius of the star Kepler-5: $r_{Star} = 1{,}248{,}541\ km$

Figure 9: Kepler-5 brightness curve. Reference: `https://arxiv.org/abs/1001.0913v1`

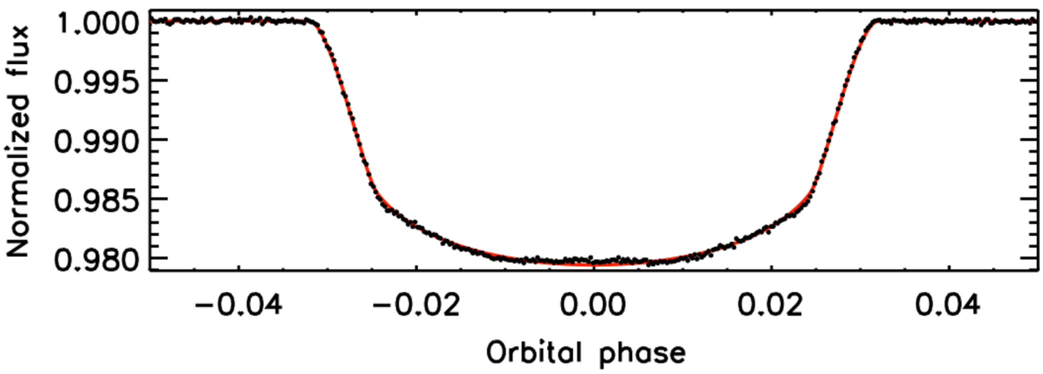


Fig. 5: Light curve of the star Kepler-17. Source: https://arxiv.org/abs/1107.5750v2

Radius of the star Kepler-17: $r_{Star} = 731{,}160\ km$

Figure 10: Kepler-17 brightness curve. Reference: `https://arxiv.org/abs/1107.5750v2`