

Extrasolar planets – an evaluation of the transit method

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Abstract

The search for extrasolar planets with the transit method became a successful science with the first discovery in 1999. The method is used to produce light curves, which are then studied in search for changes in amount of brightness (transits) of the star.

By using data from Kepler spacecraft, this study explains the science behind extrasolar planets' research. The data used in the report are four graphs 1, 2, 3 and 4 which are analyzed. In conclusion light curve one signifies a planetary occultation, which seems to be periodical and perpetual. Light curve two possibly shows transits from a planet or an eclipsing binary system, similar to planetary transits, with significant differences such as the existence of two distinguished transits from each star component. Likewise, there are actual changes in brightness depending on the stars fusion processes, the term for these occurrences is "variable". Light curve three probably shows an irregular variable. Besides variables there are star spots which cause non-periodical transits. Light curve four perhaps demonstrates star spots, since the transits increase in depth and are not entirely periodical, or maybe a Mira variable. After executed comparison with confirmed light curves, it can be written that all four light curves represent their characters quite truthfully.

Besides the analysis briefly mentioned above, mathematical operations have been used on light curve one in order to find out the characteristics and nature of the candidate extrasolar planet. The nature of the planet has been estimated to be a Hot Jupiter, more massive than Jupiter with a surface temperature at 859K and orbital velocity of 110km/s. This candidate planet can be confirmed with another method.

Keywords

Transit method, solar system, extra-solar planets, star, light curve, ETI, Kepler- and K2, light spectrum, Doppler method, Kepler's law of planetary motion, Planethunters, binary systems, variables, multi planetary systems, star spots.

1. Introduction

The purpose of this work is to introduce, explain and evaluate a method applied to the search of extrasolar planets. The evaluation is based on the analysis of four graphs and mathematical equations used to determine characteristic features of the candidate planet introduced by light curve one. This also for the sake of illuminating the usage of the method described below.

It is indeed challenging to find planets that existed in the past or exists in the presence. This due to restrictions of the methods, technology and lack of enough knowledge. Nevertheless, the search for extrasolar planets is current and a significant part of astronomy.

1.1. Question formulation

How are extrasolar planets found, by the transit method?

What characteristics of a planet can be found, by using the transit method?

2. Background

Many years ago humanity only knew of the solar system in which the planet Earth is located. In the 20:th century, prove supporting the existence of other planets somewhere else in the universe was found. The well-known planets Mercury, Venus, Earth, Mars, Jupiter, Saturn, Neptune and Uranus have never been alone in the universe!

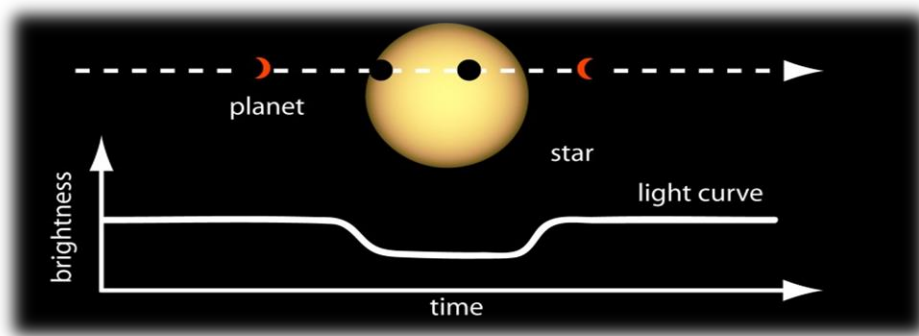
From the planet called earth humans used technology, to capture the light from faraway and view into the past, in search for planets other than earth. From this moment onwards many methods and instruments were created in order to be used for detection of stellar systems with planets.

2.1. Transit Method

By observing the only source close enough to understand in detail (the solar system of the sun) it has been possible to work out methods for the study of other parts of the universe. These have been and are always being tested in order to verify advantages, disadvantages and to initiate improvements. According to NASA/GSFC (2002); Populär Astronomi (2012) such an example is the studies done on the Venus passage, these studies have been used to advance the transit method. For example it was shown how much light a Venus sized planet blocks out and how well the instruments used for the transit method really work. Additionally, improvements have been made which have resulted in better technic, which makes it possible to detect planets which block down to 20ppm of a stars brightness.

One common method that has come to see the light of stars is the transit method. The main approach of the method is to find extrasolar planets of different forms by observing the amount of light of distant stars. This same method can also be used to confirm a candidate planet discovered by other methods. Additionally, the underlying intent is to find earth-like planets which can support life similar to that on earth. This research then indirectly makes it possible to take a step forward in the search for extraterrestrial intelligence (ETI).

This occultation method got its name from the way the curve declines over time in periodical or non-periodical patterns (Catling, 2014, p.154). These dips are called transits, thereby the name transit method. The curves are called light curves, because they signify the amount of starlight from the observed star. According to Perryman (2000); Couper & Henbest (1999); Linde (2013, p.110) the first extrasolar planet detected by using the transit method was proclaimed in 1999. Moreover, the transit method has not only helped to find many planets around a star over the years since 1999, but also whole planetary systems.



Picture 1: Here is a demonstration of a transit seen on a light curve (Wikimedia commons, 2012).

A transit from planetary systems of one or more planets occur gradually when a celestial body moves in front of the star from which brightness is measured by a photometer located in the telescope. A transit commences when the planet reaches the outer edge of the star and concludes when the planet has reached the opposite outer edge. The width and the time the transit is seen in the graph, is determined by the size and the velocity of the object. For a transit to be visible the star must be observed in straight forward or edge on angle and the orbit of the planet needs to have an inclination shortly under 90° (Zoonivers teams, 2014, p.62&68; Conway & Gilmour & Jones & Rothery & Sephton & Zarnecki, 2003, p.211-212; Pålsgård & Kvist & Nilson, 2011, p.311-312).

The above mentioned approach is an indirect procedure, which requires a photometer, which is programed to measure light from the host star. After time periods of 30-31days all the data

gather during those days are converted into a light curve, before continues observation. The light curves are analyzed in the search for transits, which may indicate an orbiting planet or perhaps an orbiting star companion (Conway& Gilmour& Jones& Rothery& Sephton& Zarnecki, 2003, p.213-214; Moore& May& Lintott, 2009, p.107; Catling, 2014, p.154). Distinguishing planets from other possible occurrences and objects is demanding but not impossible with time.

In order to be able to tell if the light curve shows a candidate extrasolar planet or not, it is vital to know how a planet moves. As for a start it is known, since Kepler published his laws of planetary movement, that planets have more or less elliptical courses with the star on one focus point, around their host stars which they complete during a period of time (Ölme, 2003, p.102). This time is called orbital period and is proportional to the speed of the planet, the longer orbital period the lower the orbital velocity will be. The course is the same for every comprehensive round the planet takes and it is known as a year, (an Earth year is 365,45 days). A “year” depends on the length of the orbit as well as the velocity of the planet. Additionally, planets closer to stars move faster than those further away, due to stronger gravity pull from the star (Rickman, NE, 2015). Moreover, by studying the formula for orbital velocity;

$$v = \sqrt{GM/r}$$

The formula is adapted from Newton’s universal law of gravitation. One can see how orbital velocity increases while the radius of the orbital path decreases, no matter the mass of the object (Pålsgård& Kvist& Nilsson, 2012, p.215). Due to the orbital period the transits caused by a passing planet come in regular and perpetual patterns with the same interval in time between each dip.

There are variations of orbital period. Some planets have longer orbits and therefore longer orbital periods. Because of the existence of different lengths of orbital periods, it is important to collect data for a long time in order to identify small and slow planets further away from the host star. By assembling data over a longer time, which results in more visible transits on a light curve, it makes it easier to confirm if what the light curve designates is indeed a planet, not another object in space or merely a macula on the star itself.

As it is explained in Lagerkvist& Olofsson (2007); Astronomica (2012, p.35) star spots come in groups and in cycles of time, they appear on the south and north, seen from the equator. As the time passes star spots multiply and move closer to the equator (Pålsgård& Kvist& Nilson, 2011, p.312). A way to exclude this error is to observe the star for a long time. This way it

will be visible when the pattern is interrupted. The pattern will be broken if the macula has finished its cycle or if it has moved out of the range in which the telescope observed the star.

As mentioned above a macula can disappear and reappear. However, planets do not vanish from their orbit without a trace or a caveat, except if it is a free planet passing the star, but those are rare and not yet accurately proven.

All work around extra solar planets is fairly new and current. At present time the transit method is moderate for detecting planets of smaller sizes which are normally difficult to identify due to the strongly ablaze host stars. Furthermore, this system does not only uncover planets around other stars, it can also be combined with different mathematic operations and some information about the host star to reveal factors and properties of the planets. It is achievable to calculate such as radius, average mass, orbital velocity, orbital time, semi-major axis (distance to the host star), density, volume and outer temperature. To be able to premeditate all the aforementioned physiology of the planet there must be at least three transits observable on the obtained light curve.

Despite the wide usage, the method has its limits, for example observation can only be done in an angle that makes it achievable to see the orbit of the celestial body. If the orbit does not cross the observers' sight then it will not be seen. Due to this restriction the very beneficial transit method becomes less functional when it comes to detecting a wide range of various planets in different distances. Therefore, it is understandable why the transit method is not enough for the search in total. However, steady research with suitable space telescopes and long observation can distinguish orbiting planets of smaller sizes from other phenomena. Moreover, the transit method has an advantage to be able to view many stars over a big area of the universe at the same time. In other times, methods of another nature such as radial velocity and gravitational microlensing can be used to complete each other. Within science it is vital to have more than one technique to use, especially in this case, for the reason that it is impossible to say for sure if what has been discovered is a planet. Hence, it can undoubtedly be a planet if at least two different procedures give the same result (Zoonivers teams, 2014, p.55-56).

2.2. Extrasolar planets missions

NASA teams planned the so called Kepler mission in order to make it possible to observe stars from outer space and search for planets. This was crucial because outside of earth there is no atmosphere to interrupt with the measurements. In the end the proposal was finally approved in 2001 and the Kepler spacecraft was launched in Mars 2009 to fulfill its duty. The aim was to search for extrasolar planets and soon focus on finding earth-like planets which may be homes to alien life (Linde, 2013, p.101-104; NASA, 2015).

Today Kepler is the dominate craft used to find extrasolar planets, it can detect light decreases down to 20ppm. Kepler is also the successor of Spitzer space telescope of 2003 (NASA,2015). There are over 4696 candidate and 1031 confirmed planets done by Kepler (NASA,2015).

In 2013 Kepler faced a failure which had to be repaired with the K2 mission, which became possible thanks to developments in technology. In other words Kepler spacecraft of 2009 has now become K2. The improvements of the craft have also contributed to more precise and wide observation of not only extrasolar planets but also galaxies and such (NASA, 2015; Planethunters, 2014). Notice that the focus of this report is not the telescope or its technological functions. Therefore, more information on how K2 works and more can be found on NASA's website listed under references.

Although focus lies on the Kepler mission, since the light curves used in this report come from the Kepler spacecraft, it is necessary to mention other missions, which also base their search of extrasolar planets on the transit method. One of them is the mission of the spacecraft CoRoT maintained by ESA (the European space agency), launched 2006 (ESA, CoRoT), which shortly said detects planets the same way as Kepler, with a photometer and by using the beneficial transit method.

2.3. Planethunters

All the four light curves analyzed in this scientific report originate from the website planethunters.org, which is a citizen science project from Zooniverse, which both are maintained by NASA. In order to use the site, receive credit and be kept up to date about a star or a planet, a sign up is required. This internet page is meant to let civilians help scientists at identifying light curves which indicate potential extrasolar planets or anything extraordinary (Planethunters, 2014). The light curves correspond to data collected by the Kepler spacecraft.

Planethunters is moderated by people from Yale, Harvard, Oxford University and NASA. On Planethunters moderators upload thousands of light curves in 30-days interval-graphs. Graphs from studies of the same stars can be found after they have been assembled and uploaded. In that way new data received from Kepler is uploaded all the time and people can study the same star for a long time (Zoonivers teams, 2014, p.76).

NASA has developed yet another project useful for this work; “Planetquest makeover”. On NASA’s website it is possible to insert information about a star and its planet to get a simplified model of a system. The model can then be downloaded to a computer hard disk as a picture. A model of the planet and star represented on light curve one can be found in chapter 4, as a way to clarify the work with light curve one.

In the case of extrasolar planet study, models have proven to be necessary since it is, as for today, impossible to visit extrasolar planets and examine them up close. By using and creating models one can reveal and eliminate misconceptions.

3. Method

How the transit method works and how it is used has been explained in chapter two. In this section you can find all the mathematical equations used to calculate the properties of the candidate planet which is indicated by the first light curve (see chapter 4, p.13). As abovementioned a number of factors about the candidate extrasolar planet can be calculated by using mathematical equations and necessary information about the host star. Those factors are radius, approximate mass, orbital velocity, orbital time, distance to the host star, density, volume and outer temperature. All the values in this report are roughly estimated from the information found on the Planethunters internet page and mathematics. By using another method and repeating measurements the properties can be assured carefully. All mathematical equations and explanations follow below.

3.1. Orbital period

This is the period of time it takes for the planet to make a full circulation around its star. On the first graph the light curve has three transits these occur in equal time intervals. Therefore, by enumerating the times between each transit and dividing by the number of intervals, the average orbital period is found. The obtained answer is the extrasolar planets year.

3.2. Semi-major axis

The value of the orbital period can help estimate the semi-major axis, which can be determined by using Kepler's third law graph (see page 14). A more correct value can be attained by using the mathematical formula beneath, but in order to do so the mass of the planet and of the star must be known (Zoonivers teams, 2014, p.93-94). The formula for the semi-major axis is also established from Kepler's third law of planetary movement. P is the orbital period, G is Newton's Gravity constant, m is the mass of the planet, M is the star's mass and a is the semi-major axis (Ekholm&Fränkel& Hörbeck, 2013, p.51).

$$P^2 = \frac{4\pi^2}{G(m+M)} a^3$$

3.3. Radius

In order to find out the radius of the planet a value of the drop in brightness is vital to know. If there are different values from each transit even if the value varies by 0.001, it is best to take it in account. The fairest way to do so is to take an average of all the brightness wane. The formula is based on the theory that a planets area covers an area on the star. By factorizing and shortening the same factors the formula will end up looking as seen below (Zoonivers teams, 2014, p. 94):

$$\frac{r^2}{R^2} = \text{Drop in brightness.}$$

In the equation r is the radius of the planet, while R , which is given on the Planethunters site, is the radius of the star. When using the equation further adaptation needs to be done on the formula. An adaptation in the case of radius is only a matter of breaking out the wanted r from the equation.

3.4. Orbital velocity

The usual equation to count velocity is:

$$v = s/t$$

In the case of planets; s is the orbit of the planet around its star and t is the orbital period (P). For the sake of simplicity set the orbit as a circular course rather than elliptical. It is not incorrect to do so since planets orbiting near stars, as the case of the candidate extrasolar planet from the first star seems to do, have more circular course rather than elliptical (Moutou & Pont, 2005). In this case the orbit has a radius which is the semi-major axis. By knowing

the semi-major axis it is possible to determine the length of the orbit, when the orbital period (P) is known the velocity of the planet can be calculated. In the equation below s is a circular distance and the circumference of a circle is calculated as follows (Pålsgård & Kvist & Nilson, 2012, p.151-154; Ekholm & Fränkel & Hörbeck, 2013, p.34);

$$s = d \times \pi = 2r \times \pi = 2a \times \pi$$

$$v = s/t = \frac{(2a \times \pi)}{P}$$

3.5. Mass

The mass can be found more accurately by using the Doppler method, but not impossible with the transits method either. The mass calculation in this report will be based on the size of the planet and the semi major-axis. The approximated values which make it possible to find the mass and general mass values for some type of planets are listed in the table below.

Table 1: In this chart there are simplified calculations which help to determine the mass of the planet approximately (Zoonivers teams, 2014, p.98-99, 94).

<i>If r_{planet} is $< 6r_{Tellus}$</i>	<i>If $6r_{Tellus} \leq r_{planet} < 6r_{Tellus}$</i>	<i>If r_{planet} is $\geq 10r_{Tellus}$</i>
<i>Then $m_{planet} = 0,9515r^{3,1}$</i>	<i>Then $m_{planet} = 1,7013r^{2,0383}$</i>	<i>Then $m_{planet} = 0,6631r^{2,4191}$</i>
r=radius of the planet	m=mass	$m_{Tellus} = 5,976 \times 10^{24}$

3.6. Density

The equation for this property of a planet is the same basic formula for density as the one used for the calculation of any matter. In order to find the density the volume of the planet must be known. Due to the approximation of the mass, the density will also be only an approximation. Below is the formula for the volume of a sphere, in this case a planet, and the formula for the density (Ekholm & Larsson & Bergström, 2002, p.26, 32-33):

$$V = \frac{4\pi r^3}{3}$$

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

3.7. Surface temperature

Many factors need to be known for this equation before trying to use it (see table three).

In the equation below T_p is the surface temperature and A is the albedo of the planet.

According to NE (2015); Climate education (2013) albedo is the capacity of a planet to reflect the amount of incoming light back into space, this ability is affected by the nature of the objects surface and atmosphere. For example ice has low capability to absorb light. If a planet has 1,00A then all light is reflected none absorbed, if a planet has 0,00A the opposite applies.

$$T_p = \left(\frac{L(1 - A)}{16\pi\sigma a^2} \right)^{1/4} = \left(\frac{R^2 T_s^4 (1 - A)}{4a^2} \right)^{1/4}$$

To make it easier to use the equation above, the table on the next page shows a list of type of planets and what their estimated albedo is. The albedo has been found by using another method and is only an approximated value. In other words it is necessary to know the type of planet in order to use the chart below.

Table 2: The chart below shows all that is required in order to find out the surface temperature of a planet. The right column of the table shows an approximate albedo of four most known types of planets. When the mass of a planet is known the type can be determined and the albedo values can be used (Zoonivers teams, 2014, p.95; Conway A.C.& Glimour I.G. & A. Rothery D.R. & A. Sephton M.S. & C. Zarnecki J.Z, 2003, p.46).

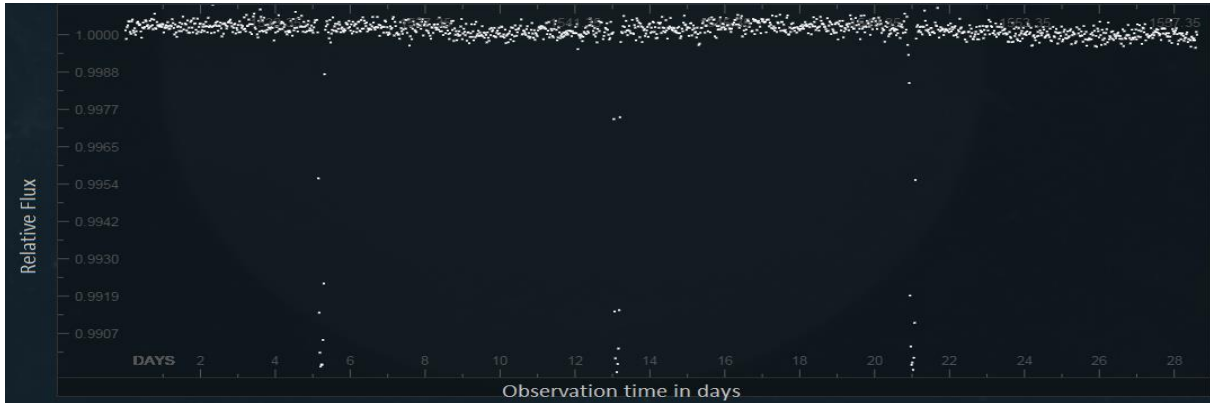
What the formula acquires :	A(albedo)for four types of planets	
L=Luminosity of the star ($L=4\pi R^2 \sigma T^4$)	Hot Jupiter:	0,52
a= Distance from the planet to the star	Hot Neptune:	0,35
Ts=Surface temperature of the star	Super-Earth:	0,39
σ= Stefan-Boltzmann's constant ($5,670 \times 10^{-8} \frac{W}{m^2 K^4}$)	Exo-Earth:	0,39
A=Planets reflection of radiation back to space		

4. Result

The equations and explanations in the method part of the report will be used here, when calculating the characteristics of the candidate extrasolar planet shown on the first light curve presented below. The AU- Astronomical Units is the measurement used here for distances.

1AU is the distance from earth to the sun which is 149597871 km (Britannica, 2015). Also the radius of the sun is 695599 km (Kiselman, NE, 2015).

All the possible properties of an extrasolar planet which can be calculated, which have been mentioned earlier in the report will follow below. The light curve used is located below together with a table of the star information available and necessary.



Graph 1: The diagram above represents the first light curve. The curve declines in three spots in a regular periodical pattern. The three transits seen indicate the existence of a candidate extrasolar planet. Brightness on the y-axis and time on the x-axis.

Table 3: This chart below shows the needed information about the star with has been studied by K2 and is represented on the first light curve.

Star information for curve 1:

Type of star	K-dwarf
Magnitude	15,961
Surface temperature	6076
Radius	0,99 R_{Sun}

4.1. Orbital period(P)

The time between the first and second transit is;

$$21 - 13,10 \approx 7,9 \text{ days}$$

The time between the second and the third transit is;

$$13,10 - 5,18 \approx 7,92 \text{ days}$$

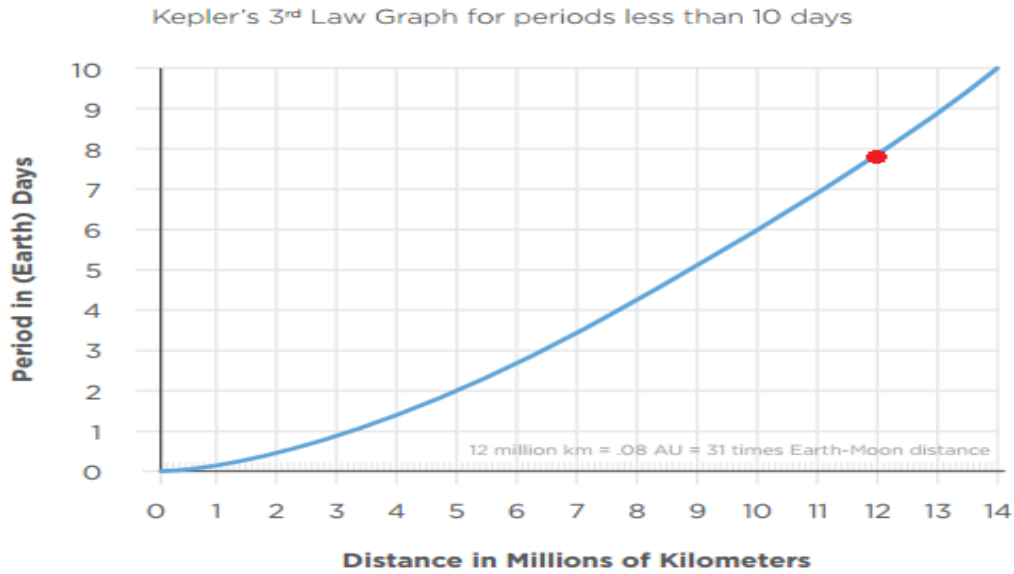
The average of the orbital period is

$$P = \frac{(7,9+7,92)}{2} = 7,9 \text{ days}$$

4.2. Semi-major axis

By using Kepler's third law graph an approximation of the semi-major axis can be read. The graph below shows a red dot where the distance is marked. The semi-major axis is;

$$\approx 11,93 \text{ million kilometers} \approx 0,08 \text{ AU (see graph 2 below).}$$



Graph 2: This is a graph based on Kepler's third law (Zoonivers teams, 2014, p.84). The red mark shows the value of the distance from the K-dwarf-star to the planet indicated by light curve one.

4.3. Orbital velocity

As shown on page twelve;

$$s = d \times \pi = 2r \times \pi = 2a \times \pi = 2(11,92 \times 10^6) \times \pi = (23,84 \times 10^6) \pi \text{ km}$$

$$v = \frac{s}{t} = 2a \times \pi / P = \frac{(23,84 \times 10^6) \pi}{683424} \approx 109,59 \text{ km/s}$$

$$t = \text{orbital period} = P = 7,9 \text{ days} = 7,9 \times 24 \times 60 \times 60 = 683424 \text{ seconds}$$

4.4. Radius

The radius of the star of light curve one is given, on the internet page Planethunters, as $0,99R_{Sun}$ which is;

$$\approx 688545 \text{ kilometers}$$

While the average drop in brightness is;

$$1,003 - \frac{(0,9894 + 0,9896)}{2} = 0,0135$$

$$\frac{r^2}{R^2} = \text{Drop in brightness}$$

$$\rightarrow r = \sqrt{\text{Drop in brightness} \times R^2} = \sqrt{0,0135 \times (0,69 \times 10^6)^2} = \sqrt{6,4 \times 10^9} \approx 80001,6995 \text{ km} \approx 12,54 r_{Earth}$$

4.5. Mass

Table four below is the same as the one in chapter three, the only difference is the red highlighting which indicates the useful column for the planet from curve one. The planet has a radius 12,54 times that of earth. According to the right column, the mass of the planet will be approximately;

$$m_{planet} = 0,6631r_{planet}^{2,4191} \approx 0,6631 \times (12,54r_{Earth})^{2,4191} \approx 301m_{Earth} \\ \approx 1,798 \times 10^{27} kg$$

Table 4: In this chart there are simplified calculations which help to determine the mass of the planet approximately (Zoonivers teams, 2014, p.98-99, 94).

<i>If r_{planet} is $< 6r_{Tellus}$</i>	<i>If $6r_{Tellus} \leq r_{planet} < 6r_{Tellus}$</i>	<i>If r_{planet} is $\geq 10r_{Tellus}$</i>
<i>Then m_{planet} $= 0,9515r^{3,1}$</i>	<i>Then $m_{planet} = 1,7013r^{2,0383}$</i>	<i>Then m_{planet} $= 0,6631r^{2,4191}$</i>
r = radius of the planet	m=mass	$m_{Tellus} = 5,976 \times 10^{24}$ $r_{Tellus} = 6378,1 km$

4.6. Density

In order to find the density of the planet the volume must be known:

$$V = \frac{4\pi r^3}{3} = \frac{4\pi \times (80002 \times 1000)^3}{3} = 2,145 \times 10^{24} m^3.$$

Thereby the density will be approximately:

$$d = \frac{m}{V} = \frac{1,798 \times 10^{27}}{2,145 \times 10^{24}} = 838,3 kg/m^3$$

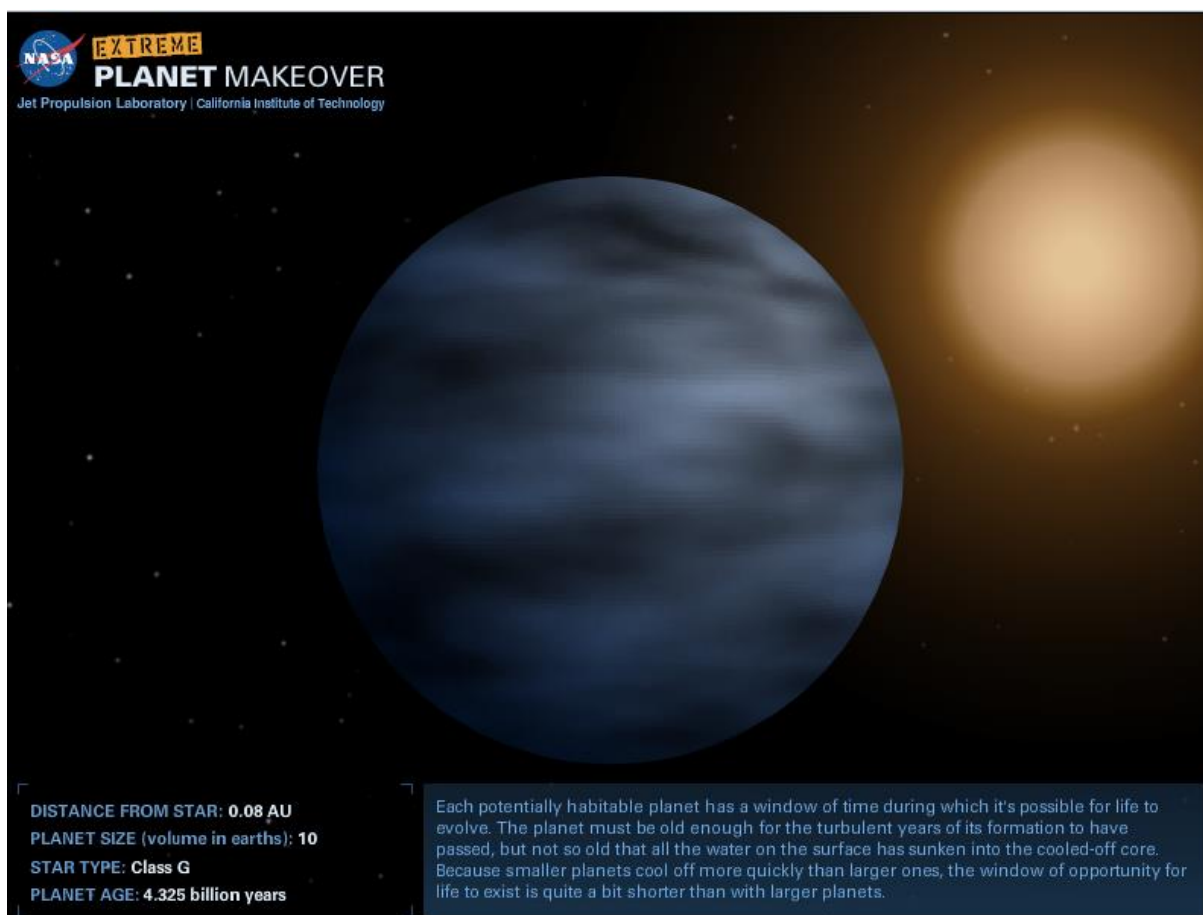
4.7. Surface temperature

This is also referred as effective temperature. As seen on the page above the candidate extrasolar planet seems to be a Hot Jupiter (see table 6, in attachments, for characteristics of a Hot Jupiter). Thereby, the approximate albedo (until the real value is known) will be that of a Hot Jupiter as seen on the table two on page 12, which is A= 0,52.

$$T_p = \left(\frac{R^2 T_s^4 (1 - A)}{4a^2} \right)^{1/4} = \left(\frac{(688545^2) \times (6076^4) \times 0,48}{4 \times (11,92 \times 10^6)^2} \right)^{1/4} = (5,184 \times 10^{11})^{1/4} \\ \approx 859,49 K$$

Table 5: This chart shows a summary of all that has been calculated about the planet. Until further the approximate values below are all that can be done in this report, when more is known and planet has been confirmed more meticulous computation on the planet can be available.

Summary of information of the candidate extrasolar planet from light curve one.	
Orbital period (P)	7,91 days or 683424s
Orbital Velocity	110 km/s
Semi-major axis	0,08 AU
Radius	$8,00 \times 10^4 km$
Mass	$1,798 \times 10^{27} kg$
Volume	$2,145 \times 10^{23} m^3$
Density	$838 kg/m^3$
Surface temperature	859,49K



Picture 2: A simple model of the star and its candidate extrasolar planet from light curve one. It was possible to make the picture after knowing the necessary properties (see on the left bottom of the picture) and by using Planetquest interactives, planet makeover (NASA, Planetquest, 2016).

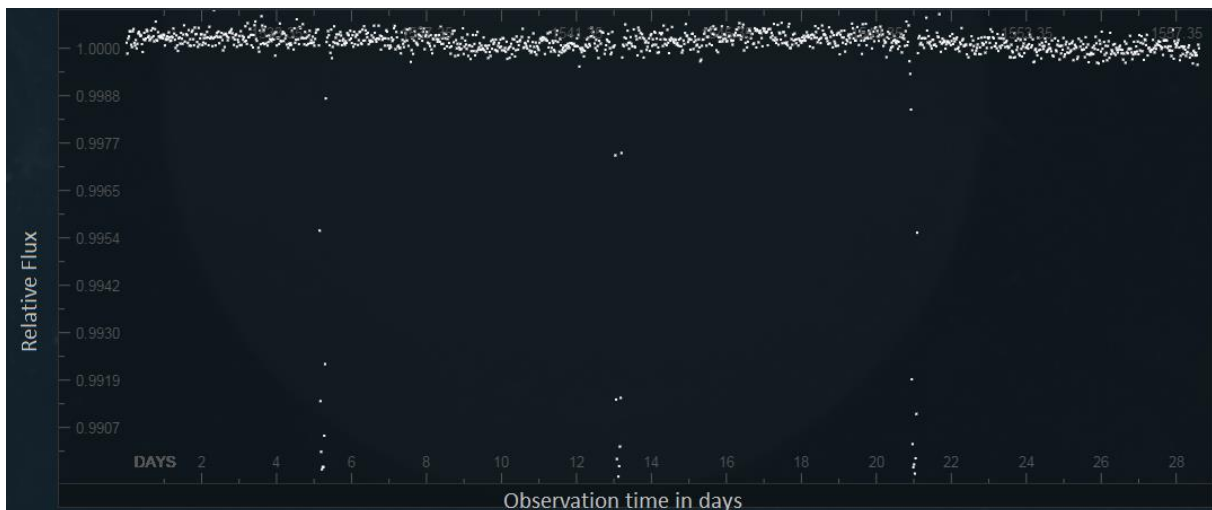
4.8. Graph analysis

Hereby one can read an analysis for each of the four light curves from four stars of the same type but with different characteristics. The light curves are in the same scale, which is time on the x-axis and the collected amount of brightness from the star (relative flux, which is a unit less number) on the y-axis. The source of the light curves is data from Kepler downloaded from Planethunters.org.

4.8.1. Star 1: First light curve

The graph below represents collected data from a K-dwarf star. On the light curve one (see graph three below) there are three visible transits in a regular pattern, this gives a strong indication of the existence of an extrasolar planet. However, it is not yet proven unless another method is used to confirm the discovery, which is why this planet is merely a candidate extrasolar planet. As mentioned before properties such as orbital velocity and orbital period can be found by usage of the light curve and mathematical equations. Although, all calculations will be approximations of the real values due to the small differences and errors in data that cannot be excluded.

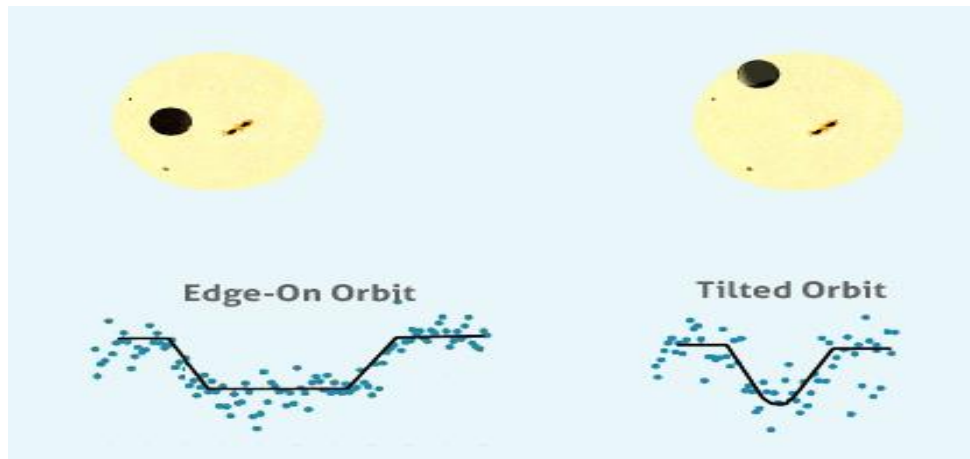
The duration of each transit on the light curve is just over a day and the amount of blocked light is considerably the same for all three transits, this gives more proof for a planet. The star is smaller than the sun by 0,001 and the planet is bigger and closer to its star than Jupiter, which explains why the transits are so deep.



Graph 3: The diagram above represents the first light curve. The curve declines in three spots in a regular periodical pattern. The three transits seen indicate the existence of a candidate extrasolar planet.

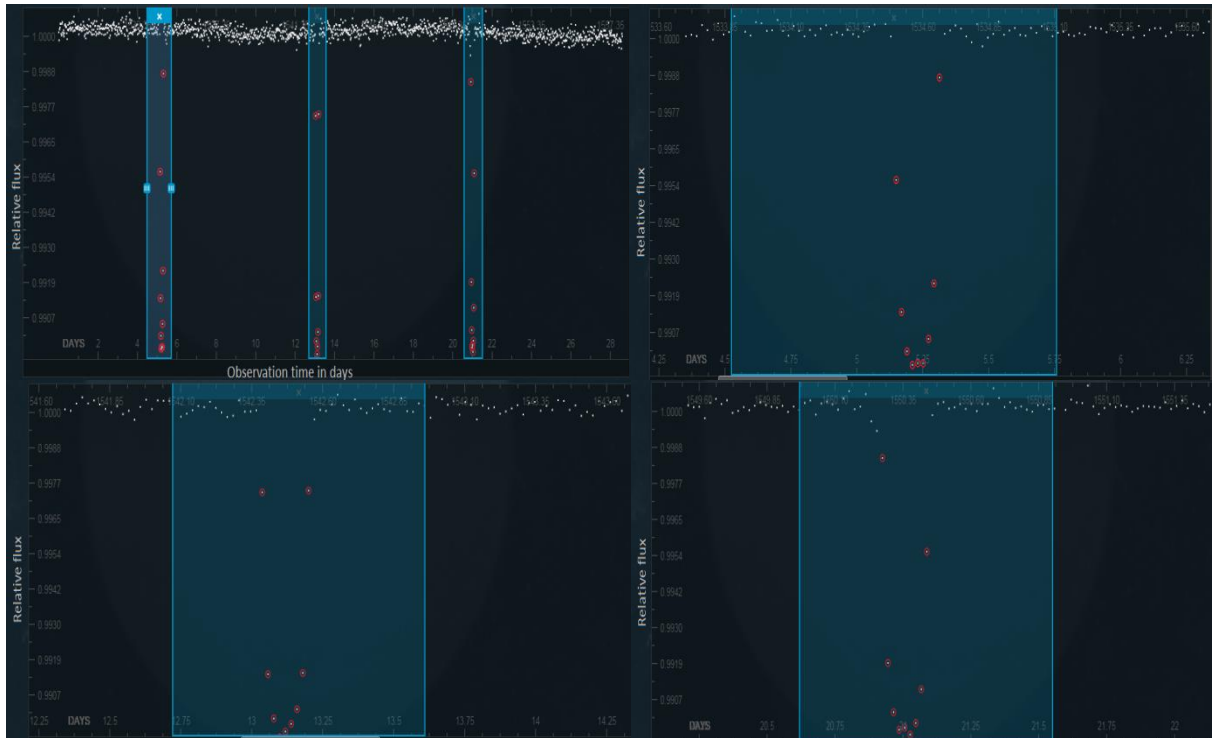
As seen on the graph four-collage on the next page, the transits gradually dip. The transit shape is not square, as it would be if the orbit was edge on, or rounded, instead rather in a

shape of a half oval elliptical course. This kind of transits are due to a tilted orbit of a planet, because a tilted orbit makes the planet block gradually less of the stars size with time seen, in this case from Kepler (see picture four below).



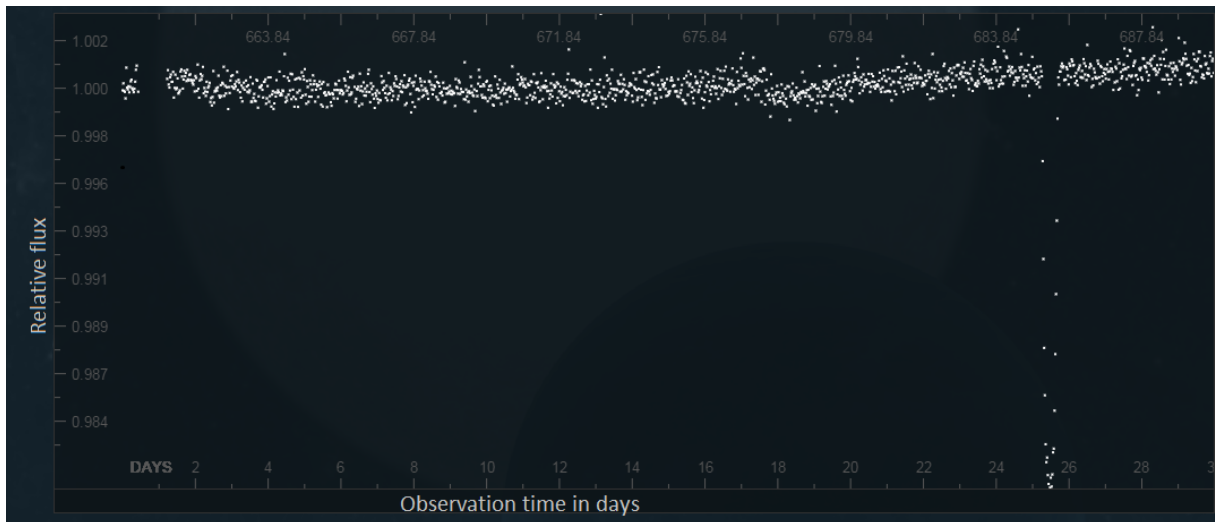
Picture 3: The differences between an edge on and tilted orbit of extrasolar planets are visible in the picture above (Harvard education, data lab, p.7).

The utterly small variety of light decrease on the transits on light curve one need to be commented, because it can be due to disturbance in the measurements or the instruments sensitivity. Another explanation to the none identical transits could be that the light curve actually does specify an eclipsing binary system of stars with equal size, nonetheless, binary systems are usually different sized stars and a systems with two K-dwarf equal sized stars is rather rare, but not impossible. If the transits had a more V-shaped form it would be more likely a eclipsing binary system, two stars orbiting each other, in this case those stars would be reasonably the same size (Moutou & Pont, 2005, p.66-67). Although, since the transits on light curve one are not sharply V-shaped (see close up on graph four below) the possibility that the graph shows eclipsing double stars is not likely, while the possibility of a planet orbiting the K-dwarf cannot be seclude without further investigation. In conclusion by taking in account the presumably quite realistic calculations on chapter four and the abovementioned facts about eclipsing binaries, it is most likely that light curve demonstrates an orbiting candidate extrasolar planet rather than eclipsing binary or anything else.



Graph 4: There are close up pictures on the three transits of the first curve. First transit is the picture on top to the right, the second transit in the one below on the left and the third is the last picture on the right. While the first picture above to the left represents the whole curve where each transit is marked with blue rectangles.

4.8.2. Star 2: Second light curve



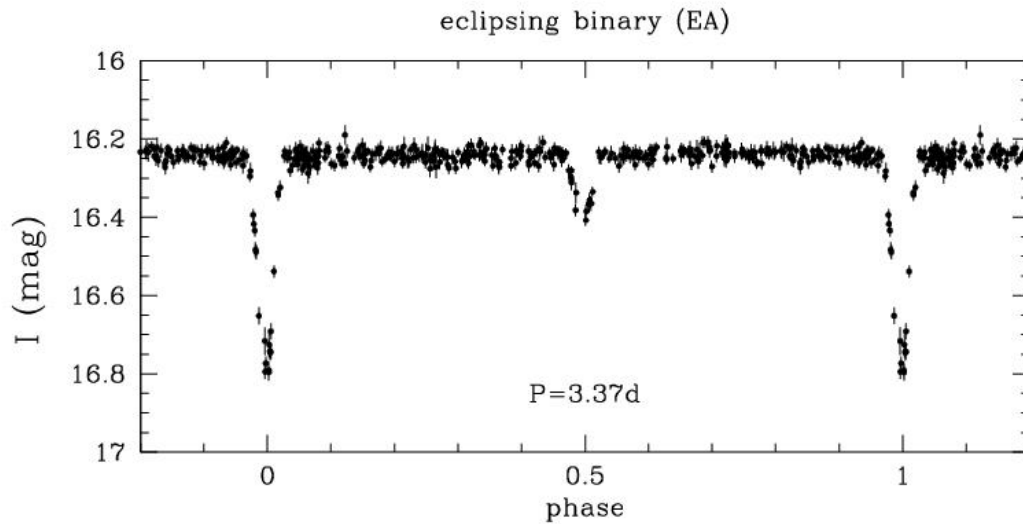
Graph 5: The below diagram contains the second curve, which has a fine transit at the approximate time 25,5 days.

The second curve also has a transit (see graph five above), although, only one transit does not make it possible to verify if it is a planet or not. Therefore, longer observation is necessary in order to thwart wrong conclusions. If it is a planet than more transits will occur in a pattern, until then nothing can be calculated or confirmed.

Another possible explanation for the transit could be a star orbiting its companion star in their binary system. About 50% of stars are estimated to be in binary systems, which move around a joint center of gravity. Therefore, light curves representing eclipsing binary, such as light curve two is quite common in the search for extrasolar planets, they can even be mistaken as transiting planets due to the similarity between them (Moutou & Pont, 2005, p.66). The problem with binary systems can be resolved by using radial velocity method to discriminate the sets of absorptions lines of each star. These stars transit each other and normally one of them is bigger than the other (Moutou & Pont, 2005, p.68-70; Lagerkvist & Olofsson, 2007, p.160& 162).

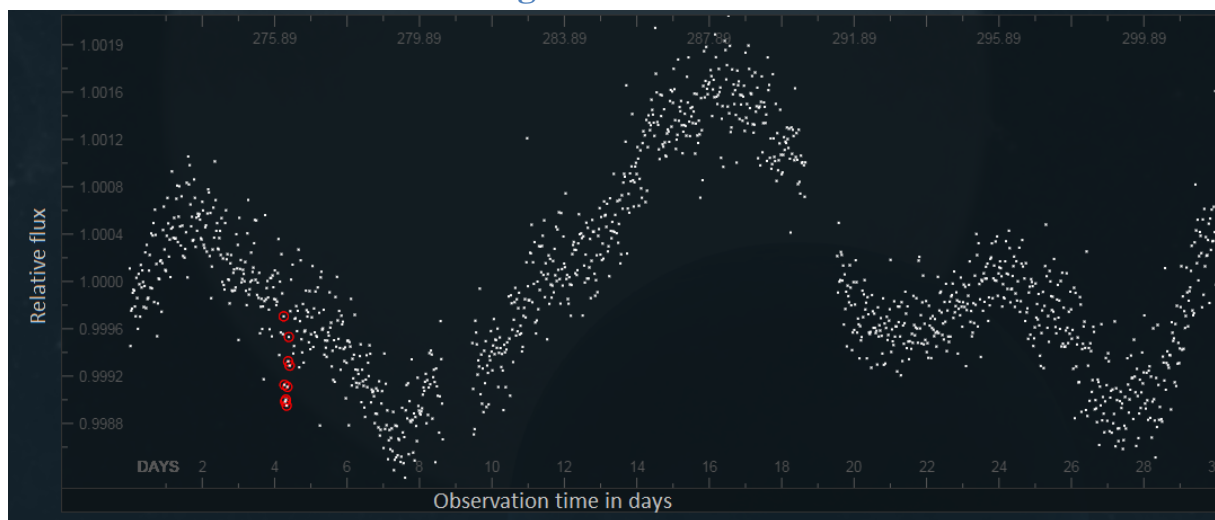
For light curve two (see graph five above) to correspond to a eclipsing binary system another kind of transit must be visible showing the other star orbiting its component, again longer observation must be done in order to determine if it is an orbiting stars in a binary system or even a triple star system. By two kinds of transits it is meant two different shaped transits with different characteristics, possibly one shorter and smaller than the other. In that case it is not unreasonable to expect a shorter transit showing the orbit of a smaller star accompanying the K-dwarf studied here. The graph six on next page is a guide to how a light curve over an eclipsing binary system might look, the curve represents a confirmed binary system, therefore it is reliable enough. As seen in the graph six below there is a shorter and a longer transit, showing the amount of brightness blocked by each companion star. The shorter transit is from a smaller star blocking less brightness of the bigger star. For the longer transits the opposite applies. Notice also the characteristic V-shape of the transits. Other binary systems show different and less fine curves.

Finally, if the light curve two shows an eclipsing binary system, than it is of that kind where there are two or three stars of different masses orbiting each other around a common center, because they are a more common occurrence. Moreover, other kind of binary systems show other changes on a light curve (Planethunters, 2014). Thereby, it can be said that the second light curve either represents an orbiting planet or an eclipsing binary system, which means one or two other shaped transits or a regular pattern of planetary transits can be seen when time is right.



Graph 6: The light curve above shows a confirmed eclipsing binary. There are two transits one shorter than the other representing the two stars in the system (Astronomical observatory university of Warsaw, 2008).

4.8.3. Star 3: Third light curve



Graph 7: This is the third light curve where a simulated transit may be seen.

According to Lagerkvist & Olofsson (2007, p.162); Jönsson (2002, p.30) there are three kinds of double star systems known today:

1. Stars orbiting each other (eclipsing binary).
2. Stars so near each other that the gravity force has changed the shape of the star components slightly and some exchange of mass can occur, which leads to a change in structure. A light curve of this type of double star systems might resemble a cardiogram of heartbeats, which are easier to spot out than other changes (Planethunters, 2014).

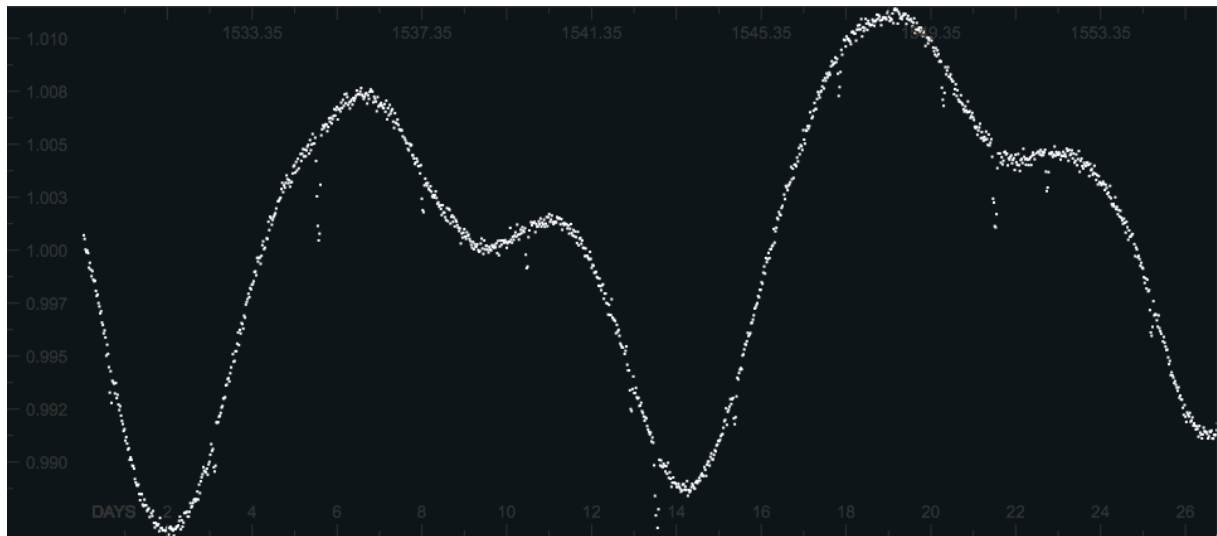
3. The third type is stars very close, causing constant exchange of mass, besides the gravity force deformation on the stars. The exchange of mass has an impact on the light curve similar to the fourth curve. Moreover, the dips seen from the last kind of double star system are almost identical due to the constant exchange of mass between the stars, which makes the two stars have the same size when aligned with the observers' plane of view.

The third light curve (see graph seven above) cannot show an eclipsing binary, because the curve has no regularity (see graph six, page 21). Therefore, that possible explanation can be excluded. On the other hand the third light curve may be of a binary star system of type three (see above) with exchange of mass between the stars, which explains the strange transits seen on the curve, also the lack of regularity.

Light curve three may show if not a binary system than a variable star, which is a star with real changes in its luminosity originating in the star itself. Actual changes in the amount of energy the star produces with time, which is affected by how helium is ionized before recombining again. This change of energy appears in the difference in luminosity because ionization uses up instead of producing energy (Lagerkvist & Olofsson, 2007, p.163-164). Variable stars pulsate in quite regular patterns, as seen on both third and fourth light curve, the dips come in patterns of three respective two transits at the time (Linde, 2013, p.91). Some may disagree about the regularity of the curve, which can be understandable. The transits seem to increase in depths and the light is never restored completely. However, it is not strange due to the fact that if the ionization of some helium has stopped, there is nothing giving any guaranty that no other helium atoms might start to ionize or have already started as the first ones stopped, therefore the luminosity is never restored entirely. As usual, longer observation will reveal more and make it easier to determine what the light curve really represents for sure.

One more reason for the appearance of light curve three might be the occurrence of a multi planetary system around a star. The three different transits may be caused by three planets with unequal size. It would indeed be interesting if it is true, although the possibilities are low. The transits are deep and wide, planetary transits will not give rise to such transits as those seen on light curve three, rather short and small ones. Below there is a graph clarifying how multi planetary transits have shown to look like on a light curve. This graph shows a real and

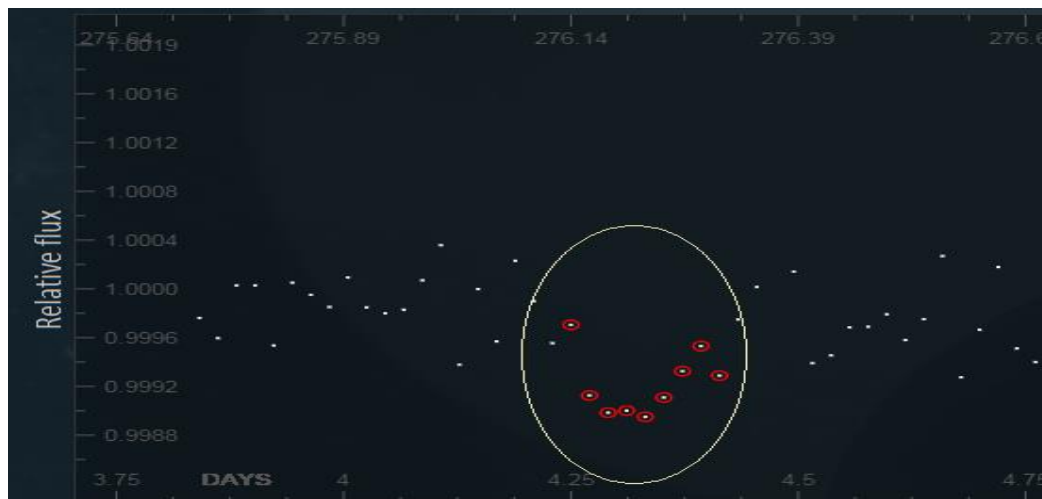
confirmed occurrence of multi planetary systems around a star. The planetary transits are the short ones dipping from the bigger depths of a variable star.



Graph 8: The graph above shows a light curve representing a multi planetary system around what looks like a variable star or perhaps a binary star system. The transits caused by the multi planetary system are those small nine ones (Planethunters, 2014).

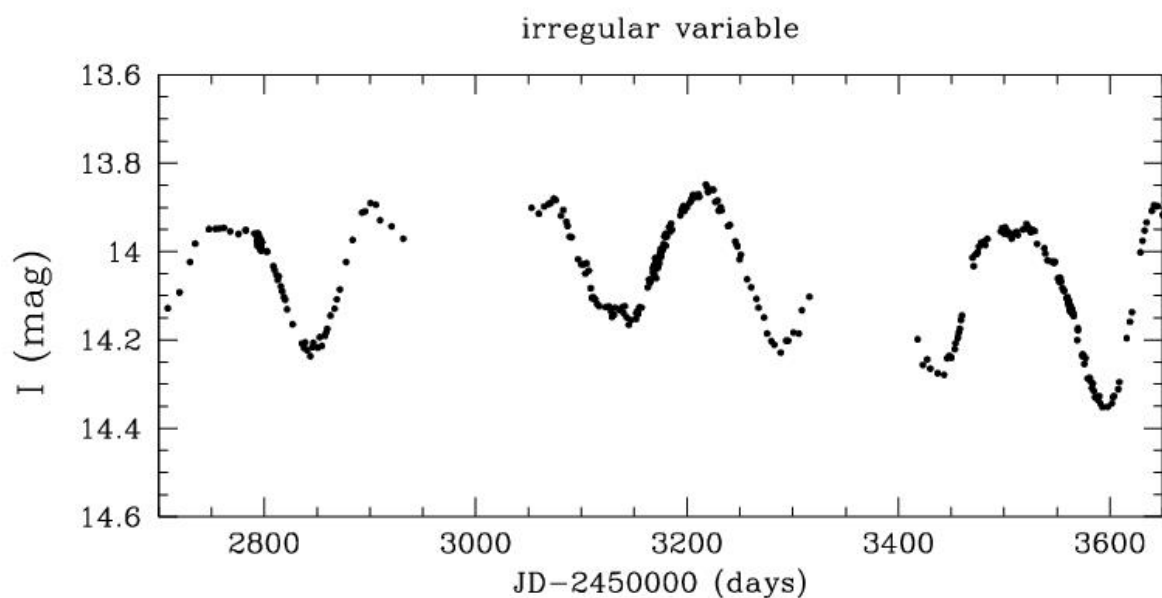
The red marked possible transit calls for a closer study. The transit could be a false measurement or an actual transit caused by an orbiting planet. In that case the transit will be seen again, additionally there will be two transits due to the planet orbiting two or three stars (Deeg, H. 1998, p.220). A planet in a binary star system or triple star systems orbits either one or two of the stars or all three, these transits might have unusual looks (see Deeg .J.H. 1998, p.5). In the case of the fourth light curve, if the small transit is caused by a planet, then that planet only orbits one of the stars. If it orbits both or all three stars it would be possible to see the same transit on the other two deeper transits seen on the curve. Therefore, if the light curve itself shows a binary system then the small transit is not a planet.

Although, if the third light curve is of a variable star the red marked transit could be a planet and only seen once each time it travels between the observer and the star.



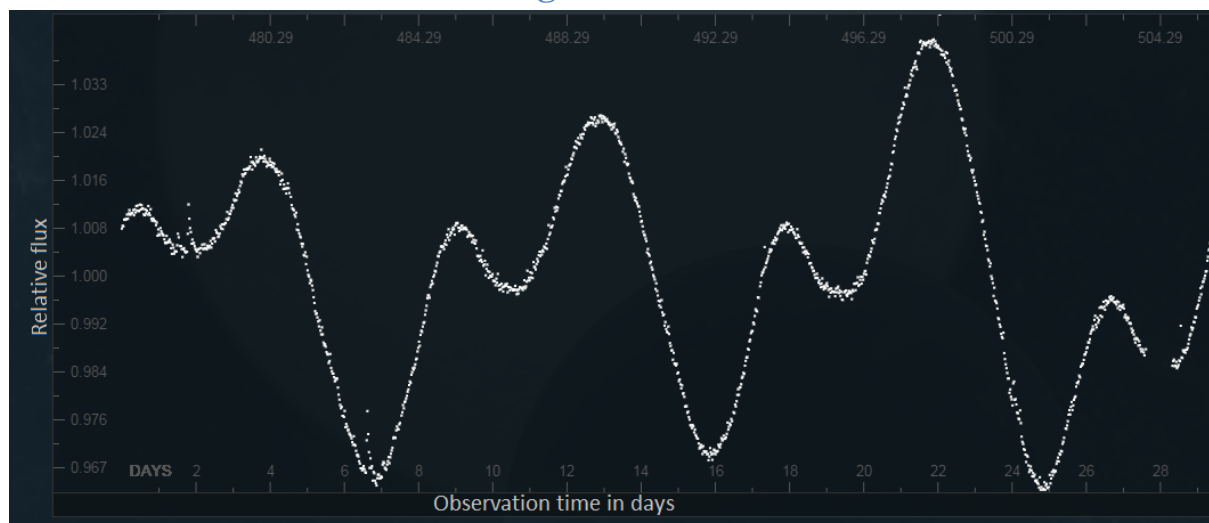
Graph 9: The graph above shows a closer look at the transit on the third curve found above.

Finally, one more phenomena the third light curve seems to represent is an irregular variable with possibly a transiting planet causing small transits as the one seen on graph nine above. Although, planets are unlikely to be formed around such unstable stars, in that case the transit might be a passing celestial body (an asteroid perhaps). In order to show a strong argument for this conclusion a light curve from a confirmed irregular variable star with similar luminosity changes as those on light curve three, is presented below (see graph ten).



Graph 10: The light curve above represents an irregular variable similar to the one represented on the third light curve, which also seems to be an irregular variable (Astronomical observatory university of Warsaw, 2008).

4.8.4. Star 4: Fourth light curve

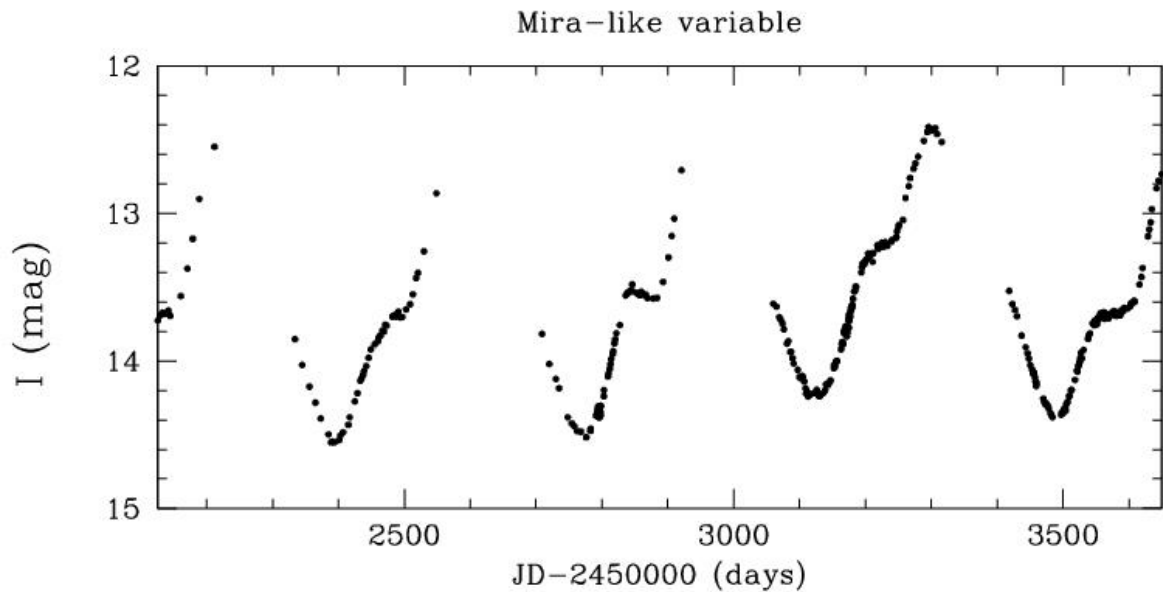


Graph 11: The curve below is the fourth one. This is an interesting curve which does not represent a transiting planet but it is still somewhat periodical. However it has three flares, which are in a way upwards transits.

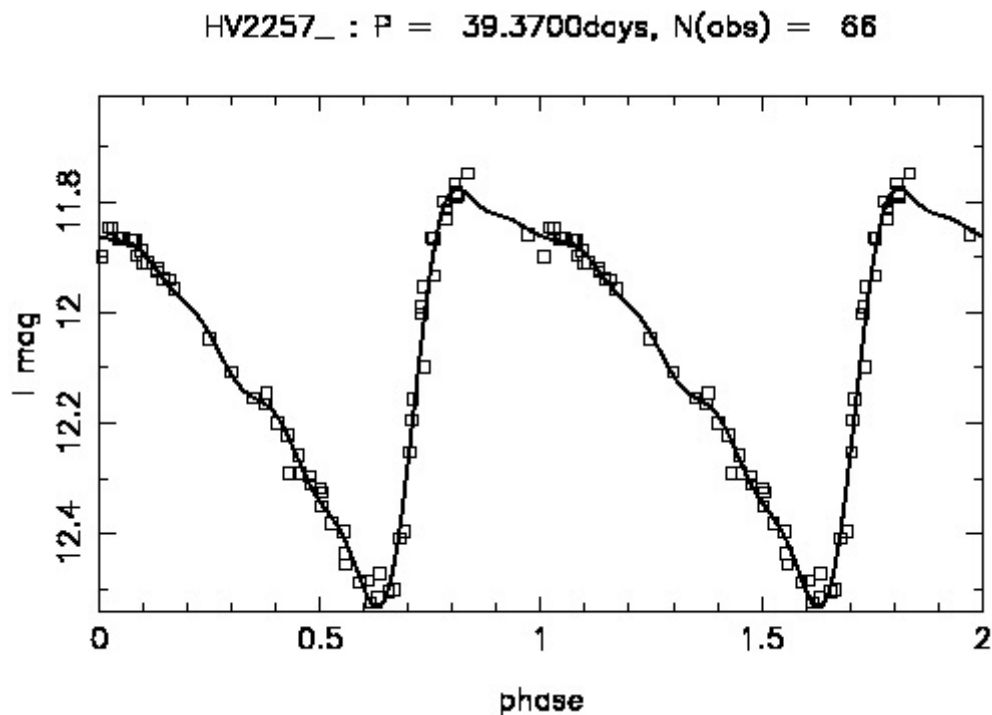
The fourth light curve (see graph 11 above) could be a variable star pulsating with the interval of about nine days for the long respective the short transits. Even though it seem to have a regular period it lacks an overall regularity in the pattern seen, because the transits increase in depths without a consistency.

There are different types of variables such as Mira variables and Cepheids. The first mentioned are less regular in patterns and have higher amplitude transits. Due to the just mentioned fact the third curve is more likely a Mira variable rather than a Cepheid, which have periodical changes of \geq day (Planethunters, 2014, Cepheid). According to Lagerkvist & Olofsson (2007, p. 164) Cepheids use up energy to ionize helium which leads to more particles on the atmosphere which in turn keeps energy from reaching out. Further, the particle amount makes the radius bigger which helps restore the balance by giving more place and lowering the density of particles and recombine helium. However, as mentioned on chapter 4.8.3 the luminosity will most likely not be totally restored. Mira variables, however, swell and shrink gradually in intervals of hundreds of days, the periods of the occurrence is not systematic at all times (Welin, 1996, p.80-81; Jönsson, 2002, 30).

The twelfth graph on page 26, contains a light curve over a confirmed Mira variable, which seems to be fairly comparable to the fourth light curve in this chapter. Relate the fourth light curve with graph 13 on the next page also, which represents a light curve over a known Cepheid to see the dissimilarities. This way more certainly one can state that the fourth light curve is a Mira variable not a Cepheid.



Graph 12: Above there is a light curve over an confirmed Mira variable, used here to compare with the fourth light curve which seems to be alike to a Mira variable (Astronomical observatory university of Warsaw, 2008).

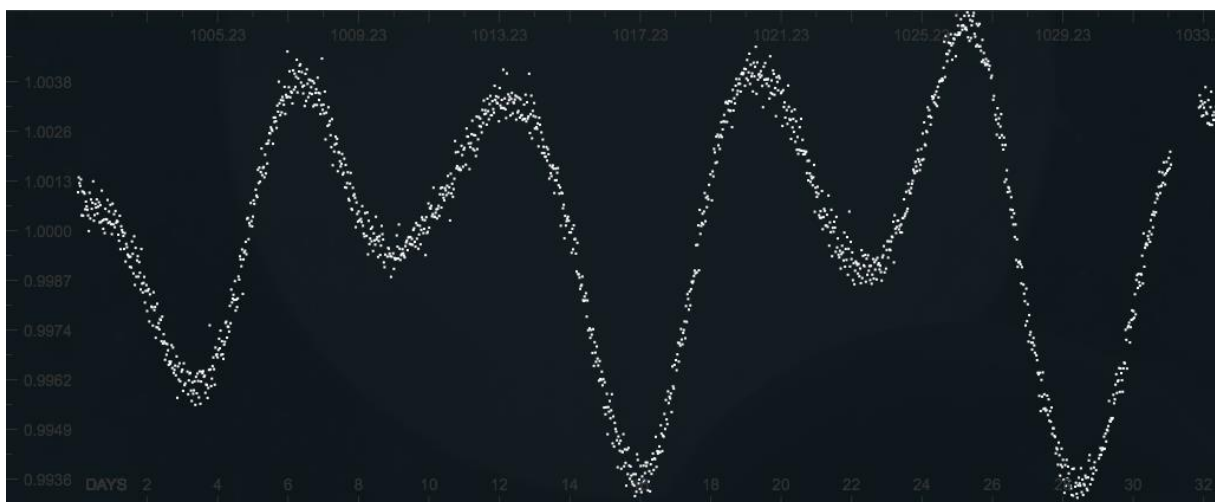


Graph 13: The graph above shows a light curve over a Cepheid. As seen here it is most certainly that the fourth light curve is not a Cepheid, which has much more regularity in the pattern of transits (Astronomical observatory university of Warsaw, 2008).

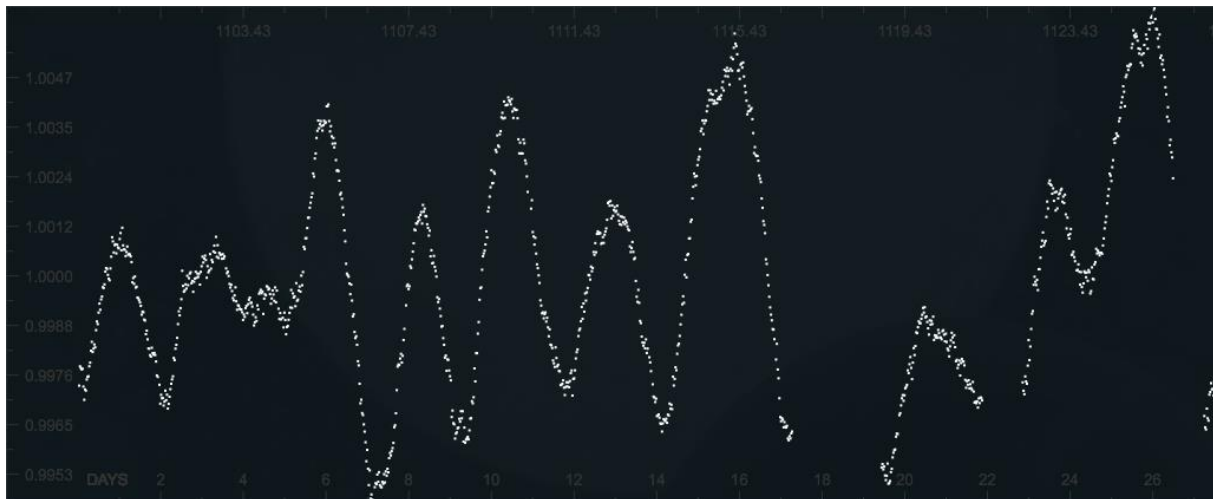
Another possible conclusion could be the existence of two planets. If the pattern was periodical; meaning the amount of brightness blocked would be the same for all long respective short transits visible, it could demonstrate the existence of two planets, where a smaller planet blocks less light from the star than the bigger planet. It is possible but rare to

see a curve of that sort, since the orbit of both planets must be aligned with the observers' point of view. Moreover, as discussed on chapter 4.8.3., planetary transits are less wider and shorter (see graph eight on page 23) than the deep transits seen on light curve four.

A third possible explanation to the appearance of the fourth light curve, could be the existence of star spots. These give non-periodical changes in brightness of the star until they complete their cycle. Moreover, the light is not reinstated until the star spots are completely out of sight and the pattern terminates. If the pattern is interrupted then it was one macula or more, if not then it is more surely a variable star, not planetary systems, longer observations will reveal the truth. In order to clarify how star spots are shown on a light curve there are two graphs below on star spots (see graph 14 and 15). As seen on graph 15 the star spots have irregular patterns. However, graph 14 has a light curve quite alike the fourth light curve. If light curve four represents transits caused by star spots then it must be star spots quite near each other, since the long transits do not conclude before the next and shorter transit begin, as they do on the light curve below (see graph 14).



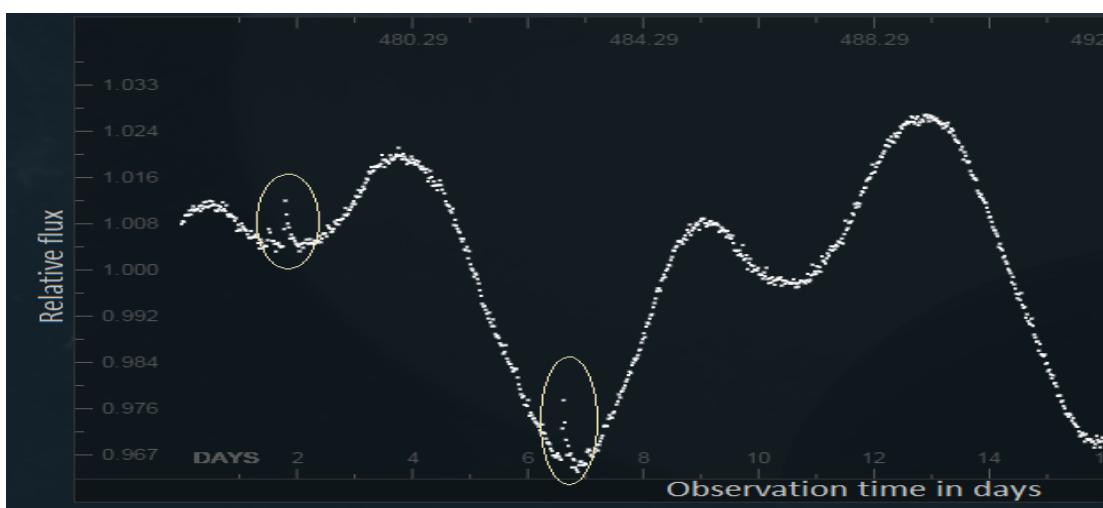
Graph 14: A light curve with transits caused by star spots. This pattern is quite regular but not corresponding to the fourth light curve so well (Planethunters, 2014).



Graph 15: The curve above is another example over star spots. As seen here star spots can give a very irregular pattern of transits. this light curve is not at all comparable to the fourth light curve (Planethunters, 2014).

In the end it cannot be excluded that the fourth light curve shows star spots on a K-dwarf star, without further investigation of the stars type and light. However, neither can the just as correct conclusion about the fourth light curve being a Mira variable be rejected. Nevertheless, in account of the similarities of the fourth light curve and the Mira variable seen on graph twelve it is more likely that the light curve four shows a Mira variable after all.

What is more, this K dwarf star does not only have clear drops in brightness, it also has solar flares (see close up on graph 16 below), which are sudden increases in brightness. Flares are according to Planethunters (2014); Astronomica (2012, p.35); Welin (1996, p.82) non-periodical, in other words they are occurrences due to high ejections of energy from the star caused by explosions on the star surface.



Graph 16: This is the same diagram as the fourth one, the only difference is all the three markings(circles on the curve) where the flares are visible.

5. Discussion

This report is mainly meant to represent the transit method together with all its advantages and disadvantages, as well as demonstrate the work with this particular method. All the mathematics and graphs are introduced as a way of answering the questions (see 1.1.). It is meant to show what can be done after finding and confirming a planet. Moreover, demonstrate how a light curve can be analyzed, which is often a challenge.

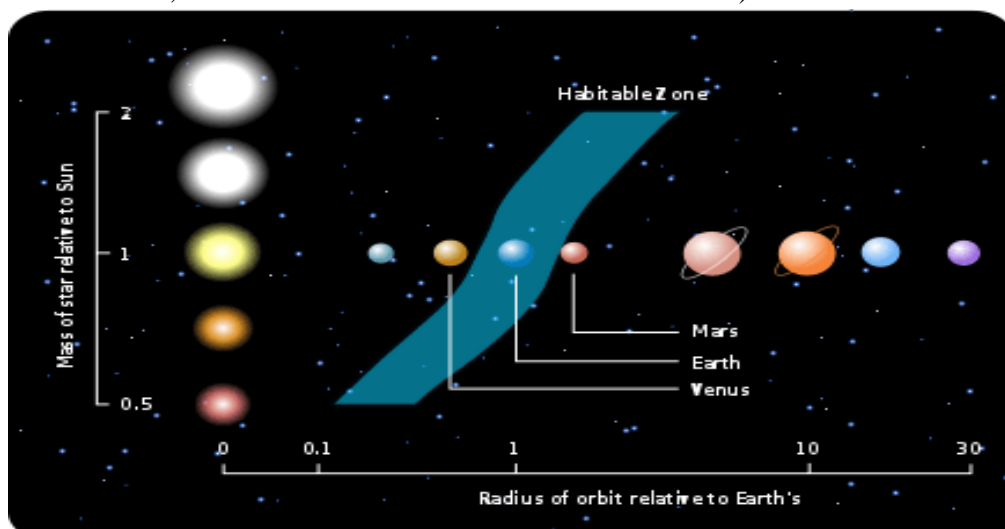
Light curves are not perfect lines, they contain noise from space or false measurements due to the telescope itself. Furthermore, planets further away from their host star have lower velocity (due to their longer distance from the star), which therefore, it takes many days or years for them to orbit a star. The longer orbits make it very difficult to detect extrasolar planets of smaller sizes. Furthermore, the boundary with a certain angle to view in, makes transits an even rarer occurrence. Due to the aforementioned reasons the search for extrasolar planets is complex and it makes it utterly impossible to rapidly exclude the possible existence of a planet around both star one and star two, represented on the first respective second light curves, or around any other star without thorough investigations of each viewed star. After thorough analysis misconceptions that can unfold on collected data can be eliminated and the reality can be revealed. With good technology and long observation time, it is not impossible to find extrasolar planets by using the transit method. As it has been proven to be true, by K2 and CoRoT and other space crafts for many years now.

Now after deciding that the first light curve possibly represents a planet, knowing even approximate value of the characteristics of a planet is important. Because it can help in analyzing and confirming its existence, by giving proof that respond to existence of a planet. Reasonable values can serve as arguments for the existence of a planet even before it is correctly confirmed. By knowing more about the planet one can also discuss the possibility of the planets hospitability. In view of all the mathematical calculations on chapter 4, the candidate extrasolar planet is a Hot Jupiter more massive than Jupiter, with a short orbital period, a short orbital path, a high velocity and an average surface temperature at 859 K.

Hot Jupiter types of planets are located closer to their host star, which as aforementioned makes them move faster (Catling, 2014, p.151). By also comparing with the characteristics of Jupiter, it seems that all the values calculated in chapter four are somewhat reasonable. This candidate Hot Jupiter planet moves 110 km/s while Jupiter moves about 13km/s due to the distance to the sun (Owen, Britannica, 2015). The high density can be explained as a false

measurement or because of the mass (it is slightly heavier than Jupiter) and the location from the star (it is much closer than Jupiter). As for example Venus (closer to sun) has higher density than Jupiter even though Venus is a smaller planet (Rickman & Davidsson, NE, 2015). The temperature is explained simply by the fact that the planet is very close to its host star and possibly due to tidal locking, this causes uneven and high temperatures in the planet. As written in Linde (2013, p.52, 127) extrasolar planets near the star encounter the highest possibility to exist in a locked rotation system with the host star. With consideration of the abovementioned reasons it can be ascertain that the candidate extrasolar planet seen on the light curve one is a Hot Jupiter, a gaseous planet with high surface temperature.

This Hot Jupiter has a short semi-major axis compared to where the habitable zone of the star most likely is, where a planet faces the highest chances for developing life. K-dwarf stars are smaller than the sun both in mass and volume. In addition the K-dwarf shown on light curve one has a magnitude of 15,961, which is a high value saying that the star does not shine very bright. Due to all these circumstances it is thought that the habitable zone of star one is nearer and thinner than the sun's. Nevertheless, a K-dwarfs habitable zone cannot be as near as 12 million kilometer away (the semi-major axis of the believed candidate planet orbiting the K-dwarf star shown on light curve one), while the sun's is about 148 million kilometers away. According to Catling (2014, p.159) the habitable zone of a K-dwarf can be as near as about the semi major-axis of Venus or Mercuries from the sun (see picture four), which is a longer distance away from the star than the position of the extrasolar planet indicated on the light curve one (the location of the habitable zone can be estimated more profound with necessary instruments, but that is outside of the frame of this work).



Picture 4: The picture above shows the sizes of types of stars compared to the sun on the y-axis and times the radius of the orbit of the earth on the x-axis. By looking at the orange star (fourth count from above-down), which is a K-dwarf with a habitable zone at distance about 0,174 times of the orbits of the earth. It can be seen that a planet with an orbit of Venus would be approximately in the middle of the habitable zone of a K-dwarf star (Yale astronomy, 2010).

Not being in the area where water can be liquid and having such high average surface temperature, the Hot Jupiter around star one is not ultimate to life other than perhaps extremophiles. These life forms may be able to exist in such strict conditions, as some seen living on very warm and extreme volcanic areas of the earth (Linde, 2013, p.46-47; Conway& Gilmour& Jones& Rothery& Sephton& Zarnecki, 2003, p.75-77, 80-83; Catling, 2014, p.114-115). It can in this report straightforwardly be mentioned that the habitable zone is important, however not a guaranty for life. A planet needs to have other right proportions for life; liquid water, a sustainable atmosphere for the greenhouse effect and protection, not too strong gravity, right pressure, a magnetic field for protection, necessary chemical molecules and more, all these cannot be present in a planet just because the planet is in the habitable zone.

Nowadays, when searching for signs of life the atmosphere of a planet is studied, which is in fact challenging due to the large distances. When studying the atmosphere light from the transits, which has traveled through the planet's atmosphere, thereby been changed by the substance of the planet's atmosphere is read in search for signs of oxygen-, water- and carbon dioxide molecules (Linde 2013, p.131-132; Moore& May& Lintott 2009, p.108). This spectrum is then compared with the distinct spectrum of the star, in order to separate the absorptions lines from the star's content and those of the planets'. The science and technic used to study atmospheres of planets is problematic and it only gives small deviations, which are intricate to detect (Linde, 2013, p.92, 131-132; Cox & Cohen, 2011, p.88-89,101). However, most surely the future will come with aptly telescopes fully capable to study and detect changes in a light spectrum in order to find out the content of a planet's atmosphere after having confirmed the planets existence and its main characteristics.

Hot Jupiter planets are not the most interesting planets in the search for ETI or primordial life, since they are not suitable for life. However, these planets have been the cause of the need for rewriting our understanding of how solar systems are formed. Before it was known that big planets cannot form close to stars. The existence of Hot Jupiter planets have resulted in two theories which explain the presence of big planets near stars. The explanation says that big planets form far from the star and migrate closer and closer, some with high velocity others slower, until they find a hole in the cloud of leftovers from the star, where they can maintain position (Linde, 2013; Conway& Gilmour& Jones& Rothery& Sephton& Zarnecki, 2003). It is true that all found planets can give some kind of knowledge which may improve current science or at least help map out as much of the content in space as possible or in some cases perhaps be candidates in search for life.

Lastly planets are confirmed by using another method then the one used to first detect a candidate planet. The radial velocity method, which is one of many effective indirect processes of detection. By using this method the candidate planet thought to be represented on light curve one can be confirmed. The doppler method is similar to the transit method, easy to follow up with other methods, easy to analyze the collected data and both of the methods are based on collections of light from the host star.

In this study the used confirmed graphs for comparision are not in the same time scale and magnitude scale. However they serve well for this study even if the light curves have other periods they have the same appereance and other resemblences. By using confirmed light curves in the same timescale and magnitude as the compared graphs, one can give a stronger argument for the similiraty of the graphs with one and other. Furthermore, even use as a more secure prove for the accuracy of the analysis presented on chapter four.

One more thought around this study is futurereviews. One can take this work further by trying to confirm the existence of the planet of star one studied on graph one. This could be done by using the raidail velocity method or microlensing. The work with analyzing graphs can be taken to another level, by longer studies. One can study many ypes of occurences in the universe and make a collection of how light curves of different celestial objects can look like and how to analyze them. These would take a lot of work and focus, but the result would be very good and very helpful for sceinists, students or even citizens who like to be active on planethunters.org in order to help scientists in their work.

6. Conclusion

The transit method together with mathematics are a valuable science in the search for extrasolar planets in general and for the search after ETI. First of all it is an intricate science to find extrasolar planets and none of the methods of today can accomplish the work individually. However, combinations of methods lead to many discoveries, such as for example Super Earth or Hot Jupiter planets and analysis of planetary atmospheres.

The transit method has many advantages, but finding planets with an orbital path that follows the angles in which the telescopes view the star are occasional and valuable innovations. As always more time is crucial and can reveal many secrets, such as those on the graphs of this study; the light curves two, three and four are common, however light curve one showing a possible extrasolar planet of type Hot Jupiter are less frequently seen. On the other hand, Hot

Jupiter extrasolar planets are more common than smaller planets. Nevertheless, they are all important and useful in their own way.

After analysis and calculations the candidate planet in this report has resulted to be a Hot Jupiter with a mass about 300 times that of earth and with a surface temperature of 859 K. The tough conditions as known today cannot be endured by other than perhaps extremophiles. Nonetheless, it is a hopeful discovery precious for science and general knowledge. The calculations together with the analysis of graphs have shown the values of the method.

The other light curves make other important properties visible, such as variables. As seen on light curve four which in all likelihood seems to display a Mira variable with a period of about nine days. Likewise, light curve three is believed to be confirming the existence of, in this case, an irregular variable. Light curve two, however, without longer observation cannot be concluded to be anything specific. The only transit seen on the curve is not enough to help determine what this light curve reveals. Even so in this report it is presumed that light curve two shows either a planetary transit or an eclipsing binary system, by taking in account the similarities of the light curve to the first light curve and the comparable light curve on graph six on page 21. To sum up, after executed comparison of all four light curves with confirmed light curves and facts from different resources and earlier knowledge in the matter, it can be written that all four light curves represent their characters quite truthfully.

In conclusion the transit method is useful and functional, it also gives much information on an object such as planets, but it also has restrictions. Lastly, the question formulations have been answered throughout the rapport in a thorough and satisfying manner, by theoretical explanations and usage of the transit method itself.

References

All the graphs were downloaded from Planethunters.org, except the ones listed below.

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Cepheid. Used 2016.02.06. <http://www.astrouw.edu.pl/~simkoz/projects/stars/variable/>

NASA, Planethunters, 2014. Star spots. Used 2016.02.06.

<http://www.planethunters.org/#/classify>

Pictures

First page photos:

1. A painting of my own presenting a small piece of the infinite universe humanity can observe with technology, made summer 2015.
2. Hubble telescope picture 10.07.2012. NASA, Brian Dunbar, last updated 30.07.2015. https://www.nasa.gov/mission_pages/hubble/multimedia/index.html?id=351795

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Attachments

The charts below contain information useful for the project. They have been set as attachments due to their lack of bringing direct function to the text in the report. Nevertheless they are necessary to look at for further information if interested and to refer to.

Table 6: In this table there are values of masses of four kinds of planets, in order to be used as a reference to the calculated mass of the candidate extrasolar planet indicated by light curve one. This to control if the mass calculated is rather reasonable at all (Zooniverse teams, 2014, p.98-99, 94).

Type of planet	Mass (kg)	Mass in earth mass
Hot Jupiter	$1,0 \times 10^{27}$	$317,8 m_{Tellus}$
Hot Neptune	$1,03 \times 10^{26}$	$17,23 m_{Tellus}$
Super Earth	$1,90 \times 10^{27}$	$317,8 m_{Tellus}$
Exo Earth	$5,976 \times 10^{24}$	$1 m_{Tellus}$

Table 7: This chart below shows the needed information about the star represented on light curve two.

Star information for curve 2:

Type of star	K-dwarf
Magnitude	15,187
Surface temperature	5114
Radius	$0,784 R_{Sun}$

Table 8: This chart below shows the needed information about the star represented on light curve three.

<u>Star information for curve 3:</u>	
Type of star	K-dwarf
Magnitude	14,365
Surface temperature	5063
Radius	0,609 R_{Sun}

Table 9: This chart below shows the needed information about the star represented on light curve four.

<u>Star information for curve 4:</u>	
Type of star	K-dwarf
Magnitude	15,279
Surface temperature	4856
Radius	0,696 R_{Sun}