Observations and Mathematical Modelling of Exoplanet WASP-52b

By

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Abstract
The purpose of this project is to show how mathematics plays an important part in the detection of exoplanets. It starts with a brief introduction on exoplanets and the methods used to detect them. Then Wasp 52-b was selected to be used as an example of the transit method. Observations of the host star were attempted at Clanfield Observatory but were not successful. Existing data was processed in AIP4Win and subsequently Microsoft Excel was used to produce a light curve graph. From this graph parameters of the chosen exoplanet were calculated. Next Maple was programmed to produce a theoretical light curve based on the physics of orbits, line of sight geometry and stellar limb darkening. Finally conclusions of the project have been reported together with recommendations into any further study as well as research into exoplanets that is currently being studied.
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Introduction

Looking up at the night sky there appears to be hundreds of stars illuminating Earth. In reality we are surrounded by approximately 300 billion stars in our own Galaxy, the Milky Way, alone. There are numerous estimates as to how many galaxies could be in our Universe, many containing even more stars than the Milky Way. When considering these vast numbers it’s very hard to believe that Earth is the only planet orbiting a star on which life has managed to evolve. Stephen Hawking famously said “To my mathematical brain, the numbers alone make thinking about aliens perfectly rational. The real challenge is to work out what aliens might actually be like” (“Stephen Hawking”, 2010).

Extra solar planets, more commonly known as Exoplanets, are planets that orbit a star that is not our Sun. “The first discovery of a planet orbiting a star similar to the sun came in 1995. The Swiss team of Michel Mayor and Didier Queloz of Geneva announced that they had found a rapidly orbiting world located blisteringly close to the star 51 Pegasi” (“Exoplanet History”, n.d). As of the 12th January 2014 there have been 1060 exoplanets discovered in 802 different planetary systems, 175 of which are multiple planetary systems (Zolotukhin, I, 2014); however no intelligent life so far has been found.

Star Types

Stars are placed into seven classes; O, B, A, F, G, K and M respectively. Stars at the top end of the spectrum, O and B, are very hot with surface temperatures up to 60,000K. They are blue or white in appearance (“Stellar Spectral Types”, n.d). The stars are then subdivided into smaller groups called spectral types. This is done by placing a number between 0 and 9 after the spectral class letter. Stars with a 0 are the hottest in the class and they get cooler as the number gets closer to 9.

There is an overwhelming amount of data that has been collected on stars in the universe and the most efficient way to represent this is by using a graph. Some properties don’t need to be included, such as the radius, as it can be calculated. Ejnar Hertzsprung noticed that “a regular pattern appears when the absolute magnitudes of stars (which measure their luminosities) are plotted against their colours (which measure their surface temperature)” (Freedman, R.A., Geller, R.M., & Kaufmann W.J., 2011, p452). Furthermore, Henry Norris Russell independently used absolute magnitude against spectral class. Together the Hertzsprung-Russell diagram was created, as seen in figure 1.1. Unlike most graphs as you move left along the x axis the temperature, and spectral class, decrease. The absolute magnitude, y axis, decreases as you move up the graph. Extremely hot and bright stars are located in the top left hand corner and cool, small, dim, red stars (red and brown dwarves) are in the bottom right hand corner. As you can see on figure 1.1 several prominent stars such as Betelgeuse, a red giant star, have been labelled.
The majority of the exoplanets detected so far are orbiting host stars similar to our Sun. They are found on the main sequence and mainly have a spectral type of F, G and K. This is mainly because astronomers tend to focus their search around Sun-like stars.

**Classification of Exoplanets**

Exoplanets can be grouped into many types based on their composition, temperature and many other properties. Some classifications are described below.

**Terrestrial**

Terrestrial planets, such as Earth, are primarily made from metals and rocks with a metallic core. They have physical features such as canyons, valleys and volcanoes. Unlike gas based planets, terrestrial planets tend to have few moons, such as Earth only having one and Venus having none.

**Hot Jupiters**

As the name suggests, these types of exoplanets have similar properties to Jupiter. They are quite big, full of gas and have approximately the same radius and mass as Jupiter; however they have a higher surface temperature as they orbit very much closer to their host star. “They were the first extrasolar planets to be confirmed, in part because they were the easiest to find. They have the largest gravitational tug on
their stars, so their signature in the Doppler method of planet hunting is the strongest” (Schkolnik, E. n.d).

**Pulsar Planets**
Pulsar planets orbit pulsar stars. “These super dense, rapidly spinning stars are the core remains of a large star after a supernova explosion” (“Types of Exoplanets”, n.d). These planets are detected using a method called pulsar timing. The planet causes the stars pulsation to undergo a regular change and this is what we detect. The first exoplanet to be discovered was orbiting “an old, rapidly spinning neutron star, PSR B1257+12, during a large search for pulsars conducted in 1990 with the giant, 305-m Arecibo radio telescope” (“Planets around pulsars”, n.d).

**Aims**
In this project I have set several aims that I wish to fulfil. I am going to:

- Look at the various methods to detect exoplanets and explain the advantages and disadvantages of each.
- Explain how the transit method is used to detect exoplanets and demonstrate this by visiting the observatory to make observations and collect data.
- To process the images collected on AIP4WIN.
- Analyse the data collected from my observations and use Excel to create a light curve graph.
- Calculate parameters of the chosen exoplanet using data obtained from the graph created and results from the internet.
- Model the data in Maple and create a theoretical light curve using the parameters of the exoplanet.
- Draw conclusions for the project and look into areas of further study.
Detection Methods

There are various methods used today to detect exoplanets and in this chapter we will explore them. The techniques fall into two categories; direct or indirect. Direct methods are more difficult and less accurate as they work by actually viewing the star and orbiting planet. Indirect methods use equations and graphs to detect the planet rather than observing it. These are described in more detail below.

Direct Methods

Direct Imaging

All of the planets in our Solar System are extremely close to us and were detected by using direct imaging from Earth. However, the further away the object is the more difficult it is to use direct imaging. This is because “the separation between an extrasolar planet and its star is minuscule compared to the distances between stars. A star like the sun is about a billion times as bright as the reflected light from any extrasolar planet orbiting it.” ("Detecting ExtraSolar Planets", n.d). Direct imaging is easiest when the star is close to Earth. However this accounts for a very minute number of stars compared to the total in the Galaxy so another method is needed when we want to observe more distant stars. Furthermore direct imaging can’t give very accurate parameters of the discovered exoplanet. Figure 2.1 shows the exoplanet DH Tau b being observed by the direct imaging method.

Figure 2.1 The Exoplanet DH Tau b (lower left) in Taurus was discovered in 2005.
Coronography
A coronagraph is an attachment to a telescope that works by blocking out the light from brighter objects to allow fainter objects to be detected. “It was invented in 1930 by the French astronomer Bernard Lyot and was used to observe the Sun’s corona and prominences” (“Coronagraph”, n.d). Astronomers have changed and adapted the original technique to find exoplanets. Stellar coronagraphs block out light from a parent star, which in turn allows the exoplanet to be seen. Stellar and solar coronagraphs are similar however in practice are quite different because of the apparent size of the objects. A nearby star to be occulted has an apparent size of a few milliarcseconds whereas the sun is 30 arcminutes.

The first exoplanet discovery using this method was Fomalhaut b orbiting the star Fomalhaut, and was discovered by NASA’s Hubble telescope. “Fomalhaut has been a candidate for planet hunting ever since an excess of dust was discovered around the star in the early 1980s by NASA’s Infrared Astronomy Satellite, IRAS” (Harrington, J.D. (2008, November 9)).

Indirect Methods

Astrometry
Astrometry is an indirect method for detecting exoplanets. It “is used to look for the periodic wobble that a planet induces in the position of its parent star.” (“Planet Detection Methods”, n.d). The first discovery of an exoplanet using this method occurred in 1943 by Kaj Strand at the Sproul Observatory of Swarthmore College. He discovered a planet orbiting the star 61 Cygni; however this has never been proved. (“The past and future of planet hunting”, n.d)
Planets orbit stars and both objects possess mass, therefore rather than the planet orbiting just around the star all bodies in the system actually orbit around the barycentre, the centre of the system as shown in figure 2.3. The star in the system will produce a small reflex orbit, as the planet orbits the barycentre, to keep the centre of the mass at the barycentre.

The semi-major axis, $a$, of the orbit is calculated by adding together the semi-major axes of the star in its reflex orbit, $a_*$, and the planets orbit, $a_p$, giving $a = a_* + a_p$.

![Figure 2.3 Orbits of a planet and its host star around the barycentre.](image)

Kepler’s third law of planetary motion states that “the square of the period of any planet is proportional to the cube of the semi-major axis of its orbit.” ("Kepler’s Laws", n.d). Generalising this and using “$a$” from above and “$P$” as the orbital period we obtain:

$$\frac{a^3}{P^2} = \frac{G(M_* + M_p)}{4\pi^2}$$

Equation 2.1

A reflex orbit of a star can be found as an angular displacement, $\beta$, from a distance, $d$. The astrometric wobble, $\beta$, is proportional to the semi-major axis.

$$\beta = \frac{a_*}{d}$$

Equation 2.2

Using the equation

$$a_* = \frac{M_p}{M_*} a_p$$

Equation 2.3
This evaluates to

\[ \beta = \frac{M_p a_p}{M_* d} \]

Equation 2.4

(Haswell, C.A., 2010, p27)

As can be seen from equation 2.4 as \( M_p \) and \( a_p \) increase the astrometric wobble increases. Therefore astrometry is best for detecting exoplanets with a large mass and orbit. However, using this method to discover exoplanets can be very difficult, as if the exoplanet is of low mass it will be quite hard to detect. This is because the barycentre is closer to the centre of the star, and thus the wobble will be smaller. Also as stated above a planet with a long orbital period should in theory make this method easy, however you need to observe more than one orbit which could take several years.

**Radial Velocity**

Similarly to the astrometry method, radial velocity relies on a star’s reflex orbit. The difference is that it looks for changes in the velocity of the star rather than its position- it’s still measuring the same wobble. It is based on the Doppler effect. A star’s radial velocity, the speed that it moves towards and away from Earth “will cause dark absorption lines in the star’s spectrum to change their wavelengths in a periodic fashion. When the star is moving away from us its spectrum will undergo a redshift to longer wavelengths. When the star is approaching, there will be a blueshift of the spectrum to shorter wavelengths” (Freedman, R.A., Geller, R.M., & Kaufmann W.J., 2011, p200). If the change in colour of a star’s spectrum between blue and red repeats itself, then the star is moving toward and away from Earth. This movement is caused by a low mass object, a planet, orbiting the star.

The main disadvantage of this technique is that it cannot give the observer an accurate mass of the exoplanet, only a minimum. Additionally the radial velocity method works best when the angle between the plane of the planet’s orbit is parallel with the line of sight to the Earth; it is more difficult if there’s little radial velocity, and impossible if it is perpendicular to the line of sight from Earth. However most of the exoplanets discovered have been detected by using this method. As mentioned in the introduction, 51 Pegasi was the first exoplanet to be discovered and it was found by radial velocity.

**Gravitational Microlensing**

Gravitational microlensing occurs when two stars are almost aligned with each other from the observer’s view. The star that is further away from Earth is normally brighter than the closer one, which we wouldn’t usually be able to see. When the dimmer star passes in front of the brighter one “its gravity causes the light from the farther star to bend and the star is magnified from our point of view. If, during the event, the background star appears to be magnified even more for a short time, that means a
planet orbiting the smaller star is increasing the effect of the magnification” (“Gravitational Microlensing”, n.d). Figure 2.4 illustrates how the lens star bends the light from the source to allow us to detect the Exoplanet.

When using this method astronomers tend to look at densely populated areas like the galactic bulge, the centre of our Galaxy where the stars are tightly packed, because there is a higher chance of an alignment of two stars to occur. The main disadvantage of gravitational microlensing events is that they are a one-off occurrence. The events are brief, lasting a few days or week and after this you would not be able to view the exoplanet in the exact same conditions. It is, however, the method that is most likely to detect an exoplanet outside of our Galaxy.

**Transits**
The transiting method to find an exoplanet is the main focus of this project. When an object passes in front of a star, some of the light is partially blocked, and this is called a transit. If it happens periodically we can assume that it is caused by a planet orbiting the star and if the change in brightness and transit duration is the same each time then it is being produced by the same exoplanet. This change in brightness can be measured to determine the size of the planet.

\[
\frac{\Delta F}{F} = \frac{R_p^2}{R_\star^2}
\]

Equation 2.5

\( F \) is the measured flux from the star and \( \Delta F \) is defined as the change in flux. The right-hand side is the ratio of the areas of the planets and star’s discs (Haswell, C.A., 2010, p39). From this we have an estimate to the planet’s size.
Observations at Clanfield Observatory

As part of the project I was required to make observations and collect data of a transiting exoplanet. I carried out this task at Clanfield Observatory with the help of my mentor David Harris. I was taught the necessary methods needed to use the 24 inch telescope to collect my data.

Transiting Exoplanet Candidates

Before I could make my observations I had to find a suitable candidate to observe. For this I looked at a Czech database where they have a section devoted to exoplanets, Exoplanet Transit Database (ETD).

Firstly I had to input the latitude, 51° north, and longitude, 359° east, coordinates for Clanfield observatory, and these were found on the Hampshire Astronomical Group’s website. After this I was presented with data of possible transits that could be seen from my location as seen in figure 3.1.

![Figure 3.1 The ETD website showing its predictions of possible transits.](image-url)
The database gives information about each of the transits. It gives you the start and end times of the transit and the duration in minutes. You also know the depth, magnitude and position of the star.

There are a number of factors that I had to take into consideration when choosing a transit. The magnitude of the star had to be at least 14 otherwise it would be too dim and therefore difficult to detect with the equipment. The timing and duration of the transit was very important. It had to take place on a day where both David and I were available to observe it. The transit needed to start late enough so that it was dark outside and be of an appropriate length, up to three hours preferably, so I could observe it fully. For a transit to be detected with the 24 inch telescope the star needs a declination of 30° above the horizon otherwise it would be affected by atmospheric conditions and light pollution from nearby towns. The dip in the magnitude (depth) has to be taken into consideration. For a ground based telescope to reliably detect a transit, the dip has to be greater than 0.015 magnitudes or we could not observe the transit. Lastly the weather is a crucial factor in observing a transit. It needs to be a relatively clear night, otherwise the clouds will block our view of the star and we would not be able to record any data.

**Observations**

There are many steps involved in observing a transit. On a visit to the observatory David demonstrated how to set up the 24 inch telescope and the other necessary equipment as described below.

1. The dome is motorised, there are clamps that need to be undone so it is free to move.
2. There is a plastic cover over the telescope that needs to be removed. This prevents condensation from forming which would obscure observations and in very low temperatures could turn to ice, possibly damaging the telescope.
3. Now the clamps on the telescope need to be undone so it can move.
4. The power to the telescope and the drive system is now turned on.
5. The telescope uses stepper motors to move. It is linked to a point targeting system where you can input the stars co-ordinates (right ascension and declination). The telescope will then slew to these coordinates.
6. The CCD camera is attached to the telescope and also connected to a laptop so the images can be viewed and captured. The camera has many functions that can be programmed by the laptop and the most important of these is the temperature. It needs to be extremely low for the CCD chip because this reduces background noise, sometimes called dark current, or thermal noise.
7. The mirror is now uncovered.
8. The dome has to be rotated to allow the telescope to view the sky.
9. Finally we are able to carry out observations and collect data for the chosen transit.
Unfortunately due to bad weather over Winter I wasn’t actually able to carry out my own observations. However David Harris allowed me to use data he had collected before of WASP-52b and this was the exoplanet transit that I have processed and analysed.
Image Processing

In this chapter the data received is going to be processed in AIP4Win and then a light curve will be created for WASP 52b using Microsoft Excel.

AIP4Win Image Analysis

The data that I received from David needed to be processed in AIP4Win (Astronomical Image processing for Windows) before a light curve for the transit could be created. The images (found in appendix B) collected from Clanfield via the CCD camera were saved as FITS (Flexible Image Transport System) files. This is because they can be “used for the transport, analysis, and archival storage of scientific data sets” (Pence, W.D 2013). These files allow the time of each image, using the Julian date, to be recorded. The process that I undertook is described in the following paragraphs.

The Multiple Image Photometry tool that AIP4Win offers allows you to extract the brightness data from a series of images to create a light curve (Berry & Burnell, 2005).

We have to tick “Auto-Calibrate” and then select all of the image files to be analysed. (Images are on Appendix B).
The first image is displayed and the next step is to identify the host star. For this software called Skymap Pro was used. It produces an image of Wasp 52 and the stars surrounding it. This image can then be compared to the original on AIP4Win.

Once the host star has been identified it is selected and a bull’s-eye appears around it. The aperture (inner circle) needs to be adjusted so that it contains all of the stars light. The annulus (outer circles) shouldn’t be too big so no background light from other stars is included.
Now we have to choose comparison stars. This is to detect any change in brightness of the host star by comparing its light levels against the comparison stars. Some criteria have to be met for the comparison stars. They should be around the same magnitude or slightly brighter than the host star. They should not overlap any other stars and lastly not be variable stars as they change in brightness.

Whilst the CCD camera is taking images of the transit the telescope moves. Therefore the host star and comparison stars will move slightly on the images. AIP4Win uses radii circles, as described above, to track the stars.

The Multiple Image Photometry Tool is then executed. While the program is running it keeps a data log (appendix C) of all the measurements it’s taking, such as magnitude and error, and then two graphs when it has run through all of the images. As seen in figure 4.7, the first graph plots the difference between the magnitudes of my host star, V, and the first comparison star, C1. The second graph plots the difference in magnitudes between the first comparison star and comparison star 2, C2.
Figure 4.7 Screenshot of graphs produced by AIP4Win.
Creating a Light Curve
To create a light curve for the data that AIP4Win has provided, Microsoft Excel was used. The data log for WASP-52b was imported into Excel and any unnecessary columns, such as the sequence number and sigma, were deleted. This reduced the data set to two columns, the Julian date and magnitude, V-C1 as shown in figure 5.1.

![Screenshot of Microsoft Excel with appropriate columns.](image)

Figure 5.1 Screenshot of Microsoft Excel with appropriate columns.

There were now a few simple steps to create the light curve graph from this data set.

The date needed to be changed so that it started from 0. This is because we want the graph to be produced to start from 0. To do this the first date is subtracted from every value in the Julian date column.

The time needs to be converted into hours by multiplying each value by 24.

An average of the last 20 values in the V-C1 column was taken and then subtracted from the original magnitudes and placed in a new column (Dm). The last 20 values were used because the beginning of the transit was missed. This is done because it estimates the out of transit magnitude of the star. It is subtracted from the transit data to obtain a magnitude difference.
To create the curve for the graph the flux needed to be calculated. Equation 5.1, below, is rearranged to form equation 5.2.

\[ m_1 - m_2 = -2.5 \log_{10} \frac{F_1}{F_2} \]

Equation 5.1

(Dhillon, V. 2013)

\[ \frac{F_1}{F_2} = 10^{\frac{m_2 - m_1}{2.5}} \]

Equation 5.2

Now \( m_2 - m_1 \) is substituted with the values from the Dm column and we have an equation for the flux.

Figure 5.2 shows Excel with the formulas used that are being performed.
Here figure 5.3 shows the Excel table with the calculated values.

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Figure 5.3 Screenshot of completed Excel table.
A scatter graph is produced by using the Time (Hours) data for the x-axis against the Flux for the y-axis.

![WASP-52b Light Curve](image1)

As you can see, there is a dip in the graph, though not too noticeable. To smooth the curve a new graph using a moving average was created. This has used 5 points before and after each observation and averaged them, and for the flux values near the beginning and end of the table similar formulas have been used.

![Moving Average Light curve](image2)

Figure 5.4 Graph produced on Microsoft Excel showing the transit of WASP-52b.

Figure 5.5 Graph produced on Microsoft Excel plotting the moving average of the flux against the time (hours).
**Data analysis**

This chapter describes the analysis of the light curve that has been created to calculate parameters of the exoplanet, such as radius, orbital period and impact parameter. Maple has also been used to model WASP 52b orbiting its host star.

**ETD Data**

After looking at the light curve that has been created I decided to use data from the Exoplanet Transit Database. As the beginning of the transit was missed I have decided that using other data would be able to determine more accurate parameters.

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<tr>
<th>#</th>
<th>HJD mid (2400000 + )</th>
<th>Epoch</th>
<th>O-C (d)</th>
<th>D (min)</th>
<th>Depth (mmag)</th>
<th>band</th>
<th>DQ</th>
<th>LC</th>
<th>Author &amp; REFERENCE</th>
<th>changed</th>
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<td>102 +/- 2.9</td>
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<td>112.2 +/- 1.9</td>
<td>31.3 +/- 1</td>
<td>R</td>
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</table>

Figure 6.1 A screenshot of the ETD website with WASP 52b data.

I chose to use the data highlighted because it has been given a quality rating of 1. This means that the light curve will have a definite beginning and ending with a smooth curve. Once the chosen data had been selected I imported it into Excel and created a light curve using the method explained in the previous chapter.
From this new light curve graph, figure 6.2, the parameters of WASP 52b could then be calculated.

**Characteristics of WASP 52**
To calculate the parameters of WASP 52b some characteristics of the host star are needed. This is because the transit method can’t give us all the information required. The host star has the following characteristics:

Spectral Type: K

Apparent Magnitude: 12

Mass: $0.87 \pm 0.03 \, M_{\text{Sun}}$

Radius: $0.79 \pm 0.02 \, R_{\text{Sun}}$

Right Ascension: 23:13:59.0

Declination: +08:45:41

(Zolotukhin, I. 2014)

**Orbital Period**
The orbital period is the time it takes for WASP 52b to complete one orbit of WASP 52. In the equation below $T_{\text{elapsed}}$ is the time between each transit and $N_{\text{cycles}}$ is the number of cycles that occurs in the time period.

$$P = \frac{T_{\text{elapsed}}}{N_{\text{cycles}}}$$

Equation 6.1
As two transits are needed for the orbital period I looked on the ETD to compare data.

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<th>#</th>
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<th>Epoch</th>
<th>ΔC (d)</th>
<th>Δ(Min)</th>
<th>Depth (m/mag)</th>
<th>band</th>
<th>DQ</th>
<th>LC</th>
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Figure 6.3 A screenshot of the ETD website with WASP 52b data.

To calculate $T$ the first column, midpoints of the Julian Date, are used to find the difference in time.

$$56614.32652 - 56600.331 = 13.99552$$

The Epoch values are used to determine the number of cycles that occur during the above period.

$$469 - 461 = 8 \text{ cycles}$$

Now using equation 6.1 we find that the orbital period is:

$$\frac{13.99552}{8} = 1.74944 = 1.75 \text{ days}$$

**Semi major Axis**

To calculate the semi major axis Kepler’s Third Law of Planetary Motion is needed. It is rearranged to give:

$$a = \left( \frac{G(M_\star + M_p)P^2}{4\pi^2} \right)^{1/3}$$

Equation 6.2
\( M_p \), the mass of the planet, is not needed in the equation because it is only a tiny fraction of the mass of the system. We will still get a good estimate of the semi major axis. The mass of the star needs to be converted into kg by using \( 1M_{\text{sun}} = 1.989 \times 10^{30} \text{kg} \) and the orbital period from days to seconds. Using equation 6.3 and:

\[
G = 6.67 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}
\]

\[
M^* = 0.87M_{\text{sun}} = 1.73043 \times 10^{30} \text{kg}
\]

\[
P = 1.74944 \text{ days} = 151151.616 \text{ s}
\]

We can compute that the semi major axis is:

\[
a = \left( \frac{6.67 \times 10^{-11} \times 1.73043 \times 10^{30} \times (151151.616)^2}{4 \times \pi^2} \right)^{1/3} = 4057407000 = 4.057 \times 10^9 \text{m}
\]

Finally this is converted into astronomical units:

\[
\frac{4057407000}{1.4960 \times 10^{11}} = 0.02712 \text{ AU}
\]

**Radius of WASP 52b**

As mentioned in chapter 2 the transit method allows us to find the radius of the exoplanet by using the flux, \( F \). An approximate for the flux of WASP 52b can be read off of the light curve graph, and using that the change in flux, \( \Delta F \), can be found.

\[
\frac{\Delta F}{F} = \frac{R_P^2}{R_E^2}
\]

Equation 6.3
From the graph we can see that $F$ is around 1.0075. The bottom dip of the curve is about 0.9775 giving

$$\Delta F = F - F_{bottom} = 1 - 0.968 = 0.032$$

Equation 6.3 can be rearranged to make $R_p$ the subject:

$$R_p = \sqrt{\frac{\Delta F \times R_*^2}{F}}$$

Inputting our values:

$$R_p = \sqrt{\frac{0.032 \times 549832100^2}{1}}$$

$$R_p = 98356956.14m$$

Looking at the exoplanet catalog (Zolotukhin, I. 2014) the radius of WASP 52b is:

$$1.27R_J = 1.27 \times 7.1492 \times 10^7 = 90794840 = 9.079 \times 10^7m$$

**Uncertainty in the Light Curve**

Comparing the calculated value against the internet value they differ by quite a bit. The uncertainty of the dip in the light curve can be determined. The standard deviations of the out of transit magnitude values and the dip of the curve values are computed to measure the uncertainty.

To find the standard deviation of the out of transit flux the last 21 values in the table were used. From each value, $x_i$, the average of the out of transit flux's was subtracted from each $x_i$ and placed in the column labelled ‘Deviation of Flux’ as can be seen in figure 6.5. Next the deviation values were squared, $(d_i)^2$, and then an average of them was found, $((d_i)^2)/n$. Lastly the square root of this value was calculated which gave the standard deviation for the out of transit flux values. After following these simple steps the standard deviation is found to be 0.004 as seen in figure 6.5.
Subsequently the standard deviation of the dip of the curve had to be calculated. Before this could be done an average of the values in the dip needed to be found. The same steps, as described for the out of transit values, are then followed to find the second standard deviation. Figure 6.8 shows that this standard deviation is 0.003.

| Deviation of M (di) | (di)^2 | (|di|^2)/n | sqrt((|di|^2)/n) |
|---------------------|--------|-----------|-----------------|
| -0.0023333          | 5.4444E-06 | 7.97111E-06 | 0.003           |
| -0.0032333          | 1.0454E-05  | 7.97111E-06 | 0.003           |
| -0.0034333          | 1.1787E-05  | 7.97111E-06 | 0.003           |
| 0.0000667           | 9.4044E-06  | 7.97111E-06 | 0.003           |
| 0.0008667           | 7.51111E-07 | 7.97111E-06 | 0.003           |
| -0.0016333          | 2.36111E-06 | 7.97111E-06 | 0.003           |
| 0.0037667           | 1.4187E-05  | 7.97111E-06 | 0.003           |
| 0.0007667           | 5.8777E-07  | 7.97111E-06 | 0.003           |
| 0.0021667           | 4.69444E-06 | 7.97111E-06 | 0.003           |
| 0.0023667           | 5.60111E-06 | 7.97111E-06 | 0.003           |
| 0.0016667           | 2.77778E-06 | 7.97111E-06 | 0.003           |
| 0.0056667           | 2.56711E-05 | 7.97111E-06 | 0.003           |
| -0.0005333          | 2.84444E-07 | 7.97111E-06 | 0.003           |
| 0.0009667           | 9.34444E-07 | 7.97111E-06 | 0.003           |
| 0.0006667           | 4.44444E-07 | 7.97111E-06 | 0.003           |
| -0.0052333          | 3.88544E-05 | 7.97111E-06 | 0.003           |
| -0.0013333          | 1.77778E-06 | 7.97111E-06 | 0.003           |
| -0.0027333          | 7.47111E-06 | 7.97111E-06 | 0.003           |

Figure 6.5 Table in Excel to compute the standard deviation of the out of transit magnitudes.

| Deviation of M (di) | (di)^2 | (|di|^2)/n | sqrt((|di|^2)/n) |
|---------------------|--------|-----------|------------------|
| -0.004221           | 0.000018 | 1.255E-05 | 0.004            |
| -0.003120           | 0.000010 | 1.000E-05 | 0.001            |
| 0.002589            | 0.000007 | 1.000E-05 | 0.001            |
| 0.000929            | 0.000001 | 1.000E-05 | 0.001            |
| -0.001660           | 0.000003 | 1.000E-05 | 0.001            |
| 0.002312            | 0.000005 | 1.000E-05 | 0.001            |
| -0.007426           | 0.000055 | 1.000E-05 | 0.002            |
| -0.007517           | 0.000057 | 1.000E-05 | 0.002            |
| 0.003329            | 0.000011 | 1.000E-05 | 0.001            |
| -0.002569           | 0.000007 | 1.000E-05 | 0.001            |
| 0.000929            | 0.000001 | 1.000E-05 | 0.001            |
| 0.000662            | 0.000000 | 1.000E-05 | 0.000            |
| 0.006929            | 0.000001 | 1.000E-05 | 0.001            |
| 0.003236            | 0.000010 | 1.000E-05 | 0.001            |
| 0.00898            | 0.000014 | 1.000E-05 | 0.001            |
| -0.000922           | 0.000001 | 1.000E-05 | 0.001            |
| -0.003120           | 0.000010 | 1.000E-05 | 0.001            |
| 0.002497            | 0.000006 | 1.000E-05 | 0.001            |
| 0.00393            | 0.000015 | 1.000E-05 | 0.001            |
| 0.005734            | 0.000033 | 1.000E-05 | 0.001            |
| -0.00269            | 0.000000 | 1.000E-05 | 0.000            |

Figure 6.6 Table in Excel to compute the standard deviation of the dip in the curve.
Finally the two uncertainties (standard deviation), 0.004 and 0.003, need to be combined. To do this a simple formula can be used:

$$\delta X = \sqrt{\delta A^2 + \delta B^2}$$

Equation 6.4

where $\delta A$ is the out of transit uncertainty, 0.004, and $\delta B$ is the dip in the curve uncertainty, 0.003. Substituting these values into equation 6.4 to find the overall uncertainty:

$$\delta X = \sqrt{0.004^2 + 0.003^2} = 0.005$$

This value of 0.005 is added and subtracted from $\Delta F$ and $R_p$ is recalculated.

$$R_p = \sqrt{\frac{(0.032 + 0.005) \times 549832100^2}{1}}$$

$$R_p = 105762316.1$$

$$R_p = \sqrt{\frac{(0.032 - 0.005) \times 549832100^2}{1}}$$

$$R_p = 90346633.2$$

This gives that the radius of WASP 52b could be anywhere between:

$$90346633.2 \leq x \leq 105762316.1$$

The value of 98356956.14 that was previously calculated for the radius fits comfortably within this boundary.

**Orbital Speed**

To find orbital speed the semi major axis and the orbital period are needed from above. Assuming a circular orbit the orbital speed can be calculated using equation 6.5:

$$v = \frac{2\pi a}{P}$$

Equation 6.5

(Wilson, P.A. n.d)
Substituting in our calculated values for $P$ and $a$ we compute that the orbital speed of WASP 52b is:

$$\frac{2 \pi \times 4057407000}{151151.616} = 168661.3794 = 1.68661 \times 10^5 \text{ ms}^{-1}$$

**Time Duration, Inclination and Impact Parameter**

Using the above parameters that have been calculated the last three, time duration, inclination and impact parameter, can be determined.

**Time Duration**

The length of a transit can be computed using the planets orbital period, semi major axis and radius of the star. The transit duration for a planet with impact parameter $b=0$ has the following equation:

$$T_{dur} = \frac{PR_\ast}{\pi a}$$

Equation 6.6

By inputting WASP 52b’s data we find that it has a transit time of:

$$\frac{2519.1936 \times 549832100}{\pi \times 4057407000} = 108.666 = 108 \text{ minutes}$$

This value can be checked by consulting the light curve that has been created. By finding the time at which the transit begins and subtracting it from the end time the duration will be found.

![WASP 52b Light Curve](image-url)

Figure 6.7 Light curve graph with lines to determine transit duration.
Here, in figure 6.7, we have that the end of the transit is around 2 hours and 24 minutes (144 minutes) and it begins at 36 minutes giving a transit duration of 108 minutes which matches our calculated value.

**Impact Parameter**

The impact parameter is the point in the orbit where the centre of the planet’s disc is at its shortest distance to the centre of the stars disc. It is the value at this vertical distance.

As can be seen from figure 6.8 there is a relationship between the impact parameter, orbital inclination and semi major axis. Using trigonometry we can deduce the formula for the impact parameter. To find the adjacent length, b, we need the hypotenuse multiplied by the cosine of the angle giving us:

\[ b = a \cos i \]

Equation 6.7

![Figure 6.8 Illustrating the math used to find the impact parameter.](image)

![Figure 6.9 Diagram demonstrating how Pythagoras’s theorem can be used.](image)
From figure 6.9 it can be seen that the hypotenuse can be expressed as $R_\ast + R_p$. As a right angle triangle has been formed Pythagoras’ Theorem can be used to find the length of $l$.

$$l = \sqrt{(R_\ast + R_p)^2 - a^2 \cos^2 l}$$

Equation 6.8

![Figure 6.10 A representation of the exoplanet moving from point A to B.](image)

From figure 6.10 we can deduce a second formula for the transit duration, which will allow us to calculate the orbital inclination, by using length $l$. When the transit is occurring the exoplanet moves from A to B. “If the orbit is circular, the distance around the entire orbit is $2\pi a$, and the arc length between A and B is $a \times \alpha$, with $\alpha$ in radians” (Haswell, C.A 2010). As can be seen in figure 6.8 a straight line from point A to B has length $2l$. A triangle is formed from A, B and the centre of the star giving:

$$\sin \frac{\alpha}{2} = \frac{l}{a}$$

Equation 6.9

Given that $\alpha$ is measured in radians and the exoplanet has a circular orbit, equation 6.9 can be rearranged to make $\alpha$ the subject. Therefore the duration of the transit is:

$$T_{dur} = \frac{P}{2\pi} \frac{\alpha}{\pi} = \frac{P}{\pi} \sin^{-1}\left(\frac{l}{a}\right)$$

Equation 6.10

We can now substitute in $l$ that we calculated in equation 6.8 to give:

$$T_{dur} = \frac{P}{\pi} \sin^{-1}\left(\frac{\sqrt{(R_p + R_\ast)^2 - a^2 \cos^2 l}}{a}\right)$$

Equation 6.11
**Inclination**

The orbital inclination of a planet is the “angle the orbit plane makes when compared to the Earth’s equator” (Hitt, D. 2010). It is usually expressed in degrees. To find the inclination of WASP 52b the values that have been calculated can be substituted into equation 6.11 and rearranged to find \(i\). We have:

\[
T_{dur} = 6519.6 \text{ seconds}
\]
\[
P = 151151.616 \text{ seconds}
\]
\[
R_p = 90794840 \text{ metres}
\]
\[
R_* = 549832100 \text{ metres}
\]
\[
a = 4057407000 \text{ metres}
\]

Substituting these values into equation 6.11, we find that the orbital inclination of WASP 52b is:

\[
6519.6 = \frac{151151.616}{\pi} \sin^{-1}\left(\frac{\sqrt{4.104028763 \times 10^{17} - 1.64655156 \times 10^{19} \cos^2 i}}{4057407000}\right)
\]

\[
0.1355058457 = \sin^{-1}\left(\frac{\sqrt{4.104028763 \times 10^{17} - 1.64655156 \times 10^{19} \cos^2 i}}{4057407000}\right)
\]

\[
0.1350915363 = \frac{\sqrt{4.104028763 \times 10^{17} - 1.64655156 \times 10^{19} \cos^2 i}}{4057407000}
\]

\[
548121345.2 = \sqrt{4.104028763 \times 10^{17} - 1.64655156 \times 10^{19} \cos^2 i}
\]

\[
3.004370091 \times 10^{17} = 4.104028763 \times 10^{17} - 1.64655156 \times 10^{19} \cos^2 i
\]

\[
-1.099658672 \times 10^{17} = -1.64655156 \times 10^{19} \cos^2 i
\]
\[6.679758408 \times 10^{-3} = \cos^2 i\]

\[0.8172978899 = \cos i\]

\[1.488975244 \text{ radians} \times \frac{180}{\pi} = i\]

\[i = 85.31^\circ\]

Looking on the exoplanet catalog website I can see that my calculation for \(i\) is very close as they state it is 85.35\(^\circ\). Now using my value for the inclination the impact parameter can finally be computed. Taking equation 6.7 and dividing the left hand side by \(R_\star\) to give a dimensionless quantity we get:

\[b = \frac{4057407000 \times \cos 85.31}{549832100} = 0.603\]
Modelling WASP 52b

Now all of the parameters that are needed for WASP 52b have been calculated, along with some useful characteristics of the host star, a theoretical light curve for the exoplanet can be created using Maple. However first it is best to collect all of the parameters we have worked out for the exoplanet and host star.

**Characteristics of WASP 52b**

\[ T_{\text{dur}} = 108.666 \text{ minutes} = 6519.6 \text{ seconds} \]

\[ P = 1.74944 \text{ days} \]

\[ R_p = 1.27 R_j = 1.27 \times 7.1492 \times 10^7 = 90794840m \]

\[ v = 168661.3794 \text{ ms}^{-1} \]

\[ a = 0.02712 \text{ AU} \times 1.4960 \times 10^{11} = 4057407000 \text{ metres} \]

\[ i = 85.31^\circ \]

**Characteristics of WASP 52**

Spectral Type: K

Apparent Magnitude: 12

Mass: 0.87± 0.03 \( M_{\text{Sun}} \)

Radius: 0.79± 0.02 \( R_{\text{Sun}} = 549832100 \text{ metres} \)

Right Ascension: 23:13:59.0

Declination: +08:45:41

(Zolotukhin, I. 2014)

**Creating a Theoretical Light Curve**

Now that a light curve has been created for the transit of WASP 52b using data that was collected at the observatory Maple is used to create a theoretical light curve. Both curves will be plotted on the same graph to illustrate how they match up. I was provided with a Maple worksheet by my supervisor Dr Michael McCabe that was modified to model WASP 52b.

Firstly in Maple a restart command is used. This resets the variables in the package and put into effect the plot tools.

\[ > \text{restart:with(plottools):with(plots):} \]

Next a ratio between the radius of the star and planet has to be calculated. For a star: planet ratio measured in metres we have:
The impact parameter needs to be inserted into the code. Maple, using Pythagoras’s theorem, calculates $x$ which is the starting point on the $x$ axis for the exoplanet.

\[ x = \sqrt{(R_{\text{star}} + r_{\text{planet}})^2 - b^2}; \]

A diagram is created from these parameters so we have a visual representation of the transit. The host star is the first line of code, c1. The center of the star is set to the origin (0, 0) and the radius, $r_{\text{star}}$, is 1 as said above. It has a yellow outline. WASP 52b is the second line of code c3. The centre of the exoplanet is set to the co-ordinates (-$x$, $b$) which gives (-0.997, 0.603) and the radius, $r_{\text{planet}}$, is 0.1651. It has been set to green to distinguish it from the star.

\[ c1 := \text{circle}([0, 0], 1, \text{color=yellow, thickness=5}); \]
\[ c3 := \text{circle}([-x, b], r_{\text{planet}}, \text{color=green, thickness=5}); \]
\[ \text{display}(c1, c3, \text{scaling=constrained, filled = true}); \]
Now the code for generating the theoretical light curve starts. A function needs to be defined which will produce the curve. It needs to include the radius of the star and planet as well as a new variable for the impact parameter, y rather than b. Several other variables are also needed to make the function work. These are defined using local. The third line in this section uses the variable ds to calculate the separation of centres for both the exoplanet and star. $r_{\text{max}}$ and $r_{\text{min}}$ are used to find the maximum and minimum radii for both objects, respectively. Lastly $d_{\text{max}}$ calculates the maximum distance of both objects.

\[
y = \text{impact parameter (rather than b)}
\]

```plaintext
> lightcurve:= proc( Rstar, rplanet, y)
  local A,B,B1,p1,p2,p3,p4,p5,ds,rmax,dmax,rmin,dmin;
  ds:=sqrt(d^2+y^2);
  rmax:=Rstar+rplanet;
  rmin:=Rstar-rplanet;
  dmax:=sqrt(rmax^2-y^2);

  if y < rmin then dmin:=sqrt(rmin^2-y^2) else dmin:=0 end if;

  A:=-r^2*arccos((ds^2+r^2-R^2)/(2*ds*r))+R^2*arccos((ds^2+R^2-r^2)/(2*ds*R))-(1/2)*sqrt((-ds+r+R)*(ds+r-R)*(ds-r+R)*(ds+r-R));
  B:=(p1*R^2-A)/(p1*R^2);
  B1:=subs([R=Rstar,r=rplanet],B);

  next variables had to be assigned to plot parts of the light curve.
  p1:=plot(B1,d=0..dmax);
  p2:=plottools[reflect](p1,[[0,1],[0,-1]]);
  p3:=plot(1,d=-2..-dmax);
  p4:=plot(1,d=dmax..2);
  p5:=plot(1-(rplanet/Rstar)^2,d=-dmin..dmin);
  plots[display](p1,p2,p3,p4,p5);
end proc:
```
This new segment of the code starts plotting sections of the theoretical curve. Maple allows txt files to be imported to the document if everything is saved in the same folder. The time in hours and flux values are pasted into notepad and saved as a txt file so they can be used.

**Read in the measured data (N.B. magnitude difference converted to brightness ratio)**

```maple
> light:=readdata(`Appendix F.txt`,2):
```

The data from Excel can then be translated and scaled so it fits with the theoretical light curve. The second part of code is used to translate the imported data and the third line is used to scale it. The last part changes the view of the x and y axes.

```maple
> pdata:=plots[pointplot](light,symbol=diagonalcross,symbolsize=20,thickness=30, color=red):
> pdata2:=plottools[translate](pdata,-1.55,0.00009):
> pdata3:=plottools[scale](pdata2,1.2,1.003):
> plots[display](ptheory,pdata3,view=[-1.9..1.5,0.97..1.003]);
```

The theoretical light curve which has been programmed has a slightly different shape to the observed light curve from the ETD data. It has a flat, straight bottom unlike the observed curve which is rounded. This is due to the effect of limb darkening which will be described in the next chapter.
**Limb Darkening**

Limb darkening is the “phenomenon whereby the Sun looks darker near its apparent edge, or limb, than near the centre of its disc” (Freedman, R.A., Geller, R.M., & Kaufmann W.J., 2011, pg G-9). This occurs because an observer sees the warmest layers at the centre of the disc and at the limb, the cooler layers which produce less light are seen.

**Limb Darkening Laws**

Astronomers cannot directly observe limb darkening in stars that are too different from our Sun. They have to use computer models and assumptions. There are four limb darkening laws that are used to make these assumptions. Each of these laws uses \( u \), the limb darkening coefficient. It represents the gradient of the intensity drop between the limb of the disc and the centre.

1. **Linear Limb Darkening Relationship**
   This is the simplest of the four laws.
   \[
   \frac{I(\mu)}{I(1)} = 1 - u(1 - u)
   \]
   Equation 8.1

   This is the law that will be programmed into Maple.

2. **Logarithmic Relationship**
   The logarithmic relationship is similar to the above linear relationship however it uses two limb darkening coefficients \( u_l \) and \( v_l \).
   \[
   \frac{I(\mu)}{I(1)} = 1 - u_l(1 - u) - v_l \ln \mu
   \]
   Equation 8.2

3. **Quadratic Law**
   \[
   \frac{I(\mu)}{I(1)} = 1 - u_q (1 - u) - v_q (1 - \mu)^2
   \]
   Equation 8.3

4. **Cubic Law**
   \[
   \frac{I(\mu)}{I(1)} = 1 - u_c (1 - u) - v_c (1 - \mu)^3
   \]
   Equation 8.4

Both the quadratic and cubic laws introduce new coefficients: \( u_q, v_q, u_c, v_c \). Laws 2, 3 and 4 are the more complex relationships. They give more flexibility which allows
data to fit more closely. However each of these laws has two coefficients that need to be determined or fixed.

**Theoretical Light Curve with Limb Darkening**

Maple can also be used to implement the limb darkening laws. The next section of the code begins by defining a new function like the one used for the original theoretical light curve. Also we define several new variables that the function will need to use. The “u” in the first line of the code represents the limb darkening coefficient.

```plaintext
lightcurve:= proc(Rstar,rplanet,y,u)
local A,B,B1,p1,p2,p3,p4,p5,ds,rmax,dmax,rmin,dmin,i,F,A1,p1L,p2L,DF1,DF5,p5L,i1;

Next ds is defined as stated previously, the separation of the centres of the host star and exoplanet. The linear limb darkening relationship is represented by i and uses ds.

\[
\begin{align*}
\text{ds} &= \sqrt{d^2+y^2}; \\
i &= 1-u \times (1-\sqrt{1-ds^2});
\end{align*}
\]

Integration is used to calculate the total intensity of the stellar disc and is defined by F. i1 is the linear limb darkening midpoint as seen in the above limb darkening section.

\[
\begin{align*}
F &= \int \left( (1-u \times (1-\sqrt{1-R^2})) \times 2 \times \pi \times R, R=0..Rstar \right) \\
i1 &= 1-u \times (1-\sqrt{1-(Rstar-rplanet+ds)/2})^2;
\end{align*}
\]

The following variables, rmax, rmin, dmax and dmin as well as the if function are all defined as they were in chapter 7.

\[
\begin{align*}
rmax &= Rstar+rplanet; \\
rmin &= Rstar-rplanet; \\
dmax &= \sqrt{rmax^2-y^2}; \\
\text{if } y < rmin \text{ then } dmin &= \sqrt{rmin^2-y^2} \text{ else } dmin &= 0 \text{ end if;}
\end{align*}
\]

Similarly A is also defined the same as previously, the value of the area produced by the two intersecting discs of the planet and star. A1 substitutes in the radius of the exoplanet and host star.

\[
\begin{align*}
A &= r^2 \times 2 \times \text{arccos} \left( (ds^2 + 2 \times r^2 - R^2) / (2 \times ds \times r) \right) + R^2 \times 2 \times \text{arccos} \left( (ds^2 + R^2 - r^2) / (2 \times ds \times R) \right) - (1/2) \times \sqrt{-(ds^2 + R^2) \times (ds^2 - R^2) \times (ds^2 + R^2 - r^2)}; \\
A1 &= \text{subs}(R=Rstar, r=rplanet, A);
\end{align*}
\]

The difference in the intensity is equal to the area of the intersecting discs multiplied by the limb darkening midpoint i1.

\[
\begin{align*}
\text{DF1} &= A1 \times i1;
\end{align*}
\]
Now the code to plot the light curve factoring in limb darkening begins. \( p_{1L} \) creates the dip in the light curve and \( p_{2L} \) reflects and orientates this. \( p_{5L} \) is defined as the minimum point of the dip from \(-d_{\text{min}}\) to \(+d_{\text{min}}\). The plot is then displayed and the function is ended.

\[
\begin{align*}
p_{1L} &:= \text{plot}(1-DF1/F, d=0..d_{\text{max}}); \\
p_{2L} &:= \text{plottools}[\text{reflect}](p_{1L}, [[0,1],[0,-1]]); \\
p_{3} &:= \text{plot}(1, d=-2..-d_{\text{max}}); \\
p_{4} &:= \text{plot}(1, d=d_{\text{max}}..2); \\
DF5 &:= (\Pi \times \text{rplanet}^2) \times i; \\
p_{5L} &:= \text{plot}(1-DF5/F, d=-d_{\text{min}}..d_{\text{min}}); \\
\text{plots}[\text{display}](p_{1L},p_{2L},p_{3},p_{4},p_{5L}); \\
\end{align*}
\]

\( p_{\text{theory}} \) is used to generate the theoretical light curve using the values for both the radii and the impact parameter.

\[
\text{ptheory} := \text{seq}([\text{lightcurve}(\text{Rstar}, \text{rplanet}, b, L), L=0.0..1.0, 0.2]):
\]

Finally the txt file with the data for WASP 52b is imported. Once again the data can be translated and scaled so that it fits the theoretical light curve with the limb darkening lines.

\[
\begin{align*}
\text{light} &:= \text{readdata}('\text{Appendix F.txt}', 2); \\
\text{pdata} &:= \text{plots}[\text{pointplot}](\text{light}, \text{symbol=diagonalcross}, \text{symbolsize=20, thickness=30, color=red}); \\
\text{pdata2} &:= \text{plottools}[\text{translate}](\text{pdata}, -1.55, 0.000); \\
\text{pdata3} &:= \text{plottools}[\text{scale}](\text{pdata2}, 1.2, 0.995); \\
\text{plots}[\text{display}](\text{ptheory, pdata3, view=[-1.5..1.5, 0.965..1.003]});
\end{align*}
\]
This graph plots the data from the ETD website along with the theoretical light curve and a series of limb darkening plots.

**NAAP Simulator**

The Nebraska Astronomy Applet Project NAAP website hosts many simulators; one very useful simulator for this project is the transit simulator. It allows you to input information about a planet and star and produces a light curve that does not factor in limb darkening. It also displays a side-on-view picture of the explanatory system illustrating the size differences between each object. Once the data for WASP 52b and its host star had been inputted it produced figure 8.1.

![Figure 8.1 NAAP transit simulator with WASP 52b and host star data.](image)

By changing some of the variables we can see what effect they have on the light curve and other data. For example, if the radius of the exoplanet is decreased the time the eclipse takes (in hours) decreases and so does the eclipse depth. Furthermore if the radius is increased, both the time and depth of the eclipse increase. Changing the mass of host star has a similar effect as changing the radius of the planet. The semi major axis moves then planet up and down the star. With the mass of WASP 52, when the exoplanets semi major axis gets above 0.058 an eclipse no longer occurs as the planet does not cross the star.

The simulator gives you approximate values for the length of the orbital period and the depth of the transit. As can be seen in figure 8.1 the simulator estimates that the orbital period is 1.76 days which is extremely close to the value of 1.75 days that was calculated in chapter 6. The transit depth can be found on the ETD website, it says that the depth is 0.029 which is also quite close to the simulators approximate value of 0.0219.
Conclusion

Detection Methods
After analysing the possible detection methods used for finding exoplanets each is good in its own way. Direct imaging is useful for detecting nearby objects but cannot help in the detection of terrestrial exoplanets as it is incapable of going beyond our solar system. Microlensing is unreliable as lensing events are a one-off occurrence so results can’t be redone to check for accuracy of results. The radial velocity method is rather good. It has been quite successful for detecting exoplanets around close stars. However its downfall is that it can only measure the radial velocity accurately if the stellar spectrum contains suitable features. Also the star it is observing has to be bright enough. Astrometry can be helpful in finding in finding stars with multiple planets however it requires a lot of precise monitoring of the stars movements. It won’t be too useful at finding terrestrial planets as it is best for detecting high mass planets as they exert a stronger pull on the host star. Lastly is the transit method. It is easiest to detect large exoplanets orbiting low mass stars as this will create a more noticeable dip in the light curve. Finding a terrestrial planet like Earth using this method could be a challenge. However it can give us quite a lot of information about the exoplanet.

Observations and Light Curve Construction
An aim for this project was to collect my own data at Clanfield Observatory. However due to bad weather over Winter this just wasn’t possible unfortunately. David Harris provided data that he had collected a couple of months beforehand. It was processed in AIP4Win which was quite simple to do. This new information was imported to Microsoft Excel to produce a light curve. The first curve produced was a bit too inconclusive. To increase the accuracy of this data more observations could have been done if the project had a longer time scale. In the end data from the ETD site was used and gave a perfect looking curve.

Parameter Analysis
From the light curve graph produced from the ETD data, most of the parameters that were calculated were quite accurate. However the calculated radius was quite far out from the value the internet provided. The uncertainty of the data was determined as this gave an upper and lower boundary for the radius of the exoplanet which the calculated value then fitted in.

Modelling in Maple
Maple was used to produce a theoretical light curve based on the parameters of WASP 52b and its host star. This was plotted on a graph with the imported data from Excel. There was supposed to be an animation that represented the exoplanet crossing the star however due to using a newer version of Maple this unfortunately did not work. Limb darkening was implemented and showed a variety of outcomes. It can be seen that the data fitted more closely to the limb darkening plots than just to the basic theoretical curve.
Aims
The main aim of this project was to show the major part that mathematics plays in the detection of exoplanets and the calculations of parameters from the collected data. It is quite clear that it plays an important role. Without maths none of the parameters would be found. If there was more time to complete the project it could have gone into more detail, such as deriving the equations for the parameters rather than just stating them. As said earlier, another aim was to collect my own data but that was not possible. Furthermore AIP4Win was used to process the images and Microsoft Excel allowed an observed light curve to be constructed. Lastly a theoretical light curve was produced in Maple and the limb darkening laws were implemented.
Future Work and Research

Future Work
If the project were to be done again, the accuracy of the data could be improved by observing more than one transit and compiling the information together. This would improve the calculated characteristics of the exoplanet. Future students could try and fix the Maple code so the animation works in Maple 17. Also they could try and determine the orbital period from their created light curve rather than using two sets of data from the ETD website like this project did.

Research

Kepler
The search for exoplanets has become very popular as people want to know if there is life beyond Earth. One of the biggest missions searching for exoplanets is the Kepler telescope launched by NASA. The Kepler telescope (seen in figure 10.1) was launched in March 2009 and detects exoplanets using the transit method and was named after the German astronomer Johannes Kepler.

Kepler is trying to find “terrestrial planets (i.e., those one half to twice the size of the Earth), especially those in the habitable zone of their stars where liquid water and possibly life might exist” (“Kepler” n.d). It surveys a large sample of stars to estimate
how many planets are in multiple star systems, to determine size and shape of orbits of exoplanets and determine the properties of stars that have planetary systems (“Kepler” n.d). The transit method for detecting earth like planets works more efficiently from the Kepler telescope than it does from Earth. This is because from Earth the drop in brightness when a planet crosses a star is very minimal and mostly impossible to detect but because the telescope is out in space the dip is a bit more apparent.

Kepler has a specially designed 0.95m diameter telescope called a photometer. This has a large field of view. It needs this large view to be able to observe a large number of stars. Kepler watches the same star field for its entire 3 and a half year mission, which can be extended, and it continuously monitors the brightness of around 100,000 stars.

The information from Kepler is stored onboard and transmitted to earth every month. This data is then released to the general public every year. As of February 2014 Kepler has “found 961 confirmed exoplanets in more than 76 stellar systems, along with a further 2,903 unconfirmed planet candidates” (“About Kepler Mission”, n.d).

On August 15th 2013 NASA announced that the Kepler mission was coming to an end after a faulty reaction wheel prevented its ability to point precisely (Clavin, W., Johnson, M., 2014).

**SuperWASP**

The SuperWASP telescope was used to discover the exoplanet WASP 52b that this project is based around. WASP (Wide Angle Search for Planets) is an academic organisation that searches for transiting exoplanets. They have two bases, SuperWASP-North located on the island of La Palma and SuperWASP-South located in South Africa. Each observatory contains eight wide-angle cameras that continuously monitor the sky for transits. These cameras can monitor millions of stars which allow rare transit events to be detected (“SuperWASP", n.d).


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Figure 2.2 Astronomy picture of the day (2008, November 14). Retrieved from a NASA webpage:  
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Figure 2.3 Haswell, C.A. (2010) *Transiting Exoplanets*

Figure 2.4 Cook, K. (n.d) Retrieved from Science and Technology Review site:  
https://www.llnl.gov/str/JulAug06/Cook.html

Figure 3.1 Poddany, S. *Exoplanet Transit Database*. Retrieved from ETD:  

Figure 6.8 Haswell, C.A. (2010) *Transiting Exoplanets* page 93

Figure 6.9 Haswell, C.A. (2010) *Transiting Exoplanets* page 93

Figure 6.10 Haswell, C.A. (2010) *Transiting Exoplanets* page 94
Figure 10.1 [http://kepler.nasa.gov/Mission/QuickGuide/](http://kepler.nasa.gov/Mission/QuickGuide/)

Figure 10.2 [http://www.superwasp.org/index.html](http://www.superwasp.org/index.html)


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Appendices

Appendix A - Project Plan

Project Plan

Provisional Title: Observations and mathematical modelling of Exoplanet...

Name: Alice Smith

Project Supervisor: Dr Michael McCabe

Mentors: Chris Priest, David Harris and Steve Futcher

Project Brief:

Extra solar planets, more commonly known as Exoplanets, are planets that orbit a star not in our Solar System. The first discovery of a planet to be orbiting a sun-like star came in 1995 when astronomers discovered 51 Pegasi B orbiting its star 51 Pegasi almost 51 light years away in the Pegasus constellation. Since then hundreds of Exoplanets have been found. In the vast expanse of the universe there’s no telling how many hundreds of thousands more are waiting to be discovered.

Aims:

- Look at the various methods to detect Exoplanets and explain the advantages and disadvantages of each
- Explain how the transit method is used to detect Exoplanets and demonstrate this by visiting the observatory to make observations and collect data
- To process the images collected on AIP4WIN
- Analyse the data collected from my observations, use excel to create light curve graphs and compare these with theoretical light curves
- Use equations and light curve fitting to determine the radius of the Exoplanet
- Model the data in Maple

Chapter plan:

- Abstract
  - Brief overview of the project
- Contents
- Nomenclature
  - List of symbol used in the project to explain to the reader their meaning
- Chapter 1-Introduction
  - Explain what an Exoplanet is and give a brief background of them
  - Explain the aims of the project
- Chapter 2-Detection methods
- Direct Imaging
  - Coronagraphy
- Radial velocity
- Astrometry
- Transits
- Chapter 3- Observations at Clanfield observatory
- Chapter 4- Image processing
  - Using AIP4WIN
- Chapter 5- Light curve observations
  - Include graphs of light curves produced on Excel
- Chapter 6- Data analysis
  - Using maple to model the Exoplanet system
- Chapter 7- Comparison of observations and models
- Chapter 8- Conclusion
  - Final brief analysis of all the data collected
- Chapter 9- Future study and current research
- Bibliography
- Appendices
  - Project plan
  - Images
  - Maple file
  - Excel spread sheet

**Timeline:**

<table>
<thead>
<tr>
<th>Month</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>Pick project supervisor and decide on a subject.</td>
</tr>
<tr>
<td>October</td>
<td>Start going to the observatory regularly. Learn how to use the equipment necessary. Find resources that will be of use. Meet with supervisor frequently.</td>
</tr>
<tr>
<td>November</td>
<td>Complete project plan and submit by the 8th. Study resources found to increase knowledge on subject area. Practice using the modelling software.</td>
</tr>
<tr>
<td>December</td>
<td>Use resources to get a strong background knowledge of Exoplanets and detection methods. Use AIP4WIN to process images collected at Clanfield</td>
</tr>
<tr>
<td>January</td>
<td>Process data on Excel and also model on Maple Begin writing project report.</td>
</tr>
<tr>
<td>February</td>
<td>Continue writing project report.</td>
</tr>
<tr>
<td>March</td>
<td>Finish writing the report. Ask mentors and supervisor to read it and improve on any of their suggestions. Submit project report by the 21st (provisional date).</td>
</tr>
<tr>
<td>April</td>
<td>Create presentation explaining what the project report is about and how I completed it. Read presentation to various people to become confident reciting it. Presentation to be presented on the 22nd.</td>
</tr>
</tbody>
</table>

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Problems to overcome:

- Weather: Cloudy nights will prevent observations from taking place; this could therefore push me back on my timeline of work. If cloudy nights are persistent I may not be able to make any observations of my Exoplanet. I will have to find data online and interpret that instead.
- Availability: Need to find time when both I and my mentors are available for observations at the observatory.
- Time management: As well as the project I have other units I need to focus on. I will need to manage my time as efficiently as possible to complete all of my work to the set deadlines and make sure that it is all of a high standard.
- Computer issues: Work I have done towards the project may get lost if there are any technical issues. To overcome this I will save my work constantly and have a backup copy.
- Choosing an Exoplanet: Various factors to take into consideration such as if the star is too faint, the planets too small, too close to the moon etc. Also want one with a reasonable transit period, for example less than 4 hours and finishing before 1 o clock.

Resources:

- ‘Transiting Exoplanet’ book by Carole A Haswell
- Maple
- AIP4WIN
- Microsoft excel
- Past projects

Appendix B - WASP 52b Images

Appendix C - AIP4Win txt file

Appendix D - Original Excel Spreadsheet

Appendix E - ETD Excel Spreadsheet

Appendix F - Data for Maple, txt file

Appendix G - Maple File