Detection and characterization of transiting exoplanet TrES-5 b

Roger Kalliomäki
Supervisor: Eric Stempels
Subject Reader: Nikolai Piskunov

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Abstract

The field of exoplanetary science is growing rapidly and more than fifteen hundred exoplanets have been confirmed to this day. Most of these planets have been found through the detection of planetary transits and to use this method for finding extrasolar planets was the main focus of the project. From the beginning the goal and purpose for the thesis work was twofold: To learn how to use the Westerlund telescope for detecting and characterizing transiting extrasolar planets. Thereafter trying to detect and confirm a transiting planet which earlier only had been detected with radial velocity measurements. Unfortunately bad weather postponed the initial observations to the point that the latter part had to be canceled. Instead a more theoretical alternative was chosen. A study on the probabilities for RV planets to transit, based on of the paper “A Posteriori Transit Probabilities” (2013) by Stevens and Gaudi. Observations where performed at two nights in March which resulted in one detected planetary transit. Using the obtained data from the observation certain properties of the planetary system was calculated and compared with the work of Mandushev et al. The results were surprisingly comparable and expected to be even more similar if one would add the effect of limb darkening.

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Chapter 1 – Introduction

“Two possibilities exist: either we are alone in the universe or we are not. Both are equally terrifying.”

- Arthur C. Clarke

Humans are curious by nature and we seem to have an urge to explore the unknown. This has made the question of whether we are we alone in the universe one of the most contemplated and discussed around the world for centuries. We now know that there are hundreds of billions of stars in our galaxy alone, and the amount of habitable planets (exoplanets) orbiting these stars seems almost unlimited. The ultimate goal in exoplanetary science today is to somehow be able to detect life on one of these planets. If this was achieved some of these age-old questions would get answered and perhaps other existential musings would evolve. However it is not only the philosophical questions that can benefit from the search and study of planets orbiting other stars. By studying other planetary systems, our knowledge and understanding about their (and the solar system’s) formation and development has increased drastically. For example the discovery of “hot Jupiters” (Jupiter sized planets orbiting near their host stars), gives a hint of the possible diversity of planetary systems in the universe. In the end this could help us to better understand the past, present and future of the planet we live on.

However finding and characterizing exoplanets is no easy task. Mostly because the enormous distances between stars, and the faint reflected shine of the planets, makes direct imaging almost impossible. This has led to a pursuit of alternative detecting methods, and the two most successful ones to this date (April 2015) have been the radial velocity method with 597 detected planets and the transit method with 1204 detected planets [1].

The radial velocity method uses the fact that an orbiting exoplanet will cause a star to wobble and therefore move back and forth as seen from Earth. This movement will lead to a Doppler effect in the star’s spectral lines which can be measured. However the main purpose of this bachelor thesis is primarily to use the Westerlund telescope (BWT) to detect and characterize exoplanets with the transit method. This is done by measuring the change in flux as a planet passes in front the star (as seen from Earth).

1.1 Purpose

First and foremost the focus of the project will be on already verified extrasolar planets with known planetary transits times. This is to learn how to use Westerlund telescope to detect the decrease in starlight that take place in an exoplanet transit. After this the light curve
which is produced by the transit will be used to calculate certain properties of the planet. Secondly the goal is to use radial velocity measurements to make a prediction of an earlier unseen transit and then attempting to detect it. If this can be achieved it would confirm the existence of the planet. Also if one has both transit and radial velocity data, even more information about the exoplanet in question can be obtained. Hence it is desirable to have data from both radial velocity and transit measurements to gain as much information about the planet as possible. Unfortunately bad weather postponed the initial observations to the point that the second part had to be canceled. Therefore one chapter in this thesis instead will be a theoretical study about transit probabilities for RV planets. As seen in Chapter 4 the theory behind this is not as simple as it first seems.

Chapter 2 – Background

The idea that extrasolar planets exist has been around for a long time. For an example it was proposed by Isaac Newton (1713) in his essay General Scholium where he wrote "And if the fixed stars are the centers of similar systems, they will all be constructed according to a similar design and subject to the dominion of One" [2]. Scientists and philosophers both before and after Newton have suggested and speculated in the existence of what were called "other worlds". It is a plausible assumption that the conditions in the creation of other stars would have been similar to the conditions in the creation of the solar system, and therefore planets around other stars most likely do exist. However without empirical evidence and data these discussions end with only speculations.

Unfortunately, to detect an exoplanet by direct imaging is an extremely challenging task. The shine of the planet, which only is reflected starlight, will be billions of times fainter compared to the brilliant glare of the giant star it orbits [3, p.1]. Also, the enormous distances to other stars from Earth, causes the angular distance between the planet and its host star to be very small. This combination makes direct imaging, with the technical ability of today, almost impossible and therefore not practical for searching after and detecting extrasolar planets [3, p.149]. So to be able to find and study exoplanets several indirect methods (measuring the planets effect on the host star) were developed in the later part of the twentieth century. The two most successful methods, the radial velocity method and the transit method, will be discussed further in this chapter. Other techniques that have been used to detect exoplanets are astrometry and gravitational microlensing.

The method of astrometry consists of measurements of a stars position on the sky as the star wobbles due to its orbit around the star-planet common center of mass [3, p.61]. This requires extremely precise measurements and to this date (April 2015) only two confirmed exoplanets has been detected with astrometry [1]. However in 2016 data from the ESA
satellite Gaia, which uses both astrometry and transit methods to search for exoplanets, is expected to be released. Gaia is going to investigate approximately one billion stars and is predicted to discover thousands of extrasolar planets [4].

Gravitational microlensing can be used when a closer star passes in front of the observed star. The closer star will act like a gravitational lens magnifying the light from the observed star. If an orbiting planet happens to align just right with the closer star, its mass will enhance the lens effect and increase the magnification for a short time [3, p.83]. To this date (April 2015) 34 planets have been detected using gravitational microlensing [1].

Since this thesis work is based on the transit method and also studies the theory behind finding transit probabilities from previous radial velocity data, a deeper introduction and background for these techniques is presented. More information about astrometry or gravitational microlensing can be found in [3, p.61-102].

2.1 Radial velocity (RV)

Just like in astrometry radial velocity measurements uses the fact that a star appears to wobble due to its orbit around the star-planet common center of mass (barycentre). This causes the star to half the time move away from us, and half the time to move towards us (see Figure 1). If the star is traveling towards us, its light will appear blueshifted, and if it is traveling away the light instead will be redshifted. Using spectroscopy this movement can be measured (Doppler shift). The measurable effect the planet has on its host star depends on how the orbit is aligned (as seen from Earth) and the mass of the planet. It is most considerable when the planets orbit lies in a plane which is parallel to the line of sight from Earth. If the orbit lies in a plane which is orthogonal to the line of sight from Earth, the radial movement of the star will be close to zero. However, in this case the conditions for astrometric measurements are ideal.
The shape of the stellar radial velocity curve will depend on the eccentricity $e$ and the argument of periapsis $\omega$ (see Figure 2 and Figure 3). From this curve the orbital period, eccentricity and time of periastron can be obtained. However, the mass of the planet can only be estimated to a minimum mass (Equation 16) due to the unknown inclination of the planet’s orbit [3, p.11]. This means that one will not be able to tell how much the inclination of the orbit reduces the full effect of the planetary pull on a star as measured on Earth. The true mass of the planet can however only be obtained if one has both RV and transit data.
The first ever confirmed exoplanet orbiting a main sequence star (51 Peg) was found with radial velocity measurements in 1995 [5]. It has a minimum mass of 0.47 Jupiter masses orbiting its host star every 4.2 days [3, p.2]. Until the Kepler mission, which detected planetary transits, the radial velocity method stood for the biggest part of the total number of detected exoplanets. To this date (April 2015) 597 confirmed extrasolar planets has been detected with this method [1].

2.2 Transits

An extrasolar planet transit can be detected if the orbit of the planet is aligned in such a way that it crosses the disk of the star, as seen from Earth. When this happens the planet will block a fraction of the star light and cause a drop in the total detected flux. Following the transit is an increase in total flux due to the continuously rising of reflected star light by the planets visible dayside (see Figure 4). A second much smaller drop in flux will occur when the planet passes behind the star and the reflected star light is blocked by the star itself.
Figure 4: Illustration of a transit with the drop in flux as the planet passes in front of the star. It shows the total transit time $t_T$, the time between second and third contact $t_F$ and the drop in flux $\Delta F$. From [3, p.117].

An extrasolar planetary transit (and the secondary eclipse) additionally provides an exclusive opportunity to learn more about the planets atmospheric spectral features. This can be done with transmission and emission spectroscopy when the planet transits or passes out of view behind the star.

From the transit light curve the planet radii can be obtained (along with additional information about the planet-star system) (see Chapter 3), and if there exist previous radial velocity data the planets true mass and density also can be determined. So to learn as much as possible about an exoplanet it is desirable to have both radial velocity and planetary transit data. If a planet transits its host star the inclination is close to ninety degrees, and the conditions for obtaining radial velocity measurements are ideal. However far from all RV planets are transiting planets, and the question of transit probabilities for RV planets is discussed in Chapter 4.

Since the first transiting exoplanet was observed in 1999 [6], the number of objects detected with the transit method has grown steadily each year and is now up to over 1200 (April 2015) [1]. The largest proportion of these has come from the analysis of data from the Kepler space telescope observations between 2009 and 2013 [7]. As a space telescope is not affected by atmospheric disturbances, it is possible to detect decreases in the brightness
down to a few ten-thousandths of the original brightness. A typical ground-based telescope, such as Ångströms Westerlund telescopes (BWT), will usually only be able to detect changes down to about one percent [8]. However, as shown by Hinse et al. in their paper “Photometric Defocus Observations of Transiting Extrasolar Planets” (2015) [9], it is possible to achieve much higher photometric precisions for ground based telescopes by applying a special telescope defocus technique. This will allow the use of much longer exposure times and therefore the possibility to collect more photons without saturation resulting in a lower noise to signal ratio.

Chapter 3 – Transit light curves

3.1 Observables

To identify and describe the transit light curve one needs four principle observables: the period $P$, the transit depth $\Delta F$, the time between the first and fourth contacts $t_T$, and the time between the second and third contacts $t_F$ [3, p.117] (see Figure 4). If one assumes a circular orbit, which is expected for short-period planets [10] and ignores the effect from limb darkening these observables will give rise to three geometrical equations which together define the properties of the transit light curve [3, p.117].

\[
\Delta F = \left( \frac{R_p}{R_*} \right)^2 \tag{1}
\]

\[
\sin \left( \frac{t_T \pi}{P} \right) = \frac{R_*}{a} \left\{ \frac{\left[ 1+\left( \frac{R_p}{R_*} \right) \right]^2 - \left[ \frac{(a/R_*) \cos i}{} \right] \cos^2 i}{1-\cos^2 i} \right\}^{1/2} \Rightarrow
\]

\[
t_T = \frac{P}{\pi} \arcsin \left( \frac{R_*}{a} \left\{ \frac{\left[ 1+\left( \frac{R_p}{R_*} \right) \right]^2 - \left[ \frac{(a/R_*) \cos i}{} \right] \cos^2 i}{1-\cos^2 i} \right\}^{1/2} \right) \tag{2}
\]

\[
\frac{\sin(t_F \pi/P)}{\sin(t_T \pi/P)} = \left\{ \frac{\left[ 1-\left( \frac{R_p}{R_*} \right) \right]^2 - \left[ \frac{(a/R_*) \cos i}{} \right] \cos^2 i}{1+\left( \frac{R_p}{R_*} \right)^2 - \left[ \frac{(a/R_*) \cos i}{} \right]^2} \right\}^{1/2} \tag{3}
\]

Here, $R_*$ is the radius of the star, $R_p$ the radius of the planet, $a$ the semi-major axis, and $i$ the inclination of the orbit. The equations describe; the transit depth $\Delta F$, which follows from the ratio between the size of the planet and the star, the total transit duration $t_T$, and the ratio between $t_F$ and $t_T$, respectively. Equation 2 and 3 follows from the fraction of the orbital period $P$ during certain projected positions of the planet on to the star. However, there still
exists a degeneracy between the three equations and the four unknowns \( R_\ast, R_p, a, \) and \( i \). To break this degeneracy one can invoke two additional equations with one more unknown: Kepler’s third law (assuming a planet mass \( \ll \) star mass) and the stellar mass radius relation \( [3, \text{p.120}] \).

\[
P^2 = \frac{4\pi^2a^3}{G(M_\ast+M_p)} \approx \frac{4\pi^2a^3}{GM_\ast}
\]

\[
R_\ast = kM_\ast^x
\]

Here, \( G \) is the universal gravitational constant, \( k \) is a constant describing the stellar type \((k = 1 \text{ for main-sequence stars}), x \) the power law of the stellar sequence \((x \approx 0.8 \text{ for F-K main-sequence stars}) [10] \), \( M_p \) the planetary mass and \( M_\ast \) the star mass.

The parameters can be derived as follows \([3, \text{p.120}]\):

\[
\frac{M_\ast}{M_\odot} = \left( k^3 \frac{\rho_\ast}{\rho_\odot} \right)^{1/(1-3x)}
\]

\[
\frac{R_\ast}{R_\odot} = k \left( \frac{M_\ast}{M_\odot} \right)^x = \left( k^x \frac{\rho_\ast}{\rho_\odot} \right)^{x/(1-3x)}
\]

\[
a = \left( \frac{p^2GM_\ast}{4\pi^2} \right)^{1/3}
\]

\[
i = \cos^{-1} \left( \frac{R_\ast}{a} \right)
\]

\[
\frac{R_p}{R_\odot} = \frac{R_\ast}{R_\odot} \sqrt{\Delta F} = \left( k^x \frac{\rho_\ast}{\rho_\odot} \right)^{x/(1-3x)} \sqrt{\Delta F}
\]

Here, \( b \) is the impact parameter which is defined as the projected distance between the planet and star centers during mid-transit in units of \( R_\ast \), \( M_\odot \) is the mass of the Sun and \( R_\odot \) is the radius of the Sun. If one uses \( (R_p/R_\odot) = (\rho_\ast/\rho_\odot)^{-0.57} \sqrt{\Delta F} \) (from Equation 10 with \( k = 1 \) and \( x = 0.8 \)), and the assumption \( R_\ast \ll a \), expressions for \( b, a, \) and \( \rho_\ast \) can be derived \([3, \text{p.120}]\):

\[
b = \frac{a}{R_\ast} \cos i = \left( \frac{(1-\sqrt{\Delta F})^2 - (t_F/t_T)^2(1+\sqrt{\Delta F})^2}{1 - (t_F/t_T)^2} \right)^{1/2}
\]

\[
\frac{a}{R_\ast} = \frac{2p}{\pi} \Delta F^{1/4} (t_T^2 - t_F^2)^{-1/2}
\]

\[
\rho_\ast = \frac{32p}{G\pi} \Delta F^{3/4} (t_T^2 - t_F^2)^{-3/2}
\]
Now there are five unknown parameters, $M_\ast, R_\ast, R_p, a, i$ and five equations. If the observation only consists of one transit the period time also is unknown. This can be resolved if one can obtain $M_\ast$ and $R_\ast$ from, for example, spectral data. Then Equation 13 can be re-written to get the orbital period.

\[
P = \frac{G \pi M_\ast (t_T^2-t_F^2)^{3/2}}{32 R_\ast^3} \frac{1}{\Delta F^{3/4}}
\]

Hence, with only four observables, $P, \Delta F, t_T$ and $t_F$ (or three if the stellar mass and radius are known) one can learn a remarkable amount of information about the observed planet-star system (Equations 6-10).

3.2 Light curve fitting

So, how does one identify these four observables ($P, \Delta F, t_T$ and $t_F$) from the collected data? The orbital period is simply found by observing two consecutive transits and measure the time period between the events. The remaining parameters $\Delta F, t_T$ and $t_F$ are obtained by fitting a theoretical function to the observed data. Although to construct this theoretical function is no easy task. The shape of the light curve is affected by additional parameters, like the reflected light from the planet, and most importantly the effect of limb darkening [12].

3.2.1 Limb darkening

Limb darkening refers to the fact that the edge, or limb, of a star appears to be less bright than the center parts of the star. This phenomenon is mainly due to the increase in star temperature and optical depth near the center of the star [3, p.118]. Limb darkening effects will mostly be seen when the planet overlaps the edge of the star. This makes the ingress and egress (edges of the dip in the light curve) more soft and less box like. Also limb darkening is wavelength dependent. So light curves observed in different colors will vary as the effects are more distinct at longer wavelengths (see Figure 5).
To achieve an as optimal fitted function for the light curve as possible one needs to include the effects of limb darkening. However to get a fairly good estimation of the observables it is sufficient enough to assume a uniform source of flux. This is because a model including limb darkening will differ from a model without limb darkening less than the usual one per cent limit for typical ground-based telescopes. For a more extensive insight in the effects of limb darkening see [11, 12, 13].

3.2.2 Constructing a theoretical light curve

To achieve an acceptable model one can treat the problem as two overlapping circles without any other additional effects on the light curve and by assuming the orbit to be circular. So without the effect of limb darkening one can assume the source of flux to be uniform resulting in a theoretical light curve which can be seen in Figure 6.
Figure 6: Definition of how a theoretical fitted light curve is constructed depending on the observables $\Delta F$, $t_T$ and $t_F$. The light curve is based on two overlapping circles and the assumption of uniformed flux from the source. From [10, p.3].

It is clear that the size of the planet, the size of the star, the total transit time and the impact parameter $b$ will change the shape of the light curve. In the model the decrease in flux between first and second (as well as the increase in flux between third and fourth) contact is approximated to be linear. This will give a fairly good estimation of the observables and a first glance at the properties and conditions of the observed planet-star system [10].

Chapter 4 – Transit probabilities for RV planets

4.1 Introduction

As mentioned in Chapter 2.2 it is desirable to have both RV and transit data to obtain as much information about the observed planet-star system as possible. If a planet transits its host star the inclination is close to ninety degrees, and the conditions for obtaining radial velocity measurements are ideal. However in the case of RV detected planets, far from all
will transit their host stars. Knowing the probability for a planet to transit its host star would therefore be a useful tool in selecting RV detected planets for transit follow-up.

For a planetary transit to be visible from Earth the minimum inclination is given by \( \cos i_{\text{min}} = \left( \frac{R_*}{a} \right) \), and a partly transiting event occur for \( \cos i = \left( \frac{R_* \pm R_p}{a} \right) \). The probability for a planet \( (R_p \ll R_*) \) with a random inclination and a circular orbit is then

\[
p = \frac{R_* + R_p}{a} \simeq \frac{R_*}{a} \simeq 0.005 \left( \frac{R_*}{R_{\odot}} \right) \left( \frac{a}{1\text{AU}} \right)^{-1}.
\]

(15)

Since the semi-major axis \( a \) and the stellar radius \( R_* \) can be obtained from radial velocity measurements, it is easy to assume that one gets the probability for a RV planet to transit simply by plugging in those values. However as Stevens and Gaudi discuss in their paper “A Posteriori Transit Probabilities” (2013), it is more complicated than that.

### 4.2 A posteriori transit probabilities

The problem lays in the assumption that the inclination angle \( i \) is randomly distributed for the RV planets in question. Of course for a completely arbitrary exoplanet the orbital inclination will be totally random. However for a planet detected with radial velocity, not all orientations are equally likely. The lower the inclination is, the lower the probability for detecting the planet will be. In fact a planet with orbital inclination of zero degrees will have zero chance of being detected with radial velocity. This is because the stars movement will be tangential as seen from Earth. Since we cannot measure infinitesimally small inclinations there will always exist a lower limit for detectable inclinations. Also, the higher the true mass of the planet the more it will cause the star to wobble. Therefore exoplanets detected with radial velocity will have a bias towards both higher inclinations and higher masses [14, p.2][3,p.9-13].

In addition to this, one more important fact has to be considered. The mass of the planet, measured with radial velocity, actually is a combination of the true mass and the inclination, called minimum mass [14, p.3].

\[
M_{\text{min}} = M_p \sin i
\]

(16)

So the mass measured with RV is really the theoretical lowest possible mass of the planet. The higher the true mass of the planet is, the lower the inclination must be. This means that the probability distribution of the true mass of exoplanets, will affect the probability distribution of the inclination for RV planets.

To get a clearer picture, one can considers a simple example: Assume that one knows the exact mass distribution of extrasolar planets. Say that this distribution predicts that there are
no planets under a minimum mass $M_{\text{limit}}$, thus this will the absolute lowest mass a planet could have (in this fictional mass distribution). Now, if a planet with a minimum mass $M_{\text{min}} = 0.1M_{\text{limit}}$ was detected nevertheless. Then one would know that the true mass must be at least ten times this detected minimum mass. So the orbital inclination of the planet therefore is going to be far from ninety degrees and the probability for a transit is will be very low [14, p.3]. Hence the posterior transit probability can be lower (or higher) than the prior, if one has knowledge about the prior probability distribution of $M_p$.

Unfortunately, the distribution of extrasolar planet masses is not well known. However, as the number of discovered exoplanets continues to grow, planetary formation scientist gets more and more data to work with. This data can be used to run simulations of solar system formations and formulate different distribution hypothesis. These distributions does not always agree, however most of them predicts that low mass planets ($\sim 0.1M_\oplus - 10M_\oplus$) are more abundant than high mass planets [15,16,17,18].

So if one could apply these planetary mass distributions, to estimate the distribution of the minimum mass of exoplanets, this could then be used for finding the probabilities for already detected RV planets to transit. Or in other words, the probability for the inclination to be in certain required range (close to ninety degrees). As already mentioned before, the problem lays in that the minimum mass depends on both the true mass and the inclination. To address this problem Stevens and Gaudi uses Bayes' theorem which gives the conditional probability density of event A given event B as [14, p.4].

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}. \quad (17)$$

In this case, $P(A)$ is the probability density of the inclination, $P(B)$ is the probability density of the minimum mass, $P(A|B)$ the probability density of the inclination given a measurement of the minimum mass and $P(B|A)$ the probability density of the minimum mass given the inclination. The authors use Bayes' theorem for two planetary formation models [16,17] which both produce similar results [14, p.9]. This is done through some lengthy mathematics and can be studied further for those who wish in [14, p.4-9]. The results using the model by [17] are shown in Figure 7 which shows mass distributions of planets orbiting Sun-like stars, with and without brown dwarf companions. Worth noting is that the slope of the mass distribution seems to affect the correlation between the two distributions. When the slope is flat the distribution of the minimum mass and the true mass is identical. If the slope is negative, the real mass distribution is underrated compared to the minimum mass distribution obtained from RV measurements. If the slope is positive the reverse is true. From this one can draw a few conclusions [14, p.9].
1. In the range $\sim 100M_\oplus - 10^3M_\oplus$, the slope is reasonably flat which means that the prior and posterior transit probabilities differ by a very small amount. So for RV planets with a minimum mass in this range, the probability for a transit can be estimated with the usual formula $p \approx R_* / a$.

2. In the range $\sim 3M_J - 13M_J$ (where $M_J$ is the mass of Jupiter), the most significant difference between real masses and minimum masses is seen. Planets in this mass range will have considerably higher probabilities for transits than expected geometrically. Stevens and Gaudi estimates a boost in transit probability with $\sim 20 - 50\%$ for these planetary masses. The evident high probability approaching fifty per cent is attained when a mass distribution excluding the existence of brown dwarf companions is used.

3. In the range $\sim M_\oplus - 30M_\oplus$, the probabilities for transits also are higher than expected. This means that the chance to find Earths and Super-Earths among known RV planets is better than earlier predicted.

4. In the regime of brown dwarfs, transit probabilities will be significantly lower compared with what one would get using $p \approx R_* / a$. So these systems do not seem to be good choices when selecting transit candidates from RV planets.

Stevens and Gaudi uses RV planets from the Exoplanets Orbit Database to investigate the posterior probability that these planets would undergo a planetary transit (presumed the models of [16,17]). They also make a comparison between the posterior probability and the probability obtained using $p \approx R_* / a$. As seen in Figure 8, extrasolar planets are in general
more likely to transit than this simple formula insinuates. The authors also lists nine transit candidates (61 Vir b, BD -08 2823 b, HD 10180c, HD 125612 c, HD 1461 b, HD 181433 b, HD 215497 b, HD 219828 b, and HD 47186 b) with promising results which possibly could be worth investigating through observations. These candidates can be seen as marked with X in Figure 8. However, to detect these transits with ground based telescopes may prove to be a challenging task. This is because the predicted depths of the relative flux for these are $\sim 0.0005 - 0.001$ [14, p.13], which is well below the usual $\sim 1\%$ limit of telescopes on the ground (see Chapter 2.2).

![Figure 8: Left: A comparison between the posterior probability using the [17] mass distribution and the solid gray line which is the probability obtained using $p = R_*/a$ for RV planets listed on exoplanets.org. The dotted line indicates 10% probability for a transit. Right: The scale factors between the posterior and prior probabilities for the same planets. The dashed line represents equal probabilities between posterior and prior probabilities and the dotted line a 20% boost for the posterior probability compared to the prior. In both panels the colors represent planet mass as displayed to the far right. A plus sign represent planets orbiting stars with $R_* \geq 2R_\odot$ and X represents planets with promising results which possibly could be worth investigating through transit observations. From [14, p.14].]

The authors end with emphasizing the fact that the distribution of extrasolar planet is not precisely known, especially in the low mass region. However they expect that the theoretical distributions used in the paper will give a considerable improvement in estimating the transit probabilities.

In conclusion one can say that Stevens and Gaudi’s results hopefully will increase the likelihood to find transiting planets from earlier radial velocity measurements. This will help astronomers to make better decisions regarding which objects to choose for observations, and perhaps reduce unnecessary (and valuable) observation time.
Chapter 5 – Method

5.1 The Westerlund telescope

Observations for this bachelor thesis were made with the 90 cm Westerlund telescope at Ångström laboratory in Uppsala (see Figure 9). The telescope belongs to the department of physics and astronomy and is mounted on the roof of the south end of the Ångström laboratory inside a 6 meter wide dome. It is an altazimuth mounted instrument with two Nasmyth foci to which the light can be sent to by a third rotatable mirror. The camera used for the observations is an SBIG STL-1001E CCD-camera, with an array of 1024 x 1024 pixels and a field of view of 18.8' x 18.8'. More information about the telescope can be found at the Westerlund telescope website.
5.2 Observations

Observations were made in March 2015 on two occasions (12/3 and 21/3). March 21st was the only night with completely clear skies, and therefore the only night to produce a good set of data. To find suitable transit candidates the Exoplanet Transit Database (ETD) was used, which is an online database with all confirmed transiting extrasolar planets. ETD contains information about predicted transit times, sky coordinates, brightness of the host star etcetera. One important fact to consider when choosing an object is that it is preferable to have a field of view consisting of stars not too bright in comparison with the transiting star. Other things to take into consideration are the time of the event, predicted transit depth and position on the sky. On March 21 there were ten known planetary transits and the transit of TrES-5 b was chosen as the best optimal target.

TrES-5 b is Jupiter sized planet orbiting close to a Sun like star with a magnitude of 13.7 and a predicted transit depth of 0.0215 [19]. The transit was predicted to begin at 19:50 (UT) and proceed for almost two hours. On the 21st of March the Sun sets at 17.06 (UT), so this gave plenty of time for preparations and obtaining calibration frames (see Chapter 5.3).

To reduce the noise level in the captured images the camera was cooled to minus twenty-five degrees Celsius and kept at this constant temperature throughout the observations. To avoid saturation of electrons in any single pixel in the CCD, the exposure time was set in such a way that the brightest star in the field of view reached around 35 000 electrons per pixel. This was achieved by taking images and varying the exposure time until the required level was reached.

To be able to fit a light curve to the obtained data (see Chapter 5.4), it is of importance to have a sufficient amount of observations before and after the transit. So observations were started twenty minutes before and continued twenty minutes after the predicted transit. Two images a minute was taken, each with a seven second exposure time, resulting in a total of 318 on-sky frames to be processed and analyzed.

5.3 Image reduction

A raw frame contains more than just useful data. There will always be noise originating from different sources and thermal current effects in the original image. Also optical issues from for example dust on the mirror will have to be taken care of. The cooling of the camera lowers thermal (dark) currents in the CCD; however the effect can never be completely removed [20]. To reduce these unwanted phenomena different calibration images are used. These calibration images were taken at the same night as the observations, ensuring similar conditions as when obtaining the on-sky frames. The more calibration frames one takes the
better noise reduction can be achieved. In fact, proper calibration is a necessity for achieving images with good quality, especially if they are going to be used for precise photometric measurements [20]. Essentially there are three basic calibration images; flat field frames, dark frames and bias frames.

5.3.1 Flat field frames

Flat field frame calibration takes care of different light variations in the obtained image. The most distinct ones can be seen as donut shaped shadows coming from dust grains on the detector window, and darkening effects at the corners of the image (see Figure 10). A flat image essentially is an on-sky frame taken at dusk to obtain an exposure of a uniform source. The exposure time is chosen so that the camera is exposed to approximately half the full well depth (half saturated). To achieve optimal results two mosaics of 3 x 3 flat field images was.

5.3.2 Dark frames

Dark current appears when electrons leak in to the CCD through thermal emission from the silicon substrate. This will result in a specific pattern noise which is time and temperature dependent [8]. Therefore it is important to hold the camera at the same constant (low) temperature during observation and when obtaining dark frames. The time dependence is rectified by using the same exposure time as the on-sky frames. Dark frames also help reducing the effect of “hot pixels” which are damaged pixels that give false signals in the image. An example of a dark frame can be seen in Figure 10. To ensure that only dark current was detected when taking dark frames, the dome was kept dark and the camera shutter was closed under the exposures. A total of ten dark frames with seven second exposure time were taken.

5.3.3 Bias frames

Bias is an offset which is added to each frame when pixels are read from the CCD. A bias frame is basically a dark frame with zero exposure time and will therefore not be time dependent (see Figure 10). The dark frames will contain the bias offset and one can use different techniques to calibrate the on-sky frames with only dark and flat frames. However, bias frames are very quick and easy to achieve, so there is essentially no reason to ignore them. Ten bias frames where taken along with the ten dark frames.
5.3.3 Calibration with MaxIm DL

The software MaxIm DL was used to do the actual calibrations of the frames. To start off, something called master frames were made by combining multiple images, resulting in a master flat, a master dark and a master bias. This is done because the calibration files also include random noise. By averaging or taking the median of multiple calibration images one can bring down the noise level to an acceptable level. These master frames were then used to remove the unwanted noise from the on-sky frames one at a time with MaxIm DL.

5.4 Retrieving data from FITS

Flexible Image Transport System (FITS) is the standard data format used in astronomy and the files obtained from the observations are in this format. The FITS format is specifically designed for scientific data and they can include more information than other image formats. They also include a header with information about the data such as camera temperature, date and time, coordinates etcetera [21].

However the calibrated frames are still just images, with objects represented by certain areas of pixels with different intensity. So to be able to make photometric measurements on the objects obtained in the observations, one has to somehow extract information about the pixel intensity of each object in the image. To do this the software source extractor
(SExtractor) was used which is generally run in text-mode from a shell in Unix. Given some input image and specific parameters to extract from the image, SExtractor will provide a list of objects in a text file with their respective values (total flux, position etcetera). To simplify the management of multiple obtained frames a script for running SExtractor on each FITS file was written in the programming language python. Python has recently become one of the standard languages in astronomical communities and was therefore used for all the programming parts of the project.

5.5 Light curve fitting

To obtain the four observables (see Chapter 3.1) from the collected data, a light curve with the change in flux over time for the star in question (TrES-5) has to be computed. Since the transit depth $\Delta F$ only depends on the ratios between the planet and star (Equation 1), the relative flux of the star can be used. This will facilitate the work of producing the light curve as no star magnitudes have to be determined explicitly. Unfortunately, although the flux coming from an observed object can be constant, the measured flux between each image is going to vary. This is due to several factors. However, the main reason is the effect of atmospheric transmission due to the altitude of the target [3, p.116]. So without any adjustments for this varying of brightness, the data is more or less useless (see Figure 11). This problem can be solved by using the mean value of several reference stars to determine how much the flux between each image varies. Obviously the more reference stars that are used, the better the final result will be. One important fact to consider when choosing reference stars is that some stars varies in brightness them self. Therefore, if a star is found to have large fluctuations, it is rejected as a reference star. Stars close to each other, or near the edges of the field of view, are rejected as well.

A total of fifteen stars from the obtained frames were first chosen as candidates for reference stars. Three of these turned out to have large fluctuations compared to the rest, and those were therefore rejected. An example of a stable reference star, and one that varies in brightness, can be seen in Figure 12 and Figure 13. The measured relative flux of TrES-5 was then determined by normalizing the flux of the star by the average fluxes of the remaining reference stars (see Figure 14).

As explained in Chapter 3.2.2, and seen in Figure 6, a theoretical fitted light curve can now be established. To construct the fitted curve, the total flux from the star is assumed to be constant before ingress, and after egress. The flux is also assumed to be constant between second and third contact. No limb darkening effects are used so the fitted curve between first and second contact as well as between third and fourth contact is set to be linear. The values for the parameters $\Delta F$, $t_T$ and $t_F$ (observables in Chapter 3.1) were found through
the method of least squares using a $\chi^2$ gradient search [22, p.153-156]. The initial values for the parameters where estimated from Figure 14. The final result and the obtained parameter values can be seen in Figure 15.

Since only one transit was observed, Equation 14 had to be used for finding the orbital period $P$. The stellar mass $M_*$, and stellar radius $R_*$, were therefore needed (see Chapter 3.1). For this purpose, values from exoplanet.eu were used ($M_* = 0.893 M_\odot$ and $R_* = 0.866 R_\odot$). With the derived orbital period $P$, Equation 8-13 could be used to find the semi major axis $a$, orbital inclination $i$, impact parameter $b$ and the planet radius $R_p$. These results can be seen in Table 1.

5.6 Error estimation

To obtain the uncertainties in $\Delta F$, $t_T$ and $t_F$ the curvature of the $\chi^2$ surface near the minimum was approximated with a parabola. With this, the standard deviation $\sigma$ can be estimated by varying the parameter in question in such a way that $\chi^2$ increases with one [22, p.144-147]. The error in $P$, $a$, $i$ and $R_p$ is then obtained by using the formula for propagation of error for a function $f(x_1, x_2, x_3, \ldots)$ [23]:

$$\sigma_f = \sqrt{\left(\frac{\delta f}{\delta x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\delta f}{\delta x_2}\right)^2 \sigma_{x_2}^2 + \left(\frac{\delta f}{\delta x_3}\right)^2 \sigma_{x_3}^2 + \cdots}$$

Finally the reduced chi-squared $\chi^2_{\text{red}} = \frac{\chi^2}{\nu}$ (or mean square weighted deviation) can be used to measure the goodness of the fitted light curve [22, p67-68]. Here $\nu$ is the number of degrees of freedom (Number of samples minus the number of parameters obtained from the data). Values close to one indicates a good fit and all three obtained parameters give a reduced chi-squared $\sim 1.2$. 

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Chapter 6 – Results

Figure 11: Detected flux from TrES-5 during transit.

Figure 12: Normalized flux for one of the used reference stars.
Figure 13: Normalized flux for one of the rejected reference stars.

Figure 14: Normalized flux for TrES-5 during transit.
Figure 15: Normalized flux for TrES-5 during transit with a fitted light curve. In the left lower corner displayed in red is the standard deviation for each measurement.

Table 1: Obtained parameters for TrES-5 b compared with values from Mandushev et al. [19].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Obtained values</th>
<th>Values from Mandushev et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta F$</td>
<td></td>
<td>0.0214(5)</td>
<td>–</td>
</tr>
<tr>
<td>$t_F$</td>
<td>min</td>
<td>58.78(220)</td>
<td>–</td>
</tr>
<tr>
<td>$t_T$</td>
<td>min</td>
<td>98.39(205)</td>
<td>–</td>
</tr>
<tr>
<td>$P$</td>
<td>days</td>
<td>1.1675(454)</td>
<td>1.4822446(7)</td>
</tr>
<tr>
<td>$a$</td>
<td>AU</td>
<td>0.0209(12)</td>
<td>0.02446(68)</td>
</tr>
<tr>
<td>$i$</td>
<td>deg</td>
<td>82.961(95)</td>
<td>84.529(5)</td>
</tr>
<tr>
<td>$b = a \cos i / R_*$</td>
<td></td>
<td>0.636(34)</td>
<td>0.579(26)</td>
</tr>
<tr>
<td>$R_p$</td>
<td>$R_J$</td>
<td>1.232(2)</td>
<td>1.209(21)</td>
</tr>
</tbody>
</table>
Chapter 7 – Discussion

The aspiration for this thesis work was initially to make an attempt to detect and characterize a never before detected transit of an extrasolar planet. To accomplish this I first had to learn how to operate the Westerlund telescope and this training took place on four nights in February and March under the supervision of Kjell Lundgren. Next step was to detect and characterize one or more already known transiting planets on my own. This took longer than anticipated resulting in a slight change of strategy. Instead of the attempt to detect a new transiting planet from RV candidates, I chose to do a theoretical study on the probabilities for RV planets to transit which can be seen in Chapter 4. The study gave me some new insights (and hopefully those reading this thesis as well) on transiting RV planets which I never had considered before.

There were several reasons the first part of the thesis work took longer time than initially intended. One being the lack of clear nights on the weeks planed for observations and training. Also I underestimated the time it took to learn how to use some of the software needed for processing and analyzing of data from the observations. Especially Sextractor, which is a completely text-based software used to extract data from the FITS files, showed to take more time than planned to grasp. Also I had to learn to program in python which I had never done before. Although the time I spend learning these is not reflected greatly in the thesis, they are valuable tools to be able to master, especially for future work in the field of astronomy.

The results from the observation seen in Table 1 exceeded my expectations, given the fairly simply constructed light curve used to find the unknown parameters. In comparison with the work done by from Mandushev et al. [19] the results differ by only a small factor. The clearly underestimated errors is most likely due to the limitations of the simple model used when obtaining the unknown parameters ΔF, tT and tF. Presumably, with the added effect of limb darkening the results would be even better. With limb darkening effects the total transit time tT would increase and the time between second and third contact tF would decrease. By adding and subtracting a few minutes to these parameters the results becomes practically identical to the compared values. In order to get accurate values, the effect of limb darkening has to be used when constructing the fitted light curve. However, this makes the task of constructing the light curve much more complicated and time consuming. Still it could be something to consider if one would continue where this thesis work left off.
The thesis work shows (as expected) that the Westerlund telescope is more than adequate for the purpose to detect and characterize extrasolar planets. A possible follow-up to this thesis could therefore be to conduct a transit search of already known RV planets and use the results from Chapter 4 (Transit probabilities for RV planets) to find transit candidates.

**Chapter 8 – Summary**

The Westerlund telescope was used to detect and measure the transit of TrES-5 b. A theoretical fitted function was constructed based on two overlapping circles and the assumption of uniformed flux from the source. The values for the observables \( \Delta F \), \( t_T \) and \( t_F \) were extracted from a least square fitted simple geometrical model. Using these the orbital period \( P \), semi major axis \( a \), orbital inclination \( i \), impact parameter \( b \) and the planet radius \( R_p \) was calculated. These values were then compared with the work done by from Mandushev et al. [19]. The second part was a study on the probabilities for RV planets to transit. This was based on of the paper “A Posteriori Transit Probabilities” (2013) by Stevens and Gaudi, and can be seen in Chapter 4.
Chapter 9 – Acknowledgements

First of I would like to thank my supervisor Eric Stempels for guiding me towards the final goal and also for answering all my questions. He helped me to develop my idea from wanting to search for exoplanets, to a structured bachelor thesis. When it looked like the weather would prevent me from performing any kind of observations he kept me calmed with alternative ideas and ways to proceed. He also suggested the excellent paper by Stevens and Gaudi for the study of RV planet transit probabilities. I would like to thank Kjell Lundgren for taking the time to train me on how to operate the Westerlund telescope and also giving me some very useful advice on the way. I would also like to thank Nikolai Piskunov for proofreading my text. Last but not least, loving thanks to my girlfriend Caroline for her endurance and support through the sometimes stressful times working on this thesis.

Chapter 10 – Epilogue

This thesis work started with me searching for available projects among the provided ones by the department of physics and astronomy at Uppsala University. My preference was to find a project in which I would learn how to operate the Westerlund telescope (BWT) and actually use it to perform observations. The field of exoplanetary science has always interested me and because it is a quickly growing field it felt like a good place to look for a suitable project. Unfortunately, I could not find any proposed projects matching what I was looking for. So instead I sent a few e-mails to different people at the department simply saying I wanted to search for exoplanets with the Westerlund telescope for my bachelor thesis. Eventually I came in contact with Eric and we began to look in to the possibilities to formulate a project for my thesis. I had no previous experience with operating big telescopes like BWT and the initial draft for the project back in January 2015 basically was me wanting to search for exoplanets. However, with the help of Eric, a more ordered project strategy was formulated. This way of finding a project has had its ups and downs. It gave me the opportunity to more freely choose in which way to direct my work. On the other hand it took away some of the potential security a more predetermined framework would give. In the end it has been a rewarding journey and I like to believe that I have learned a great deal.
References


