Photometry and Spectroscopy of Candidate Transiting Extrasolar Planets

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A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Astronomy in the Department of Physics and Astronomy

February 2016
I, Amber MALPAS, declare that this thesis titled, 'Photometry and Spectroscopy of Candidate Transiting Extrasolar Planets' and the work presented in it are my own. I confirm that:

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- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
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Signed:

__________________________________________________________

Date:

__________________________________________________________
“This is one corner... of one country, in one continent, on one planet that’s a corner of a
galaxy that’s a corner of a universe that is forever growing and shrinking and creating
and destroying and never remaining the same for a single millisecond. And there is so
much, so much to see.”

- The Doctor
Abstract

Master of Science in Astronomy

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by Amber Malpas

The search for exoplanets is often most captivating when concerning the discovery of Earth-like planets that could possibly sustain life, according to our current understanding of the environmental requirements. However, current estimates suggest that habitable planets are a minority. In order to fully understand the trends, structure and formation of planetary systems, more information about exoplanets and their systems is needed. No exoplanets offer up as much information as transiting exoplanets.

The data collected for this thesis was as part of a follow-up effort for the KELT-South (Kilo-degree Extremely Little Telescope in the southern hemisphere) project, which uses the wide-field surveying photometric telescope to search for transiting exoplanets, usually of the hot Jupiter variety. Follow-up lightcurves have been produced for many different candidate stars. Of those presented four suggest spurious survey data, and five suggest false-positives due to blended or grazing eclipsing binaries; these have been ruled out as exoplanet candidates. Eight of the lightcurves produced still appear to be likely transiting exoplanets, but require further photometry or high precision spectroscopy in order to be confirmed.

Radial velocity (RV) follow-up was performed on two KELT-South transiting exoplanet candidates (HD 113204 and HD 9468). More data is needed for both targets though an upper projected mass limit of 0.24M_\text{J} was placed on the companion of HD 9468. A meaningful estimate for the projected mass of the planetary companion of HD 113204 could not be made as there was too little data.
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<th>Full Form</th>
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<td>AAVSO</td>
<td>American Association of Variable Star Observers</td>
</tr>
<tr>
<td>ANU</td>
<td>Australian National University</td>
</tr>
<tr>
<td>BLS</td>
<td>Boxed Least Squares</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-coupled device</td>
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<tr>
<td>COM</td>
<td>Centre Of Mass</td>
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<tr>
<td>Dec</td>
<td>Declination</td>
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<tr>
<td>FITS</td>
<td>Flexible Image Transport System</td>
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<tr>
<td>FLWO</td>
<td>Fred Lawrence Whipple Observatory</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full-Width-Half-Maximum</td>
</tr>
<tr>
<td>HATnet</td>
<td>Hungarian-made Automated Telescope network</td>
</tr>
<tr>
<td>HERCULES</td>
<td>High Efficiency and Resolution Canterbury University (L) Echelle Spectrograph</td>
</tr>
<tr>
<td>H-R</td>
<td>Hertzsprung-Russel</td>
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<tr>
<td>KELT</td>
<td>Kilodegree Extremely Little Telescope</td>
</tr>
<tr>
<td>LCOGT</td>
<td>Las Cumbres Observatory Global Telescope network</td>
</tr>
<tr>
<td>LS</td>
<td>Least Squares</td>
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<tr>
<td>MCM</td>
<td>Monte Carlo Method</td>
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<tr>
<td>MCMC</td>
<td>Markov Chain Monte Carlo</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics Space Administration</td>
</tr>
<tr>
<td>OC61</td>
<td>Optical Craftsman 61mm Telescope</td>
</tr>
<tr>
<td>PEST</td>
<td>Perth Exoplanet Survey Telescope</td>
</tr>
<tr>
<td>PHOEBE</td>
<td>Physics Of Eclipsing Binaries</td>
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<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
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<tr>
<td>PSF</td>
<td>Point Spread Function</td>
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<tr>
<td>QE</td>
<td>Q Efficiency</td>
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<tr>
<td>RA</td>
<td>Right Ascension</td>
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<tr>
<td>RV</td>
<td>Radial Velocity</td>
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<td>Abbreviation</td>
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<tr>
<td>STARE</td>
<td>STellar Astrophysics and Research on Exoplanets</td>
</tr>
<tr>
<td>TESS</td>
<td>Transiting Exoplanet Survey Satellite</td>
</tr>
<tr>
<td>TRES</td>
<td>Tillinghast Reflector Echelle Spectrograph</td>
</tr>
<tr>
<td>WCS</td>
<td>World Coordinate System</td>
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## Physical Constants

<table>
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<tr>
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<th>Value</th>
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</thead>
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<tr>
<td>Solar Mass $M_\odot$</td>
<td>$(1.98855 \pm 0.00025) \times 10^{30}$ kg</td>
</tr>
<tr>
<td>Mass of Jupiter $M_J$</td>
<td>$1.898 \times 10^{27}$ kg</td>
</tr>
<tr>
<td></td>
<td>$= 317.8 M_\oplus$</td>
</tr>
<tr>
<td></td>
<td>$= 0.0009543 M_\odot$</td>
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<tr>
<td>Radius of Jupiter $R_J$</td>
<td>$69911$ km</td>
</tr>
<tr>
<td></td>
<td>$= 10.97 R_\oplus$</td>
</tr>
<tr>
<td>Mass of Earth $M_\oplus$</td>
<td>$5.972 \times 10^{24}$ kg</td>
</tr>
<tr>
<td>Radius of Earth $R_\oplus$</td>
<td>$6373$ km</td>
</tr>
<tr>
<td>Gravitational Constant $G$</td>
<td>$6.67408 \times 10^{-11}$ m$^3$kg$^{-1}$s$^{-2}$</td>
</tr>
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</table>
To my father
Chapter 1

Introduction

Our universe is bigger and better than we thought it was. And the more we learn about the universe, the more this is confirmed to be true. The world does not end at the horizon, as historically thought. Nor is our spherical planet the centre of the universe (as was proposed by Aristotle, 340 BC). Contrary to the controversial heliocentric models of the sixteenth and seventeenth centuries, the Sun is not the centre of the universe either. Our big, bright Sun is a perfectly ordinary sized star and one of billions in our galaxy. Our galaxy is one of many in our local group which is just one small part of our galactic cluster. The entire universe has a neuron-like structure to which our galactic cluster is only one inconceivably small part. One very small part at some insignificant location in a universe which is expanding. And this might not even be the only universe. The sheer scale of it all is as majestic as it is humbling.

One of the few occasions in which we seem to maintain any real consequence in amongst all that we know about the cosmos, is when considering the unparalleled habitability of our planet. Although that too may well change as the number of exoplanet\(^1\) detections increases and our ability to investigate properties of these planets improves.

To date 2019 exoplanet discoveries have been confirmed in 1307 different systems.\(^2\) Of these confirmed exoplanets, 21 are potentially habitable (see Fig. 1.1).\(^3\)

One of the most Earth-like, potentially habitable planets to be discovered is Kepler-438b (found using Kepler survey data). It orbits in the habitable zone\(^5\) about its parent star and is small enough to have a rocky surface composition (Torres et al., 2015). The

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\(^1\)Exoplanets are planets that orbit stars outside our solar system and are sometimes referred to as extrasolar planets.

\(^2\)http://www.openexoplanetcatalogue.com/

\(^3\)http://phl.upr.edu/projects/habitable-exoplanets-catalog

\(^4\)http://phl.upr.edu/projects/habitable-exoplanets-catalog

\(^5\)The habitable zone, in this context, refers to the region in which water can exist on the surface of a planet in liquid form.
Chapter 1. Introduction

distance to this system was calculated in Torres et al. (2015) as approximately 470 light-years\(^6\) (145 pc). The radius of the planet is found through the planet-star ratio parameter obtained when fitting a model to the transit lightcurve (these will be discussed a great deal more throughout this thesis) for the target star. Using this fitted parameter, Torres and his colleagues have found the radius of Kepler-438 to be \(1.12 R_\oplus\). However, the host star to Kepler-438b has a known close companion and it cannot be ruled out that the planet is in fact orbiting the companion. If this is the case then the radius of the planet would actually be larger than this. If the correct host star has been considered then there is a 71.8\% likelihood that Kepler-438b is in the habitable zone and a 69.6\% likelihood that it is rocky.

Though the search for Earth doppelgängers is a fascinating one, it is not the only worthwhile reason to search for exoplanets. Not only is potential habitability uncommon, but it seems that planetary systems most commonly contain fewer planets than our own system, with planets that are one to three times the size of Earth, which orbit much closer than Earth does (Cruz and Coontz, 2013). According to these trends, our solar system appears to be the atypical one. Though, the unfamiliar nature of all these planetary systems surely makes them all the more captivating.

\(^6\)This is about 12 billion times the distance to the moon - so it’s not exactly a feasible holiday destination.
As the number of planetary candidates has increased in recent years so too has the number of planetary systems; for example, 55 Cancri with 5 known planets (Nelson et al., 2014), or HD 10180 hosting at least 5, but possibly 7, exoplanets (Lovis et al., 2011). Alibert et al. (2013) covers a recent theoretical model of planetary formation which includes multi-planet systems.

Being the proverbial hippopotamus in the living room, hot Jupiters make up most of the exoplanets discovered to date (Southworth, 2015). Hot Jupiters, being large and massive, are the easiest exoplanets to detect, especially when they have close orbits (Horne, 2003).\footnote{A hot Jupiter is a planet with mass that is similar to that of Jupiter’s, but with a much closer orbit at $a \leq 0.1$ AU (Ryden and Peterson, 2010).} When looking for statistical trends in the characteristics of exoplanets, it therefore becomes necessary to account for selection biases, such as those for hot Jupiters (Howard, 2013). The selection biases between different exoplanet surveys, and within these surveys, have to be estimated in order to statistically correct for them.

Hot Jupiters posed a problem for planetary formation models because it is too hot for gas giants to form that close to their parent star (Ryden and Peterson, 2010). Mazeh et al. (2005) were the first to suggest that there might be a correlation between mass and orbital period for close planets, where lower mass exoplanets had larger orbits than the more massive exoplanets. Jackson et al. (2009) also suggest a relationship between the semi-major axis of orbits of close-in exoplanets and the age of the host star, where the closest planets of older stars are further out than the closest planets of younger star. It is unclear whether or not any of the close orbiting exoplanets ($a \leq 0.1$ AU) are actually formed so close to their host star (Benítez-Llambay et al., 2011).

One theory is that exoplanets of the hot Jupiter kind must have been formed further out from their parent star than they are found, and have had their orbit perturbed, causing them to lose angular momentum and fall closer towards the parent star (Ryden and Peterson, 2010). Another theory explains the statistical “pile-up” of close-in planets by proposing that magneto-rotational instability evacuates the protoplanetary disk out to a distance corresponding to about a six day period and that the planets then migrate in to this region, stopping once the region they are in has the correct Linblad resonance (Kuchner and Lecar, 2002). Theories to explain this also include tidal interactions with the host star, where the planet’s orbit is forced to decay by the tides raised on the host star.
star (Jackson et al., 2009), evaporation of close-in planets (Davis and Wheatley, 2009), and a combination of planetary scattering, tidal circularisation, and Kozai resonance (see Nagasawa et al. (2008) for more on this).

Planets with masses between that of Earth and Neptune have been shown to be the most common in the galactic neighbourhood by recent surveys (Cassan et al., 2012, Petigura et al., 2013). However, knowing the mass of a planet does not provide significant information about the size of the planet; there are degeneracies in the possible sizes for a planet of a given mass (Howard, 2013). In the case of gas giants, the size of the planet can be somewhat inferred from the stellar flux incident on the planet. The stellar flux heats up the gas of the planet causing its atmosphere to become inflated. The more flux incident on the planet, the larger it will become. An example of this is the planet, WASP-17b, discussed in Subsection 1.1.1.

Before the discoveries of the vast number of exoplanets on which these trends and models were built, it might have seemed reasonable to assume our solar system was some kind of archetype for all planetary systems in the galactic neighbourhood. Given our current understanding of exoplanets and their systems, it seems this assumption would have been echoing the erroneous beliefs of historic cosmic models. Collecting more examples of planetary systems will help us to understand our solar system with some context and infer details about planetary formation models (Howard, 2013).

In order to gain an all-encompassing understanding about planetary formation, we must also learn about the primordial origins of these planets. Critical information about planet origins can be gleaned from their atmospheric compositions (Madhusudhan et al., 2011). This can be done through the analysis of dayside photometry in multiple wavelengths (see Madhusudhan et al. (2011)), or through transmission spectroscopy (Sing et al., 2011) of transiting (see Subsection 1.1.1) exoplanets.

Studying the compositions of exoplanets has led to some extremely interesting discoveries. One of these is the diamond planet named 55 Cancri e. 55 Cancri e super-Earth at eight times the mass of Earth and two times the radius (Demory et al., 2011). The mass and radius of this planet have been used to restrict possible interior compositions. The leading theory is that this planet is composed largely of carbon (given the density of the planet much of this would be in the form of diamond), especially considering the carbon rich composition of its host star (Madhusudhan et al., 2012). Further observations are needed to confirm this theory. Since this is a very different composition to those seen in
our own solar system, claims of a carbon-rich planet are made somewhat tentatively by the authors of Madhusudhan et al. (2012).

Another rather strange and fascinating theory concerns the conditions on exoplanet HD 189733b. HD 189733b is a hot Jupiter that has been confirmed as being deep blue in colour using polarimetry\(^9\) (Berdyugina et al., 2011). The planet is tidally locked, however a heat map of the planet (Knutson et al., 2007) showed concentrated heat from this tidal locking being shifted. The likely cause is thought to be supersonic winds, caused by the dramatic differences in temperatures either side of the planet, redistributing the heat from its parent star. Pont et al. (2013) models the planet’s transmission spectrum by a prevalence of dust in the atmosphere, which is likely composed of enstatite. The silicon in enstatite explains the apparent blue colour of the planet. Enstatite is transparent in the visible wavelength and hence HD 189773b is sometimes said to “rain glass sideways”\(^10\).

1.1 Detecting exoplanets

So how exactly do we find exoplanets? Exoplanets can be detected through RV measurements of the host star, transit photometry (see Subsection 1.1.1), transit-timing variation\(^11\), microlensing, pulsar timings\(^12\), astrometry (Sozzetti, 2010), direct imaging (Marois et al., 2008), and polarimetry\(^13\).

Of all the planetary detection methods, RV and transit methods have so been able to discover, by far, the most exoplanets\(^14\). The disadvantages of both RV and transit methods, however, are their detection biases.

\(^9\)Polarimetry is also mentioned in Section 1.1.

\(^10\)https://www.spacetelescope.org/news/heic1312/

\(^11\)Transit-timing variation can be used to detect additional planets from the effects they have on the transiting planet’s orbit (Holman et al., 2010).

\(^12\)The first detected exoplanets were the two low mass planetary companions around PSR 1257+12, detected due to the variations they caused in the pulse arrival times of the host pulsar (Wolszczan and Frail, 1992).

\(^13\)Polarimetry is most useful for classifying previously discovered planetary-systems rather than identifying new exoplanets (Boccaletti et al. (2012) and Berdyugina et al. (2007))

\(^14\)http://exoplanet.eu/catalog/
1.1.1 To transit or not to transit

Current surveys show that around 50% of all stars have one or more planets (Cassan et al., 2012, Howard, 2013). Only a small subset of these are likely to have orbital inclinations that result in a transit, and exoplanets with close-in orbits will be more likely to transit than exoplanets that orbit further away from their host stars.

Transits refer to the astronomical events where one celestial body moves across the face of another from the observer’s perspective. Transiting planets offer unique opportunities to learn more about size, composition, and orbit of the planet. For this reason, many exoplanet surveys, some of which are described in Section 1.2, are specifically geared towards finding transiting exoplanets.

When a planet transits in front of its parent star, it causes a dip in brightness of around 1%, lasting approximately three hours (Horne, 2003). The shape of the dip in brightness on a star’s lightcurve is distinctly “U” shaped, as depicted in Fig. 1.2. The frequency with which the dips in brightness occur indicates the orbital period of the planets. The relative radius (radius in units of stellar radii) of a transiting planet can be analytically inferred from the lightcurve of a host star during a transit (Mandel and Agol, 2002). The spectral type of the host star can then be used to find the radius of the host star and thus the radius of the planet (Lang, 1991).

Lightcurves indicating a planetary transit are identifiable through their “U” shaped dips in brightness, as can be seen in Fig. 1.2. There are other stellar arrangements that can

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15 A lightcurve refers to the graph of a star’s apparent magnitude or apparent flux against time or phase.
16 http://wasp-planets.net/about/
mimic this shape, as can be seen in Fig. 1.3 producing false positives in transit detection surveys (transit surveys are covered in more detail in Section 1.2).

These false positives can be ruled out at different stages in the detection and follow-up processes. Grazing binaries (seen in Fig. 1.3 d.) and blended stellar binaries (Fig. 1.3 c.) can be distinguished from planetary transits during the more intensive follow-up photometry, due to their “V” shaped lightcurves. If the imposter binary stars have different temperatures, they can also be ruled out due to the varying depth of the transit in different wavelength bands. For example, if the transiting star is cooler than its companion it will block out the companions bluer light and while still producing redder light, thus making the transit appear to have a greater depth in a bluer filter than in a redder filter. The false positives caused by brown dwarfs and some small stars (Fig. 1.3 b.) can only be ruled out by investigating the mass of the transiting companion, as the brown dwarfs and small stars will be heavier than Jupiter-like planets of the same radius (Cameron, 2012).

Another common technique used in the discovery and confirmation of exoplanets is through the investigation of a potential parent star’s RV. The mass of the potential planet can be found by quantifying the effect it has on the RV of its host star. If the potential
parent star has a planetary companion then both celestial bodies will orbit a common centre of mass (COM). The separation between the star and the COM, $a_s$, will be much smaller than the separation between the planet and the COM, $a_p$, due to its much greater mass, $M_s$ ($M_p$ is the mass of the planet). This can be mathematically described by

$$a_s = \frac{M_p a_p}{M_s}. \quad (1.1)$$

The star orbits the COM with some velocity, $v_s$, for which the line-of-sight component is $v_s \sin i$. The star’s line-of-sight velocity varies sinusoidally throughout its orbit. The magnitude and direction (towards or away from the observer) of $v_s \sin i$ can be measured through resulting Doppler shifts of the absorption lines in the star’s spectrum (Ryden and Peterson, 2010). These spectral lines are observed using spectroscopy (this is covered in Chapter 2). $v_s \sin i$ is equivalent to the RV of the star when corrections for the velocity of the Earth around the Sun and the velocity of the star-planet system relative to the Earth-Sun system have been made. The amplitude of this sinusoidally varying RV is equivalent to the projected velocity of the star around the COM. From this velocity, using Kepler’s laws and assuming a circular orbit, the projected mass of the planet can be found. The derivation for this can be found in Chapter 5.

This effect also occurs in the case of eclipsing binaries, though these produce a more pronounced RV variability due to their much greater masses. The existence of a planetary companion can therefore be confirmed by the amplitude of RV variations. Photometric identification of a target is therefore followed up by RV measurements in order to rule out the false positive cases mentioned earlier (Cameron, 2012) and to find the projected mass of the planet. By knowing the projected mass and radius of the planet, conclusions about its density can be made (Howard, 2013). Knowing the density of the planet contributes to making conclusions about the planet’s composition (Rogers and Seager, 2010).

In cases where exoplanets are transiting, spectroscopic observations during the transit can be used to observe the Rossiter-McLaughlin effect (McLaughlin, 1924, Rossiter, 1924). The Rossiter-McLaughlin effect is where a transiting planet causes a deviation in the rotationally broadened stellar spectral lines, perturbing the usually sinusoidal RV measurements. An example of such a perturbation can be seen in Fig. 1.4. Tracking this effect as the planet transits allows the inclination of the transit, relative to the star’s axis of rotation, to be found (Johnson et al., 2015). The spin of stars about their rotational

\[^1\text{The tilt of the star’s orbit cannot be known and so the line-of-sight component of the velocity is what is found from the amplitude.}\]
Figure 1.4: Example of an RV curve being perturbed by the transit of a planet. This figure includes RV results of the parent star to WASP-3b from Simpson et al. (2010).

axis results in the varying doppler shifts across the star’s projection; the side of the star spinning towards the observer is blue shifted, and the side spinning away from the observer is red shifted. As a planet passes in front of a rotating star, it blocks some of the red or blue shifted light. The path it takes across the star, relative to the star’s rotational axis, determines the shape of the RV perturbation from which the inclination of the planet’s orbit can be inferred. Figure 1.5 depicts this effect.

Figure 1.5: This figure shows the effect different inclinations have on RM perturbations of the RV sinusoid.\textsuperscript{18}

Early RM results concerning the orbital inclination of planets indicated aligned orbits (Southworth, 2015). For example, the first spectroscopic transit, observed by Queloz

\textsuperscript{18}http://www.amaurytriaud.net/Main/Rossiter/index.html
et al. (2000a), demonstrated an angle between the orbital plane and the *apparent* stellar equatorial plane of 3.9° (the upper limit on the angle between the orbital plane and stellar equatorial plane was set at 30°). It now seems that there are a significant number of misaligned and retrograde orbits (Southworth, 2015). The first retrograde planet, discovered as part of the WASP (Wide-Angle Search for Planets) survey, was the “puffy” planet: WASP-17b (Anderson et al., 2009). This planet is distinctive not only for its retrograde orbit, but also its ultra-low density (its puffiness). This exoplanet (WASP-17b) was found to have a mass of 0.48M_J and a radius of 1.5 – 2M_J (approximately half the mass of Jupiter and 1.5-2 times the radius of Jupiter). The density of WASP-17b is therefore 6% – 14% of the density of Jupiter. Anderson et al. (2009) suggests that the extremely low density of WASP-17b might be the result of a bloated radius due to tidal heating. The RV measurements during transits of WASP-17b suggest a retrograde orbit with an inclination of $-150^\circ$. This planet appears to have experienced a violent history of star-planet or planet-planet scattering\(^{19}\).

### 1.2 Transit surveys

WASP is one of many photometric transit surveys currently being used for the detection of exoplanets. Some other photometric surveys include HAT\(_{\text{NET}}\) (Hungarian-made Automated Telescope Network), KELT (see Section 1.3), and the previously mentioned Kepler survey. Specific details about these surveys are covered in this section.

Photometric surveys are useful because they focus RV resources and allow for more information about a specific exoplanet to be found (Howard, 2013). Photometric surveys can monitor large portions of the sky waiting for tell-tale dips in brightness to indicate the presence of a planet, while RV surveys can only monitor one star at a time. As previously mentioned in this chapter, transiting exoplanets can be characterised not only by their projected masses, but also by their radii. From these characteristics, conclusions about density and composition can be made. Transmission spectroscopy is also able to be performed on transiting exoplanets, allowing information about their atmospheres to be found.

\(^{19}\)See Portegies Zwart and Jilková (2015) for more on the perturbations of planetary systems.
1.2.1 Space-based surveys

One cannot talk about transit surveys, and especially not space-based transit surveys, without mentioning Kepler. Of the 2019 exoplanet discoveries, more than half\(^{20}\) were discovered using NASA’s Kepler Space Telescope.

Kepler was designed to monitor 100,000 main sequence stars (of \(9 \text{mag} < V < 15 \text{mag}\)) continuously, looking for dips in brightness indicative of transiting exoplanets the size of Earth and larger (Borucki et al., 2006). Kepler’s mission was to investigate the diversity and structure of planetary systems, but interest was mostly placed in finding Earth-like planets in the habitable zone of their parent star.

Kepler uses differential photometry methods where a star’s brightness relative to nearby comparison stars over time is the only information of interest. The onboard telescope is a modified Schmidt-type telescope. The field-of-view is 100 square degrees. Images are read out from the mosaic of 42 back-illuminated CCDs every 3 seconds. These images are than co-added, reduced and returned to Earth for processing via a high gain antenna (Borucki et al., 2003).\(^{21}\)

After launch in 2009, the benefit of Kepler data sets to other areas of astrophysics quickly became apparent (Koch et al., 2010). At least three transits, with consistent characteristics such as depth and period, are required to be observed from Kepler before planets are confidently identified. Ground based follow-up measurements are required to confirm planetary candidates and find their projected masses.

Another space-based transit survey worth mentioning is the soon-to-be-launched Transiting Exoplanet Survey Satellite (TESS). TESS will be searching bright, nearby stars for transiting planets. The number of stars it has been designed to monitor is twice that of Kepler. It will be placed in a high-Earth orbit in order to provide more stability than would be possible in a low-Earth orbit, for the precision photometry it will perform (Ricker et al., 2015).

TESS will concentrate on observing M-type dwarf stars (Ricker et al., 2015). These were relatively unexplored by Kepler and rotate relatively slowly, which allows for

\(^{20}\)http://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

\(^{21}\)See Borucki et al. (2006) or Borucki et al. (2003) for more on the design and goals of Kepler.
more precise spectroscopy than can be achieved with faster rotating stars. These relatively bright targets will allow for follow-up spectroscopic observations, for investigating planetary masses and atmospheres, that were often unobtainable with the generally dimmer Kepler targets.

### 1.2.2 Ground-based surveys

The WASP transit survey has already been mentioned in this chapter due to the number of sincerely interesting exoplanets this survey is responsible for the discovery of. The WASP survey consortium detect planetary candidates using two wide-field commercial quality camera arrays covering approximately one hour in right ascension by 30 degrees in declination (Cameron et al., 2008). One of the camera arrays is located on the island of La Palma (Canary Islands) in the northern hemisphere and the other at the site of the South African Astronomical Observatory in Sutherland in the Southern hemisphere. The motivation of the WASP transit survey is to discover gas giant planets around stars bright enough (brighter than 13th magnitude) for RV follow-up for confirmation and to obtain mass measurements.

Being a ground based survey, the WASP arrays can only monitor selected fields during certain times in the night, and only in accommodating weather conditions, not continuously like Kepler can. The data obtained from these arrays is reduced and archived using the automated SuperWASP pipeline presented in Pollacco et al. (2006). As part of the SuperWASP pipeline, images are flat-fielded, bias-subtracted, and then the fields are matched to their counterparts in the TYCO-2 catalogue. The SuperWASP pipeline also perform automatic aperture photometry on the positions of all stars brighter than a magnitude of 15. The data is corrected for primary and secondary extinction and finally decorrelated for systematic error.

A fast hybrid algorithm, based on the Box Least Squares (BLS) algorithm of Kovács et al. (2002) is used on the WASP data sets for candidate identification and winnowing (Cameron et al., 2006). After this, candidates are visually inspected using follow-up photometry to remove the last of the spurious targets (Pollacco et al., 2006). This follow-up photometry is performed by consortium members. The photometric follow-up process is also useful for finding any remaining false-positive signals (see the earlier Subsection 1.1.1 for more on false positives) that have made it though winnowing.
Candidate stars are then sent for RV follow-up, performed using the SOPHIE (Bouchy and Team, 2006) and CORALIE (Queloz et al., 2000b) spectrographs. About one star in every five or six of those sent for RV follow-up are confirmed as transiting planets (Cameron et al., 2008); even at this stage there are still binaries masquerading as transiting exoplanets.

Those candidates confirmed to be exoplanets then have Monte Carlo Markov Chain (MCMC; see Chapter 3, Section 3.4) analysis run simultaneously on their lightcurve and RV data in order to draw conclusions about the physical and orbital characteristics of the newly discovered planets (Hellier et al., 2014).

The wide-field survey method of detecting exoplanets is obviously a method for success. It is a method that has been based on the promising results of the prototype STARE (STellar Astrophysics and Research on Exoplanets) instrument (Alonso et al., 2003) and has been replicated in many similar surveys.

One such survey is HATNET. HATNET uses 64K front illuminated CCD instrument array, resulting in a 10.6° by 10.6° field. The principles behind HATNET’s design and processes are very similar to that of WASP. After survey images are collected, standard techniques are used to calibrate the images. Aperture photometry is performed. The lightcurves are decorrelated using the Trend Filtering Algorithm of Kovács et al. (2005). The search for periodic events consistent with exoplanet transits is performed using BLS (Kovács et al., 2002). Automatic filters are used in order to rule out targets that are obviously not transiting eclipsing binaries. The follow-up process for HATNET targets is to go through reconnaissance spectroscopy, photometric follow-up observations, and then high precision spectroscopic follow-up. During these processes, false positives are being continually ruled out until only confirmed transiting exoplanets remain (Bakos et al., 2011).

Another wide-angle telescope survey is the KELT project (Pepper et al., 2004). Like WASP, KELT has both northern and southern-based survey telescopes (Pepper et al., 2012). Like WASP and HATNET, KELT is designed to find hot Jupiters, transiting parent stars bright enough for spectroscopic follow-up observations. The KELT project is discussed in more detail in the following section.
1.3 KELT

The photometric data collected for this thesis was submitted as follow-up photometry for the KELT (Kilodegree Extremely Little Telescope) survey. The survey uses two telescopes; KELT-North and KELT-South. The KELT-North\textsuperscript{22} telescope is located in the Winer Observatory in Arizona. It has been running since 2005 and collects data over 13 fields during a year. KELT-South is located at the South African Astronomical Observatory site in Sutherland.

Both telescopes have: a Mamiya 645 80mm f/1.9 medium format lens, a 42mm aperture, a 4096 x 4096 Apogee CCD (the Kelt-North and KELT-South telescopes have the Apogee AP16E and thermoelectrically cooled Apogee Alta U16M models, respectively), a 26.0 × 26.0 degree field of view, a 23.0 arcsec/pixel plate scale, and a Paramount ME mount. The intended KELT targets are in the brightness range of 8 < $V$ < 10 mag, though brighter and dimmer transiting exoplanetary candidates are also found. (Pepper et al., 2012)

The KELT project performs difference imaging (after bias-subtraction and flat-fielding) using a highly modified version of the ISIS\textsuperscript{23} difference-image-analysis package (Alard, 2000, Alard and Lupton, 1998). As described in (Pepper et al., 2012), the lightcurves of relative magnitude of the stars in a field are calculated using two separate\textsuperscript{24} total baselines for all KELT observations of that field.

The large 23 arcseconds per pixel plate scale results on more than one star commonly being located within a single pixel. The result of this is that the sources of perceived periodic dips in brightness are ambiguous. This ambiguity is resolved by follow-up observations of targets. Follow-up observations clarify the star at the source of any variation, and are required to measure the phase, period, shape, and depth of the transit-like signal (Cameron et al., 2008, Kuhn et al., 2015, Southworth, 2015). They also help to rule out some of the false positives mentioned in Subsection 1.1.1.

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\textsuperscript{22}http://www.astronomy.ohio-state.edu/keltnorth/Home.html
\textsuperscript{23}http://www2.iap.fr/users/alard/package.html
\textsuperscript{24}One for east and one for west due to the design of the German equatorial mount used, which requires a 180° rotation when moving from observing on different East-West sides of the meridian
The KELT-South photometric follow-up partners include: Thiam-Guan Tan who owns and operates the Perth Exoplanet Survey Telescope (PEST); Prof Eric Jensen of Swarthmore College using the Peter Van de Kamp Observatory; Prof Kim McLeod of Wellesley College using Whitin Observatory; American Association of Variable Star Observers (AAVSO) member Gordan Meyers using the Meyers T50; Prof Phill Reed using an optical telescope and a mid-resolution fiber-fed echelle spectrograph from the Kutztown University Observatory; Ivan Curtis running a 253 mm SCT from his backyard in Adelaide; and Allyson Bieryla and Prof David Latham using KeplerCam at the Fred Lawrence Whipple Observatory (FLWO). Photometric follow-up observations are also made from partners using the SKYnet network, the Las Cumbres Observatory Global Telescope (LCOGT) network, and from Mt Kent Observatory.

As with the WASP observation chain, after photometric follow-up has narrowed down the list of planetary candidates, RV measurement are made on the remaining targets.

The KELT-South spectroscopic partners include: the Australian National University

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25https://my.vanderbilt.edu/keltsouth/kelt-south-followup-partners/
26https://my.vanderbilt.edu/keltsouth/kelt-south-followup-partners/
27https://skynet.unc.edu/
28http://lcogt.net/
29https://my.vanderbilt.edu/keltsouth/kelt-south-followup-partners/
From the obtained spectroscopic results, the stellar mass and radius are calculated using the relations in Torres et al. (2010). As described in Pepper et al. (2013), the final model fitting to obtain the orbital and physical parameters of the planet uses EXOFAST (Eastman et al., 2013). EXOFAST uses MCMC to analyse the entire system, including the constraints put on stellar mass and radius.

### 1.4 Summary of work covered in this thesis

The following chapters include both photometric and spectroscopic observations made in attempts to detect exoplanets through the effect they have on the RV of their host star and the effects transiting planets have on the lightcurves of their host. These observations were made as follow-up to survey results obtained from the KELT-South photometric transmitting survey in order to assist with the confirmation and expiration of planetary candidates.

The remainder of this thesis is laid out as follows:

Chapter 2 covers the equipment and observational methods used by the author for the photometric and spectroscopic observations of 19 KELT targets. Chapter 3 is concerned with the model fitting of lightcurve data and follows the development an MCMC model fitting program. Chapter 4 contains a selection of those lightcurves obtained (the remainder can be found in Appendix C) and the model fitting of relevant lightcurves using both the created MCMC model fitting program (where possible) and using the widely available and well developed AstroImageJ (the program on which all multi-aperture, differential photometry was performed). Chapter 5 includes spectroscopic results from two of the brightest KELT planetary candidates. A final summary of the work completed is given in Chapter 6.
Observations and data processing

Observations for the purpose of this thesis were all taken from University of Canterbury Mount John Observatory (UCMJO) in Tekapo, New Zealand (170 27.9 E, −43 59.2 N, 1028 m altitude). These observations were intended to assist in the identification of transiting planetary candidates found in the KELT-South survey.

2.1 Photometry

The observation work undertaken for this thesis was primarily focussed on photometric follow-up to the KELT-South survey. Photometric observations, used for KELT follow-up, were made with the Optical Craftsman 0.61 m telescope (OC61). This was because OC61 was well suited to photometry of targets with brightnesses of the stars chased in the KELT-Survey (usually in the range $8 < V < 12$ mag) and was available for use to University of Canterbury students.
### Telescope

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<tbody>
<tr>
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<td>Focuser</td>
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### Mount

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<td>Maximum unguided tracking</td>
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<td>Restrictions</td>
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<tr>
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<td>Software</td>
<td>TheSky, MaxIm DL, ACP, ACP Scheduler</td>
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<tr>
<td>Telescope advocate</td>
<td>A. Henden</td>
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### Imaging

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<tr>
<td>Best seeing</td>
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</tr>
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<td>Filters</td>
<td>BVgri</td>
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</tr>
<tr>
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<tr>
<td>Gain</td>
<td>1.38 e⁻/ADU unbinned</td>
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<tr>
<td>Readnoise</td>
<td>11.21 e⁻</td>
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<tr>
<td>Full well</td>
<td>65 K ADU</td>
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<tr>
<td>Read time</td>
<td>5 s</td>
</tr>
<tr>
<td>Shortest exposure</td>
<td>0.2 s (iris shutter)</td>
</tr>
<tr>
<td>Compressed image size</td>
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</tr>
</tbody>
</table>

Table 2.1: Specification for the telescope, mount, imaging, and camera of OC61.²

#### 2.1.1 The Optical Craftsman 0.61 m (OC61) telescope

The Optical Craftsman 0.61 m telescope is a fork-mounted reflecting telescope, usually reserved for photometry.¹ OC61 has recently been upgraded for use as a robotic telescope. The OC61 telescope is included in the American Association of Variable Star Observers’ (AAVSO’s) Robotic Telescope Network.

The attributes of the OC61 set-up can be seen in Table 2.1

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¹http://www.phys.canterbury.ac.nz/research/mtjohn/facilities.shtml
²https://www.aavso.org/mountjohnuniversityobservatorymjuo
The Finger Lakes Instrumentation ProLine 09000 (FLI PL 09000) CCD camera\(^3\) uses an ON Semiconductor KAF-09000 sensor\(^4\), which boasts high quantum efficiency (QE) and a broad dynamic range\(^5\). The QE response graph over the entire dynamic range can be seen in Fig. 2.2. The camera is mounted with a 5-slot filter wheel containing B, V and SDSS g\('\), r\('\), and i\('\) filters. The transmission curves for these filters, showing how much of each wavelength of light is passed through the filter, can be seen in Figures 2.3, 2.4, and 2.5.

The combination of the QE at different wavelengths, the transmission percentage at different wavelengths for the different filters, and the telescope optics, result in exposure times needing to be changed between filters to detect the same amount of light. An approximate guide to how much each filter is effected is represented in the exposure ratios in Table 2.1.

![QE response graph](http://www.flicamera.com/spec_sheets/PL09000LDR.pdf)

**Figure 2.2:** QE response of the ON Semiconductor KAF-09000 sensor used in the camera on OC61, from the ProLine PL09000 Specifications sheet, for monochrome light.\(^6\)

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\(^3\)http://www.flicamera.com/spec_sheets/PL09000LDR.pdf
\(^4\)http://www.rastr.net/Download/Doc/Kaf09000.pdf
\(^5\)http://www.onsemi.com/pub_link/Collateral/KAF09000D.PDF
\(^6\)http://www.flicamera.com/spec_sheets/PL09000LDR.pdf
\(^7\)http://www.flicamera.com/filters/index.html
\(^8\)http://www.flicamera.com/filters/index.html
\(^9\)http://www.ing.iac.es/astronomy/instruments/acam/filt/filtcurve.html
Chapter 2. Observations and data processing

Figure 2.3: Transmission curve of the B filter used in OC61.

Figure 2.4: Transmission curve of the V filter used in OC61.

Figure 2.5: Transmission curves of SDSS filters with g', r', and i' being used in OC61, from the manufacturers data.
2.1.2 Observations

One third of the telescope time for OC61 was allocated to use for the University of Canterbury. Approximately 20% of nights at UCMJO are considered to be photometric, however conditions do not have to be photometric for CCD relative photometry (the type of photometry performed for this thesis) so more like 40% of nights are usable. This should have meant that about 10% of nights were spent obtaining data for this project. However, telescope upgrades and repairs meant that the number of nights actually spent obtaining data for this project were fewer than originally hoped for. This percentage also becomes reduced because observations made for this project require many hours in a row of usable conditions for a base-line flux and transit depth to be found, which makes ideal conditions for observing transits harder to come by than other photometric uses. Appendix A, Table A.1 contains a list of all requested and completed observations and which of those sets were able to be submitted to the follow-up group.

Target stars were chosen using the transit finder tool on the Swarthmore College website. The transit finder tool uses the software package TAPIR, which is a web based interface used to check for transit and eclipse observability (Jensen, 2013). This tool allows KELT-North and KELT-South follow-up member to enter observatory coordinates, their desired time-zone and date window, and to enter their desired constraints, such as a minimum elevation at ingress and egress. All active KELT targets matching these constraints are then displayed as either an HTML table or CSV file (either can be chosen). An example of the information in the CSV file is shown in Table 2.2. The comments for these targets include things observers will need to know, such as whether there is a close neighbour that needs to be resolved, previous observations made, including information about the band used and results of these observations, and what observations are still needed.

The HTML page included all the information of the CSV files, but with extra links to the star’s Simbad and 2MASS pages; the targets KELT page; a SkyMap page and annotated finding chart of the surrounding region; and an airmass plot with annotations for the transit times and nautical twilights. All of this information was used to try and find the best targets for photometry with OC61.

Preferable targets had high elevations throughout their transit and nearby stars of similar brightness. They would also have relatively short transits so that there was less chance
Chapter 2. Observations and data processing

<table>
<thead>
<tr>
<th>Name</th>
<th>KS34C029651</th>
<th>KS22C040550</th>
</tr>
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<tbody>
<tr>
<td>V</td>
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<td>12.24</td>
</tr>
<tr>
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<tr>
<td>mid time</td>
<td>01-18-2016 12:57</td>
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<tr>
<td>end time</td>
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<td>7.2</td>
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<tr>
<td>comments</td>
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</table>

Table 2.2: An example of the information found in the output CSV file from the transit finder tool.

of weather interfering with the set, or very long transit durations with a full transit being observable, as these were rare and were therefore a priority. The predicted ingress and egress would also ideally be far enough from nautical twilights so as to allow for large amounts of baseline data (data obtained from images taken not during the transit). It was also preferable to find predicted transits that required observations in a high efficiency band, such as V or i', though the effective temperature of the star (usually found through its Simbad link) needed to be taken into account here.

It was unlikely that all of these ideal specifications would be met, so targets were chosen that covered as many as possible. All KELT targets need to have follow-up photometry, so as long as a good set of observations could be made with baseline included, missing out on any other preferable attributes was not a problem. This baseline data is important because without it the depth of the transit cannot be known.

Being an automated telescope, none of the photometric observations required the presence of the observer at UCMJO. The telescope is monitored both physically and remotely. Observation requests were sent as scripts to AAVSO member and telescope advocate Arne Henderson who ran the telescope remotely. These scripts were text files with the following format:
target name, right ascension - hours (integer), minutes (integer), seconds (floating point), declination - degrees (integer), arcminutes (integer), arcseconds (floating point), maximum priority (between 1 and 10), repeats (no. of days), airmass, repeats (of the following filter pattern), filter 1, exposure 1 (seconds), no. of exposures, filter 2...

2.0 is the maximum airmass for most fields without manually lifting the wind-shield; the filter options are (B, V, SG, SR, SI). An example of one of these files is:

KS34C015828,7,19,35.2,−41,33,7.3,10,0,1.29,130,V,90,1

Each observation script was sent queued with a requested start date and time. This start time was chosen as at least an hour before the predicted ingress time found using the KELT transit finder tool, or less, if restricted by nautical twilight. The airmass values were found using the airmass plots mentioned earlier. The right ascension and declination coordinates were also provided by the transit finder. The filters were chosen depending on which filters were required by the follow-up group but targets were also chosen by those that allowed for observations in a filter with good signal to noise. The KELT targets commonly had an effective temperature, $T_{\text{eff}}$, of between 6000K and 7000K. The KELT targets are therefore more suited to bluer filters, such as the B, V, and $g'$ filters (see Figures 2.6 and 2.7). However, the transmittance of the filters and QE of the sensor have resulted in the lower exposure ratio for the V filter (see Table 2.1) compared to the B and $g'$ filters. For this reason, the V filter was predominantly requested for the photometric observations made for the KELT follow-up.

Choosing the exposure time and number of repeats was more complicated. Using past observations (the exposure times were estimated for the earliest of these sets) as a reference, an appropriate exposure time could be calculated. For example, using the observation with the lowest maximum counts (over the whole set) from the target star, whilst still having a distinguishable target, an approximation can be made at an upper bound for the fluxes that might have a detection rate of one count per second. Given that the maximum counts, $c_{\text{max}}$, for the target in this set was 1500 and the images had 60 second exposures in V, the detection rate, $\frac{dc_{\text{max}}}{dt}$, can very easily be found:

$$\frac{dc_{\text{max}}}{dt} = \frac{1500}{60} = 25 \text{ counts/s}.$$
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The flux which corresponds to this 25 counts/s is the apparent flux of the target star. Given that the target star has a visual magnitude \((M)\) of 12.33, the flux, \(F_{12.33}\), of the target can be found as follows:

\[
F = 10^{- \frac{M}{25}},
\]

(2.1)
so
\[ F_{12.33} = 10^{-\frac{12.33}{25}} \approx 1.2 \times 10^{-5}. \]

This demonstrates that a maximum of about one photon would be detected every second from a source of apparent flux \(4 \times 10^{-7}\);
\[ F \approx \frac{1 \times 10^{-5}}{25} = 4 \times 10^{-7}. \]

An approximation at a lower bound for an apparent flux that would cause a one count per second detection rate can be made by looking at the flux and exposure time of a saturated source. Saturation on this detector happens at just over 60000 counts. A source overexposing from a 30s exposure in V is being detected at a rate of 2000 counts/s;
\[ \frac{dc_{\text{max}}}{dt} = \frac{60000}{30} = 2000 \text{ counts/s}. \]

Given that the source was a target star with an 8.44 visual magnitude, the apparent flux causing the saturation is (using Eq. 2.1)
\[ F_{8.44} = 10^{-\frac{8.44}{25}} \approx 4.2 \times 10^{-4}. \]
\[ F \approx \frac{4 \times 10^{-4}}{2000} = 2 \times 10^{-7}. \]

This demonstrates that a source with flux \(2 \times 10^{-7}\) would result in maximum detection rate of more than one count per second.

An appropriate exposure time for a new target being observed in the V band can therefore be calculated by assuming an apparent flux of \(3 \times 10^{-7}\) would result in a detection rate of one count per second. For example, if a new target had a visual magnitude of 10.74 this would correspond to an apparent flux of (using Eq. 2.1)
\[ F_{10.74} = 10^{-\frac{10.74}{25}} = 5.058 \times 10^{-5}. \]

According to this ad hoc formula, this should result in a maximum detection rate in the V band of about
\[ \frac{dc_{\text{max}}}{dt} = \frac{5.058 \times 10^{-5}}{3 \times 10^{-7}} = 169 \text{ counts/s}. \]
With the intention of gaining a maximum in the target of 35000 counts throughout the set, using the V filter, the required exposure would be

$$\exp_V = \frac{35000}{169} \approx 207.1 \text{ s} \approx 210 \text{ s}.$$  

When the intention was to observe a target in another band (using a different filter), the exposure ratios in Table 2.1 were used to adjust the exposure time from V to the intended band. If the above example target was being observed using the $i'$ filter, the exposure could be found as follows:

$$\exp_{i'} = \frac{210}{1.6} \times 1.1 \approx 140 \text{ s}.$$  

The exposures used in the observations for this thesis were often limited and a number less than the one calculated was used so that there was less chance of a drive slip or jerky tracking effecting the images. The exposures were usually limited at five minutes (300s.) except in the case of very dim targets where limiting the exposure time to five minutes would be running the risk of under exposing the target.

The readout time for each image is at least 20s. The number of repeats for each set had to be calculated including this readout time. A set of observations of the above example target, intended to cover six hours of possible transit time, would need the following number of repeats:

$$\text{no. of repeats} = \frac{6 \times 60 \times 60}{140 + 20} = 135$$

The exposure time was also reduced if it meant that this number of repeats was very low. That way a good number of images would be taken and the shape of the lightcurve could be well traced by the data points obtained from these images.

### 2.1.3 Processing

After the observations had been made, they were put through a post-processing chain by the AAVSO, where the raw images were flat-fielded and uploaded to a folder, designated for this project, in an AAVSO server. It is this processed data that was downloaded and used for photometric analysis. These downloaded images were in the FITS (Flexible Image Transport System) format.
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All photometric analysis was completed using the multi-aperture photometry feature in AstroImageJ. This multi-aperture photometry calculated the difference between the brightness of the target star and all the selected comparison stars so as to provide a relative brightness of the target that has had the common effects of the Earth’s changing atmosphere removed from the signal. However, the FITS files did not always have all the information in their headers to make photometry simple. They would often be missing RA and Dec information in all the images. If one image in a set did not have this information, the multi-aperture photometry feature that tracked the targets would fail and photometry would need to be rerun in single-step mode. Single-step mode was much more time consuming as it required the target star being manually selected in each image. For this reason, each set was first aligned by either tracking the star using the RA and Dec information, by using the World Coordinate System (WCS) headers or using single step mode. Once a set was aligned, photometry could be run much more smoothly. Before this alignment process was attempted, any images that had very low signal to noise or visible drive slips were removed from the set.

Aperture sizes needed to be found before any targets could be selected. This was simple using the plot seeing profile function. An example of the seeing profile of a target star can be seen in Fig. 2.8. The seeing profile provided an aperture that measured values for the target up to a radius of 11 pixels and measured values to ascribe to background noise between radii of 20 and 30 pixels. These values could be adjusted if necessary. This would be necessary in a case where a neighbour is located partially within the background annulus.

When running multi-aperture photometry, comparison stars needed to be selected as well as a target star. Ideally these comparison stars would be evenly spread across the image and of a similar apparent magnitude to the target star. The even spread of comparison stars has the affects of averaging out variations in the signal strength that may occur across the image. The similar apparent magnitude of the comparison stars is important so that it is as bright as possible, providing the best signal to noise, without cropping too much of the point spread function (PSF). The aperture size was chosen according to the full-width-half-maximum (FWHM) of the profile of the target star. Having an aperture that is smaller than would be found from the FWHM of the comparison star’s profile, may cause systematic differences in the relative flux of the target.

11 http://www.astro.louisville.edu/software/astroimagej
12 http://big-questions.net/media/pdf/4.pdf
Chapter 2. Observations and data processing

After the photometry was run, stars could be removed as comparison stars. This was done if the comparison star was causing artefacts in the lightcurve of the target due to its own variability or if it was somehow increasing the scatter in the targets lightcurve.

Given some input parameters, such as the effective temperature of the target star or the predicted centre of the transit, a model was sometimes able to be fitted to the collected data using the model fitting tool in AstroImageJ. This program also had a detrending features which allowed for the data sets to be detrended by values such as airmass, sky counts, or CCD temperature (Kuhn et al., 2015).

Data sets that looked encouragingly like they included a planetary transit were processed using a modelling program, created for the purpose of this thesis to establish parameters such as transit depth, transit duration, ingress and egress duration, radial offset of transit, and airmass contributions. This program is described in detail in the next chapter (Chapter 3).
2.2 Spectroscopy

Spectroscopic observations were made with the High Efficiency and Resolution Canterbury University Échelle Spectrograph (HERCULES) on the McLellan 1 m telescope. These observations were made of KELT-South planetary candidate targets KS17C000302 (HD 113204) and KS17C00596 (HD 9468). These targets were chosen for spectroscopic follow-up because they were two of the brightest KELT-South candidates at $V = 7.06$ mag for HD 113204 and $V = 7.98$ mag for HD 9468. These stars were at the fainter limit of stars that could be observed, with both targets often being too dim for standard automated tracking (this is covered in Subsection 2.2.3). The exposure times for these stars was usually set at 30 minutes. Exposures were only cut short on a couple of instances due to the deterioration of the weather conditions. Thirty minutes was chosen because the intent of these spectroscopic observations was to observe the Rossiter-McLaughlin effect (described in Chapter 1 Section 1.1.1). Having longer exposures than 30 minutes would have smeared out the time-dependent broadening of spectral lines due to the radial velocity of the star, making small perturbations caused by this effect less likely to be detected.

2.2.1 The McLellan 1 – m telescope

![Figure 2.9: The McLellan 1 m telescope from the summit of Mt John.](http://www.phys.canterbury.ac.nz/research/mt_john/facilities.shtml)

The McLellan 1 – m telescope (henceforth referred to as the 1 m) is a 1 meter Dall-Kirkham reflecting telescope\(^\text{14}\). The telescope can be configured to have a cassegrain

\(^{14}\)http://www.phys.canterbury.ac.nz/research/mt_john/facilities.shtml
focus of either f/7.7 or f/13.5. The cassegrain f/13.5 focus is only used for observations of single stars. As the intention of the work done with this telescope was to take spectra of individual star, f/13.5 was the focal set-up used here. The dome of the 1 m telescope automatically tracks the movement of the telescope.

2.2.2 HERCULES

The 1 m telescope has many UCMJO instruments, which can be mounted to it. These include various different CCD attachments and HERCULES, which was the instrument used here.\textsuperscript{15}

HERCULES is a fibre-fed échelle spectrograph. The échelle in the name refers to the type of diffraction grating used to split the light from the star into diffracted lines of different wavelengths. These are different from common diffraction gratings in that they have fewer grooves, but these grooves are shaped to specifically optimise diffraction of high incidence angle light. The result of this set-up is that higher order lines can be tightly packed in an image, while the lower orders are more separate. An example of this effect is the separation of orders, which can be seen in the diffracted image of HD 9468 (Fig. 2.10).

The dispersion in HERCULES is provided primarily by the large R2 échelle grating.\textsuperscript{16} Cross-dispersion is then accomplished with a BK7 prism with a 50° apex angle (Barnes, 2004). Cross-dispersion allows for the normally overlapping higher orders to be viewed separately (Loewen and Popov, 1997).

The HERCULES instrument, as a whole, is sealed inside a vacuum tank, which maintains a 2-4 torr pressure. The vacuum tank is in an insulated and thermally isolated room. As noted earlier, light from the telescope is transmitted to HERCULES by means of an optical fibre. The resulting elliptical illumination on the échelle extends beyond the grated area; the semi-major axis of the illuminated eclipse is 272 mm compared to the half the dimension of the grating of 204 mm. 14.5% of the fibre-fed light is therefore lost. However, as explained in Hearnshaw et al. (2002), due to the larger collimator diameter (210 mm), a larger fibre-core angular size can be used and still result in a net efficiency gain.

\textsuperscript{15} Details of the UCMJO instruments can be found on the following website (though some of this information is outdated): http://www.phys.canterbury.ac.nz/research/mt_john/facilities.shtml

\textsuperscript{16} “R2” describes the tangent of the blaze angle; R2 has 63.5°, while R4 has 76°. This angle, multiplied by the beam diameter determines the resolution that can be achieved.
Different resolving powers can be achieved through the choice of different diameter optical fibres. The three optical fibres available for use with HERCULES had core diameters of 100\,\mu m, with or without a 50\,\mu m microslit on the exit face, or 50\,\mu m.

<table>
<thead>
<tr>
<th>Fibre position</th>
<th>Core diameter (\mu m)</th>
<th>Microslit (\mu m)</th>
<th>Resolving Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>41000</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>50</td>
<td>70000</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>82000</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Table of optical fibres used with the HERCULES instrument and their resolving powers (Hearnshaw et al., 2002).

2.2.3 Observations

For each night of spectroscopic observations that were made, 10 flat-field images were taken. These are diffracted and cross-dispersed images of an incandescent tungsten lamp. The resulting spectral images have no emission or absorption lines and are therefore useful for establishing the inconsistencies in the efficiency of different pixels on
Chapter 2. Observations and data processing

the CCD and also for tracking spectral order lines. Having 10 images means that cosmic rays can be removed from the flat field process during the post-processing of stellar spectra, and gains in the signal to noise ratio can be made by combining images.

Thorium-argon images were also taken, which were later used to calibrate the stellar spectra. The light from the thorium-argon lamp has thousands of emission lines at well established wavelengths. These emission lines with known wavelengths are used to provide wavelength values to the order lines in stellar spectra during post-processing. The thorium-argon images were taken at semi-regular intervals of about one hour so as to account for response changes due to changes in the temperature of the optics. However, repointing the telescope can also effect these optics, so thorium-argon images were also taken before and after a new target was observed.

The pointing of the telescope had an offset from the displayed RA and Dec coordinates. For this reason, the pointing of the telescope was checked by observing bright standard star at the beginning of a night.

A record of all of the observations made can be found in Appendix A, Table A.2.

Each star was automatically tracked using the guide camera. This auto-guiding had to be aligned by finding the position of the fibre, using the fibre to light setting on the guide camera control and selecting the centre of the observed circular feature as the fibre position. The telescope pointing was then fine-adjusted so that the maximum counts per second from the desired target were being achieved. Auto-guiding was then turned on and the exposure started. This automatic guiding had to be monitored as deteriorating weather conditions sometimes resulted in the target escaping the tracking region or being entirely obscured by cloud. In the case of persisting cloud, an exposure would have to be discontinued.

The targets HD 113204 and HD 9468 were relatively dim in comparison to targets usually observed using this equipment. This meant that the guide image of these stars were also very dim. The exposure time and gain of the guide camera could be increased so as to make the target more visible, however this reduced the responsiveness of the tracking. The guide image for these stars was often too dim for effective tracking. In order to get around this problem, when necessary, the targets were tracked with the guide camera on coarse (the usual setting was fine). The resulting larger field-of-view guide image had a smaller target image with a brighter appearance. This is the setting

\footnote{If the automated tracking was lost the target needed to be manually realigned and then automatic tracking need to be restarted}
usually used when locating the target initially. With the fibre position recalibrated for this setting, the target could be tracked more consistently. The 100 µm fibre (fibre position 1 in Table 2.3), with the lowest spectral resolving power, was used for all observations due to the dimness of the chosen targets.

### 2.2.4 Processing

The reduction chain used to obtain the reduced spectra from the raw observational data used MATLAB code written by Dr Duncan Wright, further developed by Dr Emily Brunsden (Brunsden, 2013) with usability improvements by Mr Aaron Greenwood (Greenwood, 2014). This chain is broken into two parts.

In the first half of the process, stellar images were flat-fielded, using the images taken of the white, featureless light from the beginning of each observational night. This flat-fielding process corrects the stellar spectral images depending on the pixel-to-pixel variations found by summing all of the the white light images for the relevant night, so long as they showed no significant variation when statistically compared to each other. This comparison of the flat-field images meant that images effected by cosmic rays were removed. The result of this flat-fielding is to remove noise in the spectral images created by the varying sensitivity in the CCD.

At this point in the processing, the data from the first 1000 rows of pixels was removed from the white light, thorium-argon, and stellar images. The reason for this is that the bluer spectral orders with low wavelengths, which are in this region of the CCD image, are too noisy to be useful. The white light images are also used to determine the location and width of the spectral orders in the images. With this information, the stellar and thorium-argon spectra were able to be extracted.

The extracted stellar spectra were then wavelength calibrated, using the spectra of the thorium-argon lamp (using thorium-argon spectra taken just before and just after the stellar spectral images), with its well identified spectral lines, to produce stellar spectra files with corresponding wavelengths, separated into spectral orders. The following steps were performed to achieve this. Firstly, the locations of known thorium-argon emission lines were previously saved in a calibration matrix. The calibration matrix was used to find spectral lines in the thorium-argon lamp spectral images. It was ideal to have a least 800 emission lines located at this point in the process. If this was not achieved, new calibrations could be performed where the current thorium-argon image
was used as a template. A fourth order polynomial was fitted to the located spectral lines in order to find a wavelength solution, specifying the wavelength ranges of each spectral order. The results of this calibration were applied to the stellar spectral images and, lastly, cosmic-ray removal was also performed. Forty spectral orders were processed in total (for each star) with an overall wavelength range of 4550 – 6850 Å.

In the second half of the reduction process, the calibrated stellar spectra were wavelength shifted to account for barycentric movement (movement of the Earth around the Sun) and systemic velocity (the movement of the target system as a whole, relative to our Earth-Sun system).

**Figure 2.11**: HD 9468 spectral order continuum fitting. The general shape of the order is traced (the points used to trace the order are depicted as red pluses) using a variable-order polynomial function, leaving the spectral lines and normalising the intensity. The resulting fitted data shows the data in blue and the synthetic spectrum in red.

The next step was to continuum-fit the stellar spectra using a synthetic spectrum created for a star with the same metallicity, surface gravity and effective temperature ([Fe/H], logg, and \( T_{\text{eff}} \), respectively) as the target star. The continuum fitting process allowed the spectral orders to be stitched together to form one spectrum while correcting for variations in intensity in the spectral order due to the instrumental effects. An example of the continuum fitting of a spectral order can be seen in Fig. 2.11. The top graph
shows the unfitted spectral order, which varies in intensity where there is a spectral line but the order as a whole also has variations. These spectral order intensity variations were traced with a polynomial of varying order (depending on the number of manually chosen points used to trace the line) so that they could be removed, giving a normalised intensity, and maintaining the variations due to spectral lines. The lower graph in Fig. 2.11 shows one such normalised order.

These normalised spectral orders could then be easily stitched back together to form a full stellar spectrum. An example of a full processed spectrum can be seen in Fig. 2.12. The representative line profile associated with the normalised full spectrum can been seen in Fig. 2.13. These line profiles were found by cross-correlating the stellar spectra with a synthetic template (created for a star with the same [Fe/H], logg, and $T_{\text{eff}}$) in which the positions of synthetic spectral lines were given a value of 1 and elsewhere was given a value of 0; the synthetic template contained delta functions positioned at the rest-wavelengths of stellar absorption lines. The stellar spectra used in this cross correlation had regions removed, as indicated in Fig. 2.12, due to telluric contaminations and to remove the H\textalpha{} and H\textbeta{} spectral lines from the cross-correlation process.

Radial velocity (RV) measurements were obtained through cross-correlation of selected regions of the raw spectra from different observation (giving a relative RV measurement) and through investigating the shift in the minima of the line profiles, which directly relates to the RV of the star during an observation. The MATLAB code that achieved this is in Appendix D. The cross-correlation process is covered in more detail in Chapter 5.
Figure 2.12: HD 4968 stellar spectrum, showing the synthetic spectrum in red and the orders of the stellar spectrum in various colours. The missing sections are where data has been removed from the cross-correlation process to find the line profiles. The cropped regions are where telluric lines and the Hα and Hβ spectral lines, which would adversely affect the cross-correlation process, have been removed.
FIGURE 2.13: Line profile of HD 9468. The mean of the line profiles is depicted in red and each individual line profile is shown as a blue line. The difference in these line profile would be more dramatic if larger changes in the velocity of the star were being observed.
Chapter 3

Developing the transit modelling program

A bespoke model fitting program was created in order to obtain information from the relative magnitude data about the potential planet-star system being observed. This chapter describes how the program evolved over the course of its creation, becoming more complex, more efficient, and providing more system parameters. It has also been compared to other available leading model fitting programs.

A model fitting program for this data is only necessary in order to understand the results presents. As mentioned in Chapter 1 (Section 1.3), all KELT lightcurves, including follow-up lightcurves, are fitted simultaneously with RV results using the EXOFAST program, which utilises MCMC (see Section 3.4) techniques.

3.1 Existing transit modelling programs

Two of the most commonly used model fitting programs for stellar observations are Wilson-Devinney and PHOEBE 2.0. These two programs, both primarily concerned with eclipsing binaries, will be discussed and compared to the custom program created in Section 3.5.

The Wilson-Devinney (WD) model/program was first released in 1971 and has been extended in many releases since then. WD is designed around modelling eclipsing binary systems. It models lightcurves according to an elliptical orbit, with eccentricity, $e$, semi-major axis, $a$, and a phase-dependent distance between stars, $d = d(\phi)$, all scaled according to the temperature of the stars. In the newest versions of WD, it also takes into account surface gravity and chemical composition, when modelling the lightcurves. (Kallrath and Milone, 2009)

1http://phoebe-project.org/1.0/?q=node/1
2Details of this program are covered extensively in Kallrath and Milone (2009).
Due to the programs continual improvement and common use, WD has stimulated the development of, and now coexists with, many other programs that are based on it. One such program is PHOEBE, which offers the added benefit of a particularly appealing graphical user interface (GUI).

PHOEBE 2.0 is an open source program that fits model to photometric, spectroscopic, astrometric, interferometric, and spectropolarimetric data (the GUI for PHOEBE 2.0 is still under development). This program is designed for use in conjunction with the most advanced research telescopes, such as the Kepler or Gaia space telescopes. It has been designed to cope with phenomena such as multiplicity, rotation, and pulsations. (Pavlovski et al., 2013)

PHOEBE 1.0 was built from the framework of the previously mentioned Wilson-Divinney code, however, much of the basic features were re-written or re-designed in PHOEBE 2.0. (Pavlovski et al., 2013)

PHOEBE models Keplerian orbits by using a hierarchical nesting numerical method (Skilling, 2006). It allows for the varying of some orbital parameters over time, such as period and eccentricity. PHOEBE includes an interactive tool used for correcting light time travel effects in these nested Keplerian orbits. This complex modelling results in orbits that are fully defined in all three-dimensions. (Pavlovski et al., 2013)

Another program used for the transit model fitting is AstroImageJ. AstroImageJ is driven through an intuitive GUI that is designed to be easy to use for everyone from high-school student to serious researchers. AstroImageJ is primarily for use in differential photometry and lightcurve fitting and detrending, though it maintains all the multi-purpose image processing capabilities of ImageJ (the program on top of which it was built).

The AstroImageJ (Collins et al., 2016) program allows the user to perform differential photometry using the multi-aperture photometry tool. During this process, the program allows for self-updating lightcurve plots to be built. From here, there is a plotting panel to control the plotting aesthetic, and define the information that will be displayed. Fitting panels allow the model fitting and detrending to be controlled. After photometry

---

3 According to Pavlovski et al. (2013), as of 2013, PHOEBE 2.0 contained only initial support for fitting with Bayesian framework. The code had been interfaced with a Metropolis-Hastings algorithm, an affine invariant algorithm, the Nelder-Mead simple method, the Levenberg-Marquardt gradient method, Minuit, simulated annealing, the possibility to use genetic scanning algorithms, and a full grid search.

4 This is the program KELT photometric follow-up contributors are recommended to use.

5 http://imagej.nih.gov/ij/docs/index.html
Figure 3.1: Relative lightcurve of KELT target KS24C007628, imaged in V from Mt John on 2015 March 26, with fitted model (this fit used a fixed transit centre). The predicted ingress and egress indicated on the plot were the times calculated from the BLS fitted KELT data.

has been run, the comparison stars used in the differential photometry can be systematically cycled or removed from the differential calculations if necessary.

AstroImageJ was the tool used to perform the differential photometry in Chapter 4 and Appendix C. The model used in this fitting process is described in Mandel and Agol (2002). The AstroImageJ model is parameterised by a baseline flux and six physical values, which include a planet-star radius ratio (or rather the radius of the planet in units of stellar radii), the semi-major axis of the planetary orbit in units of stellar radii, the transit centre time, the impact parameter, and two limb darkening coefficients used to describe the limb darkening of the host star with a quadratic model. The quadratic
limb darkening model is described in more detail in Howarth (2011) and limb darkening in transit models is discussed more in Subsection 3.4.5. The AstroImageJ fitting process uses $\chi^2$ minimisation with the downhill simplex method (Nelder and Mead (1965) contains more information on this method) to find the $\chi^2$ minima. $\chi^2$ minimisation is covered in Section 3.3 of this chapter.

Examples of the fits achieved using AstroImageJ can be seen in Chapter 4 and Appendix C. For the sake of easy comparison between models, the results obtained using AstroImageJ with the photometric images of KSC24C007628 from 2015 March 26\textsuperscript{6} can be seen in Fig. 3.1.

PHOEBE uses orbital parameters to describe transits/eclipses. It is not sensible to be used in model fitting orbital parameters based on the single transit lightcurves demonstrated in this thesis. The AstroImageJ fitting model uses a fixed orbital period input in order to get past this limitation.

### 3.2 Goals of the modelling program

The following modelling program was developed in order to obtain information about physical properties of the potential transiting star-planet systems from the photometric data obtained. This program needed to be able to derive details about the transit occurring by fitting a model to the data. Given details about the radius of the host star, the dip in light seen in the transit data would allow for the size of the planet to be found. Fitting a model to find the duration of the transit, as well as the ingress and egress, would allow for conclusions about the planetary candidates orbit to be made. The model would be developed to become more complex, so as to provide a more accurate fit, by including features such as limb darkening.

This program was designed specifically to work with data obtained for the purpose of this thesis, but with the intention of it being robust enough to be easily modified for any planetary transit data sets. Creating this bespoke program aided in learning about the model fitting process for exoplanetary transits and the need for data detrending.

\textsuperscript{6}This is the target used during transit modelling program development discussed in the rest of this chapter.
3.3 Least squares fitting

The first versions of the program developed here used a least squares (LS) method to fit a mathematical model, with adjustable parameters, to the data. This model is a function that describes the basic shape of the lightcurve of a planetary transit.

Using an LS method to fit a model to data requires the creation of a “merit function”. This function measures the agreement between the model and the data – data that is closer to the model conventionally has a smaller value than data that is further from it (Press et al., 1986). Taking the sum of these values over the set gives a numerical value to how well the model with these particular parameters agrees with the data, referred to in Press et al. (1986) as the goodness-of-fit. The parameters of the fit can then be adjusted to minimise this goodness-of-fit value and hence find the parameters that provide the best fit.

\[ P(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp \left[ -\frac{1}{2} \left( \frac{x - x_0}{\sigma} \right)^2 \right], \]

where \( x \) is the data and \( \sigma \) is its uncertainty \( (x \pm \sigma) \), \( x_0 \) is the actual or model value, and \( P(x) \) is the probability of observing the data value \( x \) given that the model, or reality, has the value as \( x_0 \).

The spread of photometric data about an underlying physical model can be described by a Gaussian curve (see Fig. 3.2); i.e. the probability of measuring a single relative flux value around the actual relative flux value can be described by the following function (Press et al., 1986):

**Figure 3.2**: A Gaussian curve showing the shape of the probability function (the likely spread of the data) from Eq. 3.1.
This same principle can be applied to sets of data. For example, for a set of data \((\bar{x} \pm \sigma)\) where \(\bar{x} = (x_1, x_2, x_3, ..., x_i, ..., x_n)\) and \(\sigma = (\sigma_1, \sigma_2, \sigma_3, ..., \sigma_i, ..., \sigma_n)\) this becomes:

\[
P(\bar{x}, \sigma) = \prod_i P(x_i, \sigma_i)
\]

\[
= \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} \exp \left[ -\frac{1}{2} \left( \frac{x_i - m(t_i)}{\sigma_i} \right)^2 \right],
\]

where \(m(t)\) is a function representing some time-dependent model.

This probability function can also be written as

\[
P(\bar{x}, \sigma) = ae^{-\chi^2/2},
\]

where \(a\) is a constant \((a = \frac{1}{(2\pi)^n/2} \prod \frac{1}{\sqrt{\sigma_i}})\) and

\[
\chi^2 = \sum_i \left( \frac{x_i - m(t_i))}{\sigma_i} \right)^2,
\]

\(\chi^2\) can therefore become the “merit function” for this model fitting, because the \(a\) term is a constant. To get the best fit possible, one must maximise the probability by maximising \(e^{-\chi^2/2}\) and thus minimising \(\chi^2\).

To minimise \(\chi^2\) one can produce a matrix to solve for the parameters of \(m(t)\) from the equations of the partial derivatives of \(\chi^2\), for each parameter, set to zero; e.g.

\[
\frac{\partial \chi^2}{\partial m_0} = 0,
\]

which, in this case, would form a basic equation from which \(m_t\) could be found (as opposed to a matrix equation) due to there being only one parameter.

### 3.3.1 Basic transit model

The first and most basic model developed looped over non-linear parameters (time of ingress \(t_{\text{ing}}\) and time of egress \(t_{\text{egr}}\)) so that the function for the model could remain linear. This model simplified the transit to have negligible airmass and instantaneous ingress and egresses; the system was modelled by a square shaped star and 1-dimensional planet (see Fig. 3.3). The planet travelled in front of the star with constant velocity and in a straight line. The result was a piecewise function where the magnitude (relative to the
comparison stars in the field) was some value, $m_0$, out of transit (this is considered the base-line) with the depth, $d$, added to this value in transit (the light dims and so the apparent magnitude of the star increases) and the transit occurring between time of ingress, $t_{\text{ing}}$, and time of egress, $t_{\text{egr}}$:

$$m(t) = \begin{cases} 
m_0 & : t < t_{\text{ing}}; t_{\text{egr}} < t \\
m_0 + d & : t_{\text{ing}} \leq t \leq t_{\text{egr}}
\end{cases}$$

The equation for finding $\chi^2$, given this model, is therefore:

$$\chi^2 = \sum_{\text{baseline}} \left( \frac{x_i - m_0}{\sigma_i} \right)^2 + \sum_{\text{transit}} \left( \frac{x_i - m_0 - d}{\sigma_i} \right)^2. \tag{3.6}$$

The partial derivatives of this equation, which are equated to zero and used to minimise $\chi^2$, are shown in the following two equations (transit refers to values where $t_{\text{ing}} \leq t \leq t_{\text{egr}}$ and baseline refers to values where $t < t_{\text{ing}}; t_{\text{egr}} < t$), 3.7 and 3.8:
\[
\frac{\partial \chi^2}{\partial m_0} = -2 \sum_{\text{baseline}} \frac{(x_i - m_0)}{\sigma_i^2} - 2 \sum_{\text{transit}} \frac{x_i - m_0 - d}{\sigma_i^2} = 0
\]
\[
= \sum_i \frac{x_i}{\sigma_i^2} - \sum_i \frac{m_0}{\sigma_i^2} - \sum_i \frac{d}{\sigma_i^2} = 0
\] 

(3.7)

\[
\frac{\partial \chi^2}{\partial d} = -2 \sum_{\text{transit}} \frac{x_i - m_0 - d}{\sigma_i^2} = 0
\]
\[
= \sum_{\text{transit}} \frac{x_i}{\sigma_i^2} - \sum_{\text{transit}} \frac{m_0}{\sigma_i^2} - \sum_{\text{transit}} \frac{d}{\sigma_i^2} = 0
\] 

(3.8)

These two equations are solved simultaneously to find the values for \(m_0\) and \(d\) that minimise \(\chi^2\), given set values for \(t_{\text{ing}}\) and \(t_{\text{egr}}\). This is done by solving a matrix equation of the form \(Ax = b\), where

\[
A = \begin{bmatrix}
\sum_i \frac{1}{\sigma_i^2} & \sum_{\text{transit}} \frac{1}{\sigma_i^2} \\
\sum_{\text{transit}} \frac{1}{\sigma_i^2} & \sum_{\text{transit}} \frac{1}{\sigma_i^2}
\end{bmatrix},
\]

(3.9)

\[
x = \begin{bmatrix}
m_0 \\
d
\end{bmatrix},
\]

(3.10)

and

\[
b = \begin{bmatrix}
\sum_i \frac{x_i}{\sigma_i^2} \\
\sum_{\text{transit}} \frac{x_i}{\sigma_i^2}
\end{bmatrix}.
\]

(3.11)

A \(\chi^2\) value was found for every possible combination of the non linear parameters (\(t_{\text{ing}}, t_{\text{egr}}\)) – provided that \(t_{\text{ing}} < t_{\text{egr}}\) and the matrix denoted \(A\) (Eq. 3.9), formed by the partial derivatives in Equations 3.7 and 3.8, was not singular. From the results, a matrix of \(\chi^2\) values were formed. Minimising this matrix gave the optimum non-linear parameters.

An example of the resulting fitted model at this point in development can be seen in Fig. 3.4.
3.3.2 Airmass detrending

It is often useful to detrend for airmass so as to remove the artefacts in the data that the changing elevation of the field causes. Airmass has therefore been included as a parameter in this model. When the effect of airmass on the apparent intensity of a star, \( I \), is included, the model during baseline period can be described by this equation:

\[
I = I_0 c^z, \tag{3.12}
\]

where \( I_0 \) is the intensity of the star unaffected by airmass dampening, \( z \) is the airmass value at a given time, and \( c \) scales the contribution of the airmass value depending on atmospheric conditions at the time and place of the observation. Converting these intensities into visual magnitudes is useful as it results in the airmass contribution being able to be represented by a linear parameter;

\[
M = -2.5\log_{10}(I_0/c^z) = -2.5\log_{10}I_0 + (2.5\log_{10}c)z = M_0 + (2.5\log_{10}c)z \tag{3.13}
\]

If we let \( C = 2.5\log_{10}c \), then

\[
M = M_0 + Cz. \tag{3.14}
\]
This is used in the piecewise function, which describes the airmass contribution inclusive model (Eq. 3.3.2);

\[
m(t) = \begin{cases} 
  m_0 + Cz_i & : t < t_{\text{ing}}; t_{\text{egr}} < t \\
  m_0 + d + Cz_i & : t_{\text{ing}} \leq t \leq t_{\text{egr}} 
\end{cases}
\]

An example of how this airmass contribution might effect the model can be seen in Fig. 3.5.

The matrix equation, \(Ax = b\), used to find this contribution for given \(t_{\text{ing}}\) and \(t_{\text{egr}}\) values had elements of the following form:

\[
A = \begin{bmatrix}
\sum_i \frac{1}{\sigma_i^2} & \sum_i \frac{z_i}{\sigma_i^2} & \sum_{\text{transit}} \frac{1}{\sigma_i^2} \\
\sum_i \frac{z_i}{\sigma_i^2} & \sum_i \frac{z_i^2}{\sigma_i^2} & \sum_{\text{transit}} \frac{z_i}{\sigma_i^2} \\
\sum_{\text{transit}} \frac{1}{\sigma_i^2} & \sum_{\text{transit}} \frac{z_i}{\sigma_i^2} & \sum_{\text{transit}} \frac{1}{\sigma_i^2}
\end{bmatrix}, \quad (3.15)
\]

\[
x = \begin{bmatrix}
m_0 \\
C \\
d
\end{bmatrix}, \quad (3.16)
\]

and

\[
b = \begin{bmatrix}
\sum_i \frac{x_i}{\sigma_i^2} \\
\sum_i \frac{x_i z_i}{\sigma_i^2} \\
\sum_{\text{transit}} \frac{x_i}{\sigma_i^2}
\end{bmatrix}. \quad (3.17)
\]

A downfall of the least squares method here is that constraints cannot be put on the parameters and thus it is possible for physically impossible values to be returned; a
negative value for $C$ could be returned implying that increased airmass would result in increased flux. This can be solved through the use of Markov Chain Monte Carlo (MCMC) methods to find non-linear parameters and linear parameters requiring constraints.

### 3.4 Markov Chain Monte Carlo (MCMC)

Markov Chain Monte Carlo is just one example of Monte Carlo Methods (MCM). So what exactly is meant by a Monte Carlo Method? Monte Carlo, in this sense, refers to simulation, using a computer, by means of generating random samples. This can be useful when modelling situations that may occur naturally, such as the transport of neutrons (Metropolis, 1987). When these random outcomes are generated based on a probability distribution (using MCM), this allows us to solve more deterministic problems. In both these situations, the methods require many samples to be generated in order to obtain meaningful results; the meaningful results come from the statistical distributions, not individual outcomes. (Kroese et al., 2014)

Using an MCM to fit this model is beneficial for many reasons: the MCM is efficient and so less computing time is required, which makes development and use much easier (it can also be parallelised to further reduce computing time); the inherent randomness of MCM allows it to escape the local optima that sometimes appear when stochastic algorithms are used, which is a rare characteristic in deterministic fitting methods; there is expansive knowledge underpinning Monte Carlo techniques that allows for conclusions about the accuracy of a particular method to be made, through methods such as square-root convergence. (Kroese et al., 2014)

MCMC is a Monte Carlo method that uses a Markov chain methods of sampling, which is to say that the next outcome to be generated will be dependent on the current outcome, but not on any of the outcomes before it (Abdullah et al., 2016). This process is often described as “memorylessness”.

Bayesian MCMC, in particular, is useful in this situation (Hou et al., 2012) because of the constrained multidimensional parameter space and the non-linear nature of many of these parameters. Bayesian MCMC uses a “prior” probability distribution, which gives subjective relative weightings to the parameters (Bolstad, 2013). In this fitting program,
the prior is non-normalised and constrains the model parameters to those which corres-
pond to physically allowed values (for example, positive stellar radii or the aforemen-
tioned airmass contribution coefficient, $C$). It is also used to constrain the parameters to
those that the model can cope with. For example, the complete transit is constrained to
occur during the observation.

In the Bayesian MCMC process, sample parameters are drawn based on the posterior
probability distribution. The posterior probability distribution is constructed from a
likelihood probability distribution and the prior. The likelihood probability distribu-
tion is a probability of the data matching the model, where the model is built from the
previously drawn sample parameters.

MCMC requires a burn-in, for which the parameters of each attempted fit do not con-
tribute to the posterior means. This allows the random draws to become settled around
the fit before before the draws affect the final fitted value for each parameter. The fitted
parameters are obtained from the posterior means and the uncertainties for these fitted
parameters are found using the credible interval.

This program uses EMCEE (Foreman-Mackey et al., 2013) to perform Bayesian MCMC.
EMCEE executes the ensemble sampler technique described in Goodman and Weare
(2010). In order to implement the EMCEE sampler accompanying MCMC functions,
likelihood and probability functions needed to be created as well as a function that re-
turns the model as a function of time. The creation of the function building a model as
a function of time is describes mathematically in each section and the accompanying
Python functions created can be found in Appendix B.

The output of the EMCEE sampler and MCMC with the model building functions is the
probability distributions for each fitted parameter. Figures 3.11, 3.16, and 3.22 show
one and two dimensional projections of this outputted posterior distribution.

### 3.4.1 Ingress and egress duration

Duration of ingress and egress, $D$, can be easily added to the MCMC fitting as another
constrained parameter. However, adding $D$ to the model makes for a slightly more
complicated piecewise function:
The fitting program was tested on target KS24C007628. The MCMC results can be seen in Fig. 3.7.

### 3.4.2 Round planet

Introducing a circular planet silhouette to the model complicated the mathematics behind ingress and egress regions of the piecewise function, however it did not add any new fit parameters. The circular planet projection passing across a square shaped simplification to the star was modelled by integrating over the overlapped part of a shifted equation for a circle;

\[
A(t') = \frac{2}{\pi r^2} \int_0^{t_n} y(t') dt'
\]  

(3.18)
where

\[ y'(t') = \sqrt{r^2 - (t' - r)^2} \]  \hspace{1cm} (3.19)

and \( t'_n \) is the distance between the edge star and edge of the planet (the shifted origin).

The JD data, \( t \), has been shifted to become \( t' \) so that the function of a circle describing the planet remains the same in this frame. In this frame, the planet is described by a circle that has its centre at \( t = r \) in the origin of the frame (see Fig. 3.9). This has been done so that the area of the circle is always positive.

For the conceptualisation of this problem, time was related to space in the \( x \)-direction. That is to say that the radius, \( r \), of the planet was considered to be half the duration (\( D \)) of the ingress or egress. The “front” edge of the planet (i.e. the side that first crosses in front of the star) corresponded to the “current” time, \( t_n \). The width of the star, \( R \), was the time between the start of ingress, \( t_{\text{ing}} \), and the start of egress, \( t_{\text{egr}} \). The start of ingress corresponded to the “back” edge of the square star (i.e. the side where ingress occurs).
FIGURE 3.8: Depiction of the transit model being presented. This figure shows a round planet projection with the star being estimated as a square in two-dimensions. The effect this model has on the model is shown on the corresponding “model” lightcurve.

and the “front” corresponds to the start of egress.

For each time-step in the ingress \( (t_{\text{ing}} < t_n < t_{\text{ing}} + D) \) and egress \( (t_{\text{egr}} < t_n < t_{\text{egr}} + D) \) of the model, a shifted coordinate system was created \( (t' = 0, \ldots, t'_n, \ldots, D) \) for which

\[
t' = t - t_{\text{ing}} - D
\]  

(3.20)
during ingress and

\[
t' = t - t_{\text{egr}} - D
\]  

(3.21)
during egress.

In the moving frame, the \( t' \) bound of the integral representing the area of the planet that was covering the star during ingress was

\[
t'_n = t_n - t_{\text{ing}}.
\]  

(3.22)

The total area of the planet \( A(t') \) also needed to be normalised so that it could be scaled to provide a dip in brightness equal to the depth of the transit, \( d \).
During egress the integral was used to find the normalised area of the planet no longer covering the star and the bound for this was

\[ t'_n = t_n - t_{egr}. \]  

This is where the \( 1 - A(t) \) comes from in the piecewise function for this model; it swaps from describing the normalised area of the planet not in front of the star to finding the normalized area of the planet still in front of the star.

The piecewise function for this model is as follows:

\[
 m(t) = \begin{cases} 
 m_0 + Cz & : t < t_{ing}; t_{egr} + D < t \\
 m_0 + d + Cz & : t_{ing} + D < t < t_{egr} \\
 m_0 + A(t)d + Cz & : t_{ing} < t < t_{ing} + D \\
 m_0 + (1 - A(t)d) + Cz & : t_{egr} < t < t_{egr} + D 
\end{cases}
\]  

where

\[
 A(t') = \frac{1}{\pi r^2} \left( r^2 \tan^{-1} \left( \frac{\sqrt{r^l}}{\sqrt{2}rt'} \right) - \frac{\sqrt{r^l}(2r^3 - 3r^lt' + t'^2)}{2\sqrt{2}r - t'} \right) 
\]  

\[
 \text{Figure 3.9: In-transit area of the planet being found, where the origin is shifted to correspond to the edge of the planet, so that all areas found are positive and the same integral can be used for all of ingress and egress.}
\]

The parameters of the MCMC fit for this model were the baseline relative magnitude, transit depth, airmass contribution coefficient, ingress start time, egress start time, duration of ingress/egress \((m_0, d, C, t_{ing}, t_{egr}, D)\). This model fitting program was tested on target KS24C007628. The results of this test can be seen in Fig. 3.10.
### Table 3.1: MCMC fitted parameters of the lightcurve of KS24C007628

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{ing}}$ (d)</td>
<td>0.0398 ± 0.0012</td>
<td>0.0014</td>
</tr>
<tr>
<td>$t_{\text{egr}}$ (d)</td>
<td>0.1318 ± 0.0013</td>
<td>0.0015</td>
</tr>
<tr>
<td>$D$ (d)</td>
<td>0.0269 ± 0.0021</td>
<td>0.0019</td>
</tr>
<tr>
<td>$m_0$ (mag)</td>
<td>1.426 ± 0.005</td>
<td>0.006</td>
</tr>
<tr>
<td>$d$ (mmag)</td>
<td>10.9 ± 0.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>$C$</td>
<td>0.016 ± 0.005</td>
<td>-0.005</td>
</tr>
</tbody>
</table>

The $t_{\text{ing}}$ and $t_{\text{egr}}$ values are shifted by the Julian date of the first relative magnitude measurement of the data set. Uncertainties used represent the standard deviation of the posterior distributions.

### Figure 3.10: MCMC model fitting on KS24C007628 with constrained airmass correction and a circular planet projection

This shows samples from the MCMC in black with the mean sample parameters forming the magenta line. Predicted transit parameters, used as the initial MCMC input, are shown in red.

### 3.4.3 Round star

The next evolution of the model included a circular star projection. This meant integrating to find area of the circular star covered by the circular planet through finding the intersecting area of two circles. It was assumed that the planet was passing in front of the centre of the star. This meant that the duration of the transit could be considered as the diameter of the star and the duration of ingress or egress could again be considered to represent the diameter of the planet. As with the previous version of this model, discussed in Subsection 3.4.2, the ingress and egress parameters were considered to be the start of ingress and start of egress ($t_{\text{ing}}$ and $t_{\text{egr}}$, respectively). The area of intersection
Figure 3.11: Posterior distributions of parameters in MCMC model fitting of the lightcurve of KS24C007628 with constrained airmass correction and a circular planet projection.

of the two representative circles was found by integrating either side of the intersection point (in Cartesian space) of the semi-circle functions used to describe them.

To make the integration simpler, each semi-circle function was integrated over in a shifted coordinate system. The origin of the shifted frames used for integration were at the edge of the semi-circle so that the area found through integration was entirely positive. Figure 3.13 depicts the coordinate systems used. These three shifted sets of time data were defined as follows.

$t$ was the set of Julian dates corresponding to each relative brightness measurements. The coordinate systems with its origin at the beginning of the planet could be described
by

\[ t' = t_n - 2r = t_n - D \]  \hspace{1cm} (3.25)

where \( r \) related to the radius of the planet while \( D \) related to its diameter and is also the duration of ingress/egress and \( t_n \in t \). The coordinate systems with its origin at the beginning of the star could be described by

\[ t'' = t - t_{\text{ing}}. \]  \hspace{1cm} (3.26)

To find the fraction of the projection of the planet that was in front of the star during ingress (we shall call this \( F_{\text{ing}} \)), \( A_1 \) and \( A_2 \) (see Fig. 3.13) are first found, because

\[ F_{\text{ing}}(t) = \frac{A_1(t) + (A - A_2(t))}{A}, \]  \hspace{1cm} (3.27)

where \( A \) is the area of the planet (as in the previous model, \( A = \pi r^2 \)). The equation for finding the fraction of the planet’s projection in front of the star during egress was very similar;

\[ F_{\text{egr}}(t) = \frac{A_2(t) + (A - A_1(t))}{A}. \]  \hspace{1cm} (3.28)

The \( A - A_1 \) or \( A - A_2 \) terms was to cope with cases where the integral in the \( A \) function started from the wrong side of the circle.
To find $A_1$ and $A_2$, the intersection of the two circles was calculated so it could be used as a bound when integrating over the circle function. Choosing a coordinate system at the centre of one of the circles simplified this process. A star centred coordinate system was chosen, which shall be denoted by $x$;

$$x = t - (t_{\text{ing}} + R).$$

(3.29)

$R$ was related to the radius of the star. Due to the earlier mentioned assumption that the planet passes through the centre of the star’s circular projection, $R$ can be defined as

$$R = \frac{t_{\text{egr}} - t_{\text{ing}}}{2}.$$

(3.30)
In this coordinate system, the equations for the circles representing the planet and star are as follows:

\[ r^2 = (x + s)^2 + y^2 \]  
\[ R^2 = x^2 + y^2 \]

(3.31) \hspace{1cm} (3.32)

describes the planet (where \( s \) was the “distance” between the centre of the planet and the centre of the star) and describes the star.

The intersection of the circles at \((y_{\text{int}}, x_{\text{int}})\) can be found by equating \(y^2\) from both Equations (3.31 and 3.32) during ingress or egress and solving for \(x_{\text{int}}\):

\[
R^2 - x_{\text{int}}^2 = r^2 - (x_{\text{int}} + s)^2
\]

\[
R^2 - r^2 = x_{\text{int}}^2 - x_{\text{int}}^2 - s^2 - 2x_{\text{int}}s
\]

\[
2x_{\text{int}}s = r^2 - R^2 + s^2
\]

(3.33)

The intersection of these two lines is also needed in the coordinate system that will be used for integration. \( x \) was related to \( t'' \) by the following simple equation:

\[ t'' = x + R. \]  
\[ t_{\text{int}}'' = \frac{r^2 - R^2 - s^2}{2s} - \frac{s}{2} + R. \]

(3.34) \hspace{1cm} (3.35)

Clearly, the intercept in the \( t'' \) reference frame was

\[
x_{\text{int}} = \frac{r^2 - R^2 - s^2}{2s} = \frac{r^2 - R^2}{2s} - \frac{s}{2},
\]

(3.36)

Given that the separation between the planet and star centres was \( s \), the \( t' \) and \( x \) frames must have been related by

\[ t' = x + s + r. \]

(3.37)
Figure 3.14: The areas of the star and planet found using the integrals in Equations 3.38 and 3.39.

(A) Figure showing an example of the area that was found when integrating over the planet’s circle function. Notice that, during ingress, this is not the area contributing to the total area covering the star, hence $\pi r^2 - A_2$ is used.

(B) This figure shows the area, $A_1$, of the star’s circle found through integration. During ingress this is the area that contributes to the total area of the planet covering the star. During egress $\pi R^2 - A_1$ is used, because the area found with the integral is the area not contributing to the total area of the planet covering the star.

$A_1$ and $A_2$ could then be found. The function describing the planet segments is the same as the one used in the previous section (Eq. 3.24):

$$A_1(t''_{\text{int}}) = 2 \int_0^{t''_{\text{int}}} \sqrt{R^2 - (t'' - R)^2} \, dt''$$

$$= \left[ R^2 \tan^{-1} \left( \frac{\sqrt{t''}}{2Rt''} \right) - \frac{\sqrt{t''}(2R^3 - 3Rt'' + t''^2)}{2\sqrt{2R - t''}} \right]_0^{t''_{\text{int}}}$$

$$= \left( R^2 \tan^{-1} \left( \frac{\sqrt{t''_{\text{int}}}}{2Rt''_{\text{int}}} \right) - \frac{\sqrt{t''_{\text{int}}}(2R^3 - 3Rt''_{\text{int}} + t''_{\text{int}}^2)}{2\sqrt{2R - t''_{\text{int}}}} \right)$$

(3.38)
\[
A_2(t_{\text{int}}') = 2 \int_0^{t_{\text{int}}'} \sqrt{r^2 - (t' - r)^2} \, dt'
\]
\[
= \left[ r^2 \tan^{-1}\left( \frac{\sqrt{t'}}{\sqrt{2}r} \right) - \frac{\sqrt{t'}(2r^3 - 3rt' + t'^2)}{2\sqrt{2r - t'}} \right]_0^{t_{\text{int}}'}
\]
\[
= \left( r^2 \tan^{-1}\left( \frac{\sqrt{t_{\text{int}}'}}{\sqrt{2}rt_{\text{int}}'} \right) - \frac{\sqrt{t_{\text{int}}'}(2r^3 - 3rt_{\text{int}}' + t_{\text{int}}'^2)}{2\sqrt{2r - t_{\text{int}}'}} \right)
\]

These integrals are depicted in Figures 3.14a and 3.14b.

This model results in the following piecewise function:

\[
m(t) = \begin{cases} 
  m_0 + C_z & : t < t_{\text{ing}}; t_{\text{egr}} + D < t \\
  m_0 + d + C_z & : t_{\text{ing}} + D < t < t_{\text{egr}} \\
  m_0 + F_{\text{ing}}(t)d + C_z & : t_{\text{ing}} < t < t_{\text{ing}} + D \\
  m_0 + F_{\text{egr}}(t)d + C_z & : t_{\text{egr}} < t < t_{\text{egr}} + D
\end{cases}
\]

An example of the results obtained using this model can be seen in Fig. 3.15. The parameters fitted here are displayed in Table 3.2 and the posterior distributions of each parameter can be seen in Fig. 3.16.

<table>
<thead>
<tr>
<th>( t_{\text{ing}} (d) )</th>
<th>( t_{\text{egr}} (d) )</th>
<th>( D (d) )</th>
<th>( m_0 (\text{mag}) )</th>
<th>( d (\text{mmag}) )</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0386 ± 0.0015</td>
<td>0.1335 ± 0.0012</td>
<td>0.026 ± 0.002</td>
<td>1.427 ± 0.006</td>
<td>10.8 ± 0.5</td>
<td>0.016 ± 0.006</td>
</tr>
</tbody>
</table>

**Table 3.2:** MCMC fitted parameters of the lightcurve of KS24C007628. The \( t_{\text{ing}} \) and \( t_{\text{egr}} \) values are shifted by the Julian date of the first relative magnitude measurement of the data set. Uncertainties used represent the 85\% credible intervals of the posterior distributions.

### 3.4.4 Radial offset

The next obvious evolution to this program was to include a radial offset parameter into the model. This meant that the transit would be modelled by a circular planet projection, travelling past a circular star projection of uniform brightness, in a straight line that may not be through the centre of the star. This is depicted in Fig. 3.17.

This addition to the model meant that \( D \) could no longer be used to represent the diameter of the planet and \( (t_{\text{egr}} - t_{\text{ing}}) \) could no longer be used to represent the diameter of the star. A parameter change seemed like the best way to deal with this problem.
The MCMC parameters for this model were chosen as $r$, $R$, $p$, $t_c$, $m_0$, $d$, and $C$. The variables $r$, $R$, $m_0$, $d$, and $C$ were used to denote the same quantities as in previous models.

The new parameter $p$ denoted the $y$-direction offset of the planet’s trajectory from the centre of the star ($y = 0$). The radial offset, $p$, was restricted to being positive in the model as, due to the symmetry of this problem, there were no differences in the lightcurve between a negative and a positive $p$ of the same magnitude. $p$ was also restricted so that grazing transits were not considered, as these cases were outside the capabilities of functions created.

The other new parameter added to this iteration of the model was $t_c$. The $t_c$ parameter performs the function of phasing the transit. It is the time, which corresponds to the unmoving\(^7\) star.

\(^7\)The star was assumed to be unmoving as, during a transit, the movement of the star would be mostly away from the observer with radial velocity that was assumed to be negligible in comparison to the movement of the planet.
The first step in building this model was to find the intercepts of the planet and star functions during ingress and egress. To simplify the mathematics the centre of the planet was chosen as the centre of the coordinate system for this step.\footnote{Choosing a coordinate system with the origin at the centre of the star would have equally simplified the problem. The mathematics for this is very similar to the planet centred system} This shifted coordinate system was defined by

\[ y' = y - p \]  \hspace{1cm} (3.40)

and

\[ t' = t - t_n + r. \]  \hspace{1cm} (3.41)
where \( t_n \in t \). In this frame the equations for the planet and star circles were

\[
y' = \sqrt{R^2 - (t' - s)^2 - p}
\]

(3.42)

for the star and

\[
y' = \sqrt{r^2 - t'^2}
\]

(3.43)

for the planet, where \( s \) was the \( t \)-direction separation between the centre of both circles (as in the previous models). The value for \( s \) varied throughout the transit and was defined by

\[
s = t_c - t_n + r.
\]

(3.44)

The intercepts of the circle were found by equating Equations 3.42 and 3.43 and solving for \( t' \). The results is a quadratic of the form \( at'^2 + bt' + c = 0 \), where

\[
a = s^2 + p^2, \quad b = s(R^2 - r^2 - p^2 - s^2), \quad \text{and} \quad c = \frac{(s^2 + p^2 + r^2 - R^2)^2}{4} - p^2 r^2.
\]

(3.45)
The intercepts could therefore be found using the quadratic equation\(^9\):

\[
t'_{\text{int},1} = -\frac{b + \sqrt{b^2 - 4ac}}{2a},
\]

\[
t'_{\text{int},2} = -\frac{b - \sqrt{b^2 - 4ac}}{2a}.
\]

These intercepts were also needed in the star centred reference frame, where

\[
t'' = t - t_c.
\]

These two reference frames were related by \(^10\)

\[
t'' = t' - s.
\]

The intercepts in the \(t''\) (star centred) reference frame are therefore

\[
t''_{\text{int},1} = -\frac{b + \sqrt{b^2 - 4ac}}{2a} - s,
\]

\[
t''_{\text{int},2} = -\frac{b - \sqrt{b^2 - 4ac}}{2a} - s.
\]

In order to obtain coordinates for these intercepts, their positions in the \(y'\) (planet centred) and \(y\) (star centred) frames were also needed. These were firstly found in the planet’s frame by substituting the intercepts (Equations 3.46 and 3.47) into the equation for the planet’s circles (Eq. 3.43):

\[
y'_{\text{int},1} = \pm \sqrt{r^2 - t'_{\text{int},1}^2}
\]

and

\[
y'_{\text{int},2} = \pm \sqrt{r^2 - t'_{\text{int},2}^2}.
\]

However, this resulted in four intercept values because of the square root. There were usually two points on the planet circle relating to each \(t'\) intercept value (there was only one exactly at ingress and egress start and finish). This problem was solved by checking that the \(y'\) intercept value also lay on the circle representing the star in this frame. The

---

\(^9\)Note that when \(p = 0\) the intercepts are the same as in the previous subsection

\(^10\)This statement can be verified through substitution of Equations 3.41 and 3.48 into Eq. 3.44.
resulting intercepts were transformed into the planet centred frame using Eq. 3.40:

\[ y_{\text{int}, 1} = y'_{\text{int}, 1} + p \]  (3.54)

and

\[ y_{\text{int}, 2} = y'_{\text{int}, 2} + p. \]  (3.55)

\( s(R) \) The geometry of the planet-star system at the start of ingress or end of egress.

\( s(A) \) The geometry of the planet-star system at the end of ingress or start of egress.

**Figure 3.18:** Conceptual triangles formed by the centres of the planet and star at ingress and egress start and finish. The planet projection is depicted by the solid gray circle and quarter the star projection by the quarter-circle.

The times of ingress start and finish \((t_{i\text{i}}, t_{i\text{f}})\) and egress start and finish \((t_{e\text{i}}, t_{e\text{f}})\) were found by considering the geometry of the projection system at ingress and egress start and finish. At the times of ingress start and egress finish, right-angle triangles with sides \(s\), \(p\), and \((R + r)\) could formed (see Fig. 3.18). At the times of ingress finish and egress start, right-angled triangles could be formed with \(s\), \(p\) and \((R - r)\). Using these triangles equations for \(s\) at the times of ingress and egress start and finish could be found:

\[ s = \pm \sqrt{(R + r)^2 - p^2} \quad \text{and} \quad s = \pm \sqrt{(R - r)^2 - p^2}, \]  (3.56)

respectively. Using Eq. 3.44, these \(s\) values were converted into \(t\) values:

\[ t_{i\text{i}} = -\sqrt{(R + r)^2 - p^2 + t_c + r} \quad t_{i\text{f}} = -\sqrt{(R - r)^2 - p^2 + t_c + r} \]  (3.57)

\[ t_{e\text{i}} = -\sqrt{(R + r)^2 - p^2 + t_c + r} \quad t_{e\text{f}} = -\sqrt{(R - r)^2 - p^2 + t_c + r} \]

The next step was to solve the integrals of the circle functions to find the area of the star and planet \((A_1 \text{ and } A_2, \text{ respectively})\) contributing to the fraction \((F)\) of the planet.
FIGURE 3.19: This figure shows the Cartesian coordinate systems in which the points of intersection of the two circle functions were found.

projection that was blocking light from the star;

\[ F = \frac{A_1 + A_2}{A}, \]  

(3.58)

where \( A \) was the area of the planet. Unless \( p = 0 \), this was no longer a symmetric problem. To cope with this, the integrals were performed in polar coordinates.

The bounds were converted into angles for the integration process. This will be described for the star centred intercepts, where 0 was the positive \( t'' \)-direction, \( y = 0 \). The planet centred intercept angles were found similarly. The bound angle in the star’s frame were found by forming conceptual right-angle triangles with the \( t'' \) and \( y \) intercept coordinates and using basic trigonometric rules to find the angle they form. For example, for \( t_{\text{int},1}'' > 0 \) and \( y_{\text{int},1} < 0 \),

\[ \phi_{1''} = \frac{3\pi}{2} + \sin^{-1} \left( \frac{I}{r} \right) . \]  

(3.59)

Problems arise, however, when the lower bound angle for the integral becomes smaller
than the upper bound. This occurs in the star’s integral for cases when \( p < r \), where the lower bound is greater than \( 3\pi/2 \) but the upper bound is less than \( \pi/2 \). In order to avoid the issues that arise in these cases the reference frame of the bound angles for both the planet and the star were effectively rotated in order to restore symmetry to the integral, thus removing the need for two bounds in each reference frame.

This frame “rotation” replaced the two intercept angles with one angle; the difference between the two earlier angles:

\[
\phi'' = \frac{\phi''_1 - \phi''_2}{2},
\]

where \( \phi''_1 - \phi''_2 \) was replaced with \( \phi''_1 - \phi''_2 \) depending on whether ingress or ingress was occurring. The modulo by \( \pi \) of this angle had to be taken in order to cope with the \( \phi'' > \pi \) case which occurs when when one of the angles transition across the 0 radians point. A similar scenario plays out in the planet’s case.

The integral to find area of the segment of this circle \( S_1 \) constrained by the bounds in polar coordinates was, very simply,

\[
S_1(\phi'', R) = 2 \int_0^{\phi''} \int_0^R r' dr' d\phi'',
\]

for the star segment and

\[
S_2(\phi', r) = 2 \int_0^{\phi'} \int_0^r r' dr' d\phi',
\]

for the planet.

To find the area of the section of the star wanted, as indicated by \( A_1 \) in Figures 3.20b and 3.19, the area of the triangle, \( T_1 \), created by the intercept and the origin of the shifted coordinate \( (t'') \) system needed to be subtracted from \( S_1 \): i.e.

\[
A_1 = S_1 - T_1.
\]

The area of the triangle was found by conceptualising it as two equal-size right-angle triangles. This meant that the area of the triangle \( T_1 \) was the size of the base of one of the right-angled triangles multiplied by its height, which were found using trigonometric rules;

\[
T_1 = R^2 \cos \phi'' \sin \phi'',
\]
During egress and $\phi''$ was replaced with $\pi - \phi''$ during ingress (the opposite is true for the planet).

![Image of planet and star circles](image)

**Figure 3.20**: This figure depicts the area of the planet and star circles that contributed to the total area of the planet that is covering the star. It also shows the reference frame that was used when integrating to find the segment corresponding to the shifted intercept angle.

Finding the area of the planet contribution to $F$ (see Eq. 3.58) required the same method;

$$A_2 = S_2 - T_2,$$

(3.65)

where

$$T_1 = R^2 \cos \phi'' \sin \phi''.$$  

(3.66)

The value of $F$ was then able to be found.

<table>
<thead>
<tr>
<th>$R$ (d)</th>
<th>$r$ (d)</th>
<th>$p$</th>
<th>$t_e$ (d)</th>
<th>$m_0$ (mag)</th>
<th>$d$ (mmag)</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.066^{+0.023}_{-0.015}$</td>
<td>$0.010^{+0.003}_{-0.002}$</td>
<td>$0.05 \pm 0.03$</td>
<td>$0.09^{+0.002}_{-0.003}$</td>
<td>$1.427 \pm 0.006$</td>
<td>$10.8 \pm 0.5$</td>
<td>$0.015 \pm 0.005$</td>
</tr>
</tbody>
</table>

**Table 3.3**: MCMC fitted parameters of the lightcurve of KS24C007628 with constrained airmass correction and estimated as a circular planet and star projections, allowing for an off centre transit. The $t_{lag}$ and $t_{egy}$ values are shifted by the Julian date of the first relative magnitude measurement of the data set. Uncertainties used represent the 85% credible intervals of the posterior distributions.
Figure 3.21: MCMC model fitting on KS24C007628 with constrained airmass correction and circular planet and star projections, allowing for an off centre transit. This shows samples from the MCMC in black with the mean sample parameters forming the magenta line. Predicted transit parameters from the KELT-Survey data are shown in red.

The piecewise function for this model was

$$m(t) = \begin{cases} 
    m_0 + Cz & : t < t_{ii}; t_{ef} < t \\
    m_0 + d + Cz & : t_{if} < t < t_{ei} \\
    m_0 + F(t)d + Cz & : t_{ii} < t < t_{if} \\
    m_0 + F(t)d + Cz & : t_{ei} < t < t_{ef} 
\end{cases}$$

The MCMC process using this model was again tested on the KELT target KS24C007628. The results of this test can be seen in Figures 3.21 3.22, with the fitted parameters and their uncertainties in Table 3.3.

Figure 3.22 appears to show a correlation between the fitted $R$, $r$ and $p$ parameter. There may have been redundancies in the parameters causing this effect. The literature sometimes shows planet-star radius ratios being used instead of the two separate parameters (for example, see Torres et al. (2015) or Mandel and Agol (2002), which is the model...
used in AstroImageJ). However, this is not always the case (see Hellier et al. (2014)). Using a parameter similar to a radius ratio instead of individual radii may resolve redundancy issues in the model. The transit model used by AstroImageJ equates the transit depth and ratio of the planet and star areas. Thus equating the transit depth with the square of the planet-star radius ratio, previously mentioned. This is the likely cause of degeneracy in the parametrisation of the model.
3.4.5 Limb darkening

The glaringly obvious omission from this transit modelling program is the inclusion of limb darkening effects. The in-transit regions of the models in this program are dominated by airmass corrections. The result is an inverted bottom to the “U” shape of the fitted lightcurves. This does not agree with the data and the result is that airmass corrections are underestimated. An example of what the model might look like with limb darkening included can be seen in Fig. 3.23.

Limb darkening is estimated in lightcurve models by ad hoc “laws” that are not always physically valid (Howarth, 2011)(Kipping, 2016). Recent advances in observational techniques have allowed for further advancement in understanding the intensity distribution of stellar sources (Howarth, 2011). The LDTK (Limb Darkening Toolkit presented in Parviainen and Aigrain (2015)) is an example of recent efforts to better model stellar limb darkening profiles.

Schwarzschild (1906) describes the first limb darkening law, deduced from observations of the Sun, in which one parameter can be used to describe the effect, as it is linear in optical depth. Howarth (2011) describes this with two other limb darkening laws and how they are typically incorporated into fitting processes. These include a quadratic law, which is commonly used in MCMC fitting processes due to its computational efficiency, and the more accurate four-parameter (non-linear) law proposed in
Claret (2004). Mandel and Agol (2002) demonstrates an example of quadratic and non-linear limb darkening being applied to the model of a transiting exoplanet. Emphasis is put on the cases that occur when using these models with different planet-star size ratios.

If it is quite reasonably assumed that the transiting exoplanet is spherical, completely dark, and has no effect on the photometric properties of the host star, exoplanetary transits offer a somewhat rare opportunity for direct investigation of the limb darkening profile of the host star (Howarth, 2011).

Further development of this program could be undertaken in order to use it as a tool for investigating different limb darkening laws or characterisation of stellar atmospheres.

3.5 Program comparison and summary

WD and PHOEBE were designed with eclipsing binary stars in mind. PHOEBE is also intended for use with more resolved data than the lightcurve data in the following chapters. Development of PHOEBE is being pushed to keep up with some of the best telescopes, which are capable of much more precise measurement than the OC61 at Mt John (they either have much larger telescope mirrors, which collect more light, or are space-based telescopes, which do not need to contend with the fluctuating atmosphere around Earth). The use of PHOEBE was not applicable here, however, due to the singular nature of the transit observation; it would be more suited to survey data to which it can fit an orbit.

AstroImageJ appears to provide the best results, due to its inclusion of limb darkening parameters. However, transit periods needed to be fixed in order to obtain a fitted model as this program also fits according to orbital parameters that cannot be solved for with lightcurves of single transits.

The MCMC program discussed in this chapter obviously will not compete with the efficiency and accuracy of the model shown in these program distributions. Its usefulness diminishes when extensive detrending of data sets is required and in cases where insufficient baseline data is obtained or only partial transits are observed. However, the development of the MCMC program served its purpose of helping to provide an understanding of the complexities of the modelling process. They are many. With some adaptations to rule out redundancies in the model parametrisation, this program may
well become useful in the investigation of limb darkening models, even if the result is only to determine the validity of a model for a given data set.

For all compatible “U” shaped transits covered in Chapter 4, both AstroImageJ and the MCMC program discussed in this chapter were used to obtain fitted models.

In the case of the test set of KSC24C007628 from 2015 March 26, the fitted parameters obtain from AstroImageJ and the MCMC program of this chapter are compared where possible in Table 3.4, for which they show reasonably similar results.

<table>
<thead>
<tr>
<th></th>
<th>AIJ</th>
<th>MCMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(r/R)^2$</td>
<td>23 mmag</td>
<td>7.3 mmag</td>
</tr>
<tr>
<td>$d$</td>
<td>23 mmag</td>
<td>10.9 mmag</td>
</tr>
<tr>
<td>$t_c$ (Julian date)</td>
<td>2457108.054</td>
<td>2457108.051</td>
</tr>
</tbody>
</table>

**Table 3.4:** Comparing fitted model parameters of AstroImageJ and an MCMC program (referred to in the column label as AIJ and MCMC, respectively) for the lightcurve of KS24C007628, observed on 2015 March 26.
Chapter 4

Photometric results

The photometric lightcurves obtained for the purpose of this thesis are too numerous to discuss each one at length. For this reason, only results of particular interest are presented in this chapter. All other photometric results can be found in Appendix C. Table A.1 in this appendix holds a record of all the observations made by OC61 for KELT-South photometric follow-up. As mentioned in Chapter 2, the multi-aperture photometry for all of the following observation sets was performed using the multi-aperture feature in AstroImageJ.

4.1 “Flat” lightcurves

Not all KELT targets show events at the expected times. This could be due to the period of the transit being slightly off, spurious survey data, scatter in the data of the obtained lightcurve being greater than the depth of the transit, or possibly variations in a nearby star being attributed to the KELT target during the survey stage where the wide pixel scale is detrimental in resolving dim stars. This section includes three examples where no event has been visible in the photometric measurements of KELT target stars at the expected times.

4.1.1 KS29C10785

KS29C10785 (RA 00h00m24.67s; Dec −52°27′52.0″) is a V = 11.0mag star with a predicted period of 1.039091 days. Phasing of the KELT survey data (seen in Fig. 4.1) also has its transit durations and depth at 1.75 hours and 5.5 mmag respectively, with an effective temperature of 6247K.

KS29C10758 was expected to transit, and be visible from Mt John, on 2015 September 8. It was observed using OC61 with the V filter. 74 images of 200s exposures were
Chapter 4. Photometric results

FIGURE 4.1: Phased survey data for KELT target KS29C10785, with fit showing a possible transit.

taken, covering the predicted transit time. The set was started at 7:30 UTC, which was just after nautical twilight, resulting in the pre-transit baseline being shorter than would have been ideal. The set was therefore designed to provide a much longer post-transit baseline to compensate for this and ensure a decent number of out-of-transit measurements could be made and compared to those measurements made during the predicted transit.

An example of one of the images in the set can be seen in Fig. 4.2, which also shows the field of view available for the selection of comparison stars for multi-aperture differential photometry.

Figure 4.3 shows the apertures that were selected; the green aperture, T1, surrounds the target star KS29C10785 and the red apertures, C2, C3, C4, C5, and C6, show the

FIGURE 4.2: Field of view captured in images for photometry of KELT target KS29C10785 on 2015 September 8.
Chapter 4. **Photometric results**

**Figure 4.3**: Apertures used in the multi-aperture photometry of KELT target KS29C10785 on 2015 September 8. T1 was the target star (KS29C10785) and C2, C3, C4, C5, and C6 were the comparison stars used to find the relative flux of T1.

Comparison stars used. The aperture size was chosen depending on its seeing profile (see Chapter 2, Fig. 2.8 for an example of this). The inner annulus took measurements of the source and measurements from the outer annulus were used to determine the contribution from the background in that part of the image.

The results from these measurements can be seen in the lightcurve in Fig. 4.4, which shows the normalized relative flux of the target star (relative to the comparison stars) over the predicted transit time. However, the raw data (pink) appeared to have a curve to it. When detrended for airmass (blue), the curve becomes much flatter and does not appear to have any features that could be attributed to a planetary transit or eclipse. The scaled airmass curve (grey) can be seen tracing approximately with the shifted raw data. This detrended data shows a much more comprehensive and convincing result.

Further RV follow-up of this target from the ANU detected no RV variation ($T_{\text{eff}} = 7467\, \text{K}; \log g = 1.4; \text{Fe/H} = 0.0$). This target was therefore expired from the candidate list.

With no evidence supporting a transit in either the follow-up photometry or RV, the target can only be considered a false positive in the survey data. It is unclear what might have caused this false positive. With no close neighbours visible in the field, it is very unlikely that this would be a blended stellar binary. Without a dip of any kind in the follow-up photometry, the false-positive in the survey data also cannot have been from a grazing binary. The 5.5 mmag periodic drop in the lightcurve of KS29C10785 is
FIGURE 4.4: Relative lightcurve of KELT target KS29C10785 showing how the raw data follows an airmass curve with coefficient -0.022 and how detrending for airmass removes this feature.

likely to be merely a coincidence in the random spread of the data; the predicted transit was the result of spurious data. More survey data here may well have ruled this target out.

4.1.2 KS27C010840

KELT-South planetary candidate KS27C010840 (RA 18°25′25.5″; Dec −61°15′54.1″; $T_{\text{eff}} = 6206K$) is a 10.61 magnitude star with a predicted transit period and duration of 1.25 days and 2:52 hours, respectively. The following figures show data taken in the V filter during and around the predicted transit on 2015 July 19. The observations
Figure 4.5: Apertures used in the multi-aperture photometry of KELT target KS27C010840 on 2015 July 19. T1 was the target star (KS27C010840) and C2, C3, C4, C5, C6, and C7 were the comparison stars used to find the relative flux of T1.

started at 13:45 UTC and was planned to cover ingress at 14:54 UTC and egress at 17:46 UTC and finish at approximately 18:40 UTC (just before nautical twilight); the set was planned to have 252 images at 50 s exposure times. However, weather affected the later images in the set resulting in the predicted egress not being observed and only pre-transit baseline being observed.

As can be seen in Fig. 4.5, there were plenty of stars of similar brightness available in the field of view, which could be used as comparison stars. This figure also shows that the comparison stars (red apertures; C2, C3, C4, C5, C6, and C7) were concentrated on the lower half of the image. This is not ideal as any inconsistencies in visibility across the image will be over-represented in that area and may effect the relative flux of the target (T1).

Figure 4.6 shows the lightcurve obtained from the July 19 set. The first half of the detrended lightcurve does not appear to have any transit-like features. The data closer to egress, which was clouded out in some places, shows the relative flux having a generally decreasing trend. On closer inspection of the images during this period, the dimmer stars are showing sign of occultation (see Fig. 4.7).

This occultation could possibly be caused by the dome not tracking properly and partially blocking the stars, or by the stars beginning to set and being blocked by either land or the wind-shield. The latter can be ruled out by looking at the airmass plot for KS27C010840 during this set: Fig. 4.8.
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FIGURE 4.6: Lightcurve of KELT target KS27C010840 showing the raw data aligned with the airmass according to its fitted value. The end of this set shows a possible late transit ingress.

FIGURE 4.7: Stars showing sign of occultation towards the end of the set of observations for KS27C010840 from 2015 July 19

The airmass value for KS27C010840 never makes it below 1.8. The wind-shield of OC61 does not interfere with images until the elevation of the stars falls to 30°, which corresponds to an airmass of 2.0. Therefore, interference from the wind-shield and the stars setting can be ruled out as the cause of the occultation. It then seems likely that the dome is instead not tracking correctly here. This occultation may be causing the feature
seen at the end of the lightcurve.

**Figure 4.8:** Airmass plot for KS27C010840 on the night of 2015 July 19 showing in-transit times in magenta and night in blue, with the airmass values during the times of the data set in black.

**Figure 4.9:** Relative phased lightcurves of KELT target KS27C010840 with sets from multiple collaborative sources, including the original KELT data.

It is now being investigated whether or not the period of the transit was slightly off and instead of this set being during the transit time, it was just before the transit. This set, overlapping the KELT survey data, with the new phase can be seen in Fig. 4.9.
4.1.3 KS17C01888

KELT-South candidate KS17C01888 RA $22^h39^m54.6^s$; Dec $-54^\circ7'35.2''$) was observed on 2015 September 13. It is a 9.17 magnitude, very hot star ($T_{\text{eff}} = 8903$ K). The transit on this day was predicted to start at 09:15 UTC. The transit was predicted to have a duration of 7:01 hours (ending at 16:16 UTC), a depth of 4.27 mmag, and a period of 7.90 days.

The set of observations for this transit was constrained by twilight at both the start and end. The set was queued to start at 8:00 UTC (nautical twilight was at 7:26 UTC), taking 570 images of 40 s exposures in the V filter, lasting until 17:50 UTC; this would mean the set finished after nautical twilight (17:41 UTC). This was purposefully done to obtain the maximum post-transit baseline, but the result is that the last few data points are not particularly trustworthy as they may be affected by the twilight light. This is reflected by the increased size of the error bars of this later data.

Problems arose in the multi-aperture photometry of this set, as the field of view for these images contains no other stars near the brightness of the 9.7 magnitude target. The significantly higher magnitude, dimmer neighbours are not particularly well resolved as they require a much longer exposure time to become resolved than the target. However, the exposure time could not be greatly increased without running the risk of overexposing the target.

The exposure chosen for this set was calculated from the maximum counts of previously observed targets (see chapter 2 for a similar calculation) with the aim of a 40 000 counts maximum. Despite the detector only becoming saturated at 60 000 counts, 40 000 was
chosen as an estimate to allow leeway for lower airmass or better seeing conditions. Overexposing the target would render the set more or less useless and, especially given its length, that would be a waste of telescope time, hence the estimated 20,000 counts of contingency.

Multi-aperture photometry was performed multiple times on this set in an attempt to get the best possible combination of comparison stars. Two examples of the comparison stars chosen can be seen in Fig. 4.11. Some of the dim neighbours appeared to be causing variations in the relative flux of the target. These features were often removed with the exclusion of the responsible comparison star from the differential photometry calculations. Stars were also removed as comparison stars if they were increasing the scatter in the lightcurve. The lowest scatter in the lightcurve (Fig. 4.12) came from the comparison stars shown in Fig. 4.11a.

The lightcurve in Fig. 4.12 had the least scatter, but there were two dips visible just after ingress and egress. The dip after egress is possibly the result of the rising sun around this time skewing the data, but this is not enough to rule this feature out. Different combinations of apertures were chosen to try and rule out a comparison star as the

(A) The apertures used in multi-aperture photometry where T1 was the target star (KS17C01888) and C2, C3, C4, C5, C6, and C7 were the comparison stars used to find the relative flux of T1.

(B) The apertures used in multi-aperture photometry where T1 was the target star (KS17C01888) and C2, C3, C4, and C6 were the comparison stars used. T6 was initially selected as a companion star, but it was later removed as doing so reduced the spread of the data.

FIGURE 4.11: Two different aperture configurations used for multi-aperture photometry of KELT target KS17C01888 on 2015 September 13 in an attempt to resolve the lightcurve by removing companions which seemed to add artefacts or increase the spread of the relative magnitude data.
Chapter 4. Photometric results

Figure 4.12: Relative lightcurve of KELT target KS17C01888 corresponding to the comparison stars shown in 4.11a.

cause of these dips. Figure 4.13 does not show these dips in the lightcurve, but it is likely because the noise has been increased by this combination of comparison stars (Fig. 4.11b) and not that some offending companion has been removed.

Figure 4.13: Relative lightcurve of KELT target KS17C01888 corresponding to the comparison stars shown in 4.11b.
The same problem occurs when looking for signs of the predicted transit of depth 4.27 mmag. The data in the lightcurve with the least scatter (Fig. 4.12) is spread over more than 150 mmag. Nothing conclusive can therefore be said about the existence of a transiting body from this data. There may well have been a transit here, but without good comparison stars the spread is too great to get a signal.

However, one of the aforementioned comparison stars, removed because of the variations it was causing in the target lightcurve, happened to be a rather interesting variable neighbour. Photometry was performed with this neighbour (USNO-A2 0300-37720825 at coordinates 22h40m15.08s −54°08′24.4″) as the target. USNO-A2 0300-37720825 can be seen in the T1 aperture in Fig. 4.14. Photometry of this star gave the lightcurve seen in Fig. 4.14. This lightcurve demonstrates how transiting exoplanet surveys and follow-up can also be useful for the discovery and characterisation of variable stars. Hartman et al. (2004) covers the discovery and analysis of lightcurves of 1439 variable stars found through the HATNET project, for which the main purpose is the detection of transiting exoplanets. Pepper et al. (2008) covers some of the variable star that have been observed by KELT in the past. This variable source appears to be a contact eclipsing binary system (Pribulla et al., 1999, Zhou and Leung, 1990).

![Figure 4.14: Apertures used in the multi-aperture photometry of the variable neighbour star USNO-A2 0300-37720825, at coordinates 22h40m15.08s −54°08′24.4″, on 2015 July 19. T1 was the target star (USNO-A2 0300-37720825) and C3, C6, and C7 were the comparison stars used to find the relative flux of T1. T2, T4, and T5 were removed as comparison stars, after the initial photometry attempt, to improve the resolution of the variable lightcurve.](image)
4.2 “V” shaped eclipses

Grazing binaries and blended stellar binaries (mentioned in Chapter 1) can be distinguished from planetary transits during follow-up photometry due to their “V” shaped lightcurves. The following subsections show sets with “V” shaped eclipses.

4.2.1 KS34C047274

KS34C047274 (RA 10°8′49.9″; Dec −62°2′6.4″; $T_{\text{eff}} = 6891$ K; $V = 11.99$ mag; ) was predicted to have a transit occurring on 2015 May 2 with ingress at 9:00 UTC and egress at 11:02 UTC; the predicted duration was 2:04 hours. The period of these predicted transits was 1.214185 days and the predicted depth was 18.7 mmag.

This set started half an hour later than requested (presumably due to weather) so the beginning of the ingress of the transit and pre-ingress baseline, were missed. As this was one of the first sets observed, the number of baseline observations was underestimated at half an hour. The KELT transit finder also specifies the time of ingress as the middle of the ingress, but when planning this set, it was incorrectly assumed that the ingress time was the beginning of ingress. However, this set still covers the egress well. The 211 images for this set were taken with the V filter with 50s exposures.
This star sports a far more crowded field (Fig. 4.16) than those previously discussed in Section 4.1. This is more ideal for the multi-aperture photometry performed here, as there is a better selection of comparison stars. Comparison stars can be chosen that are more ideally similar to the target in magnitude and more evenly spread across the image. The challenge here becomes choosing comparison stars that do not encounter other neighbour stars within the background annulus of their aperture. The downfall of such a busy field is that the low resolution, wide angle KELT telescope cannot distinguish between stars so close together (see Chapter 1, Section 1.3) and so the potential for a blended eclipsing binary is higher.

Figure 4.17a shows the apertures chosen for the photometry of KS34C047274 resulting in the lightcurve seen in Fig. 4.18. There is a small section of data missing towards the end where images were removed from the photometric processing because they contained a ring artefact that was not removed during flat-fielding, probably due to dust. This artefact was on the target star and so the lightcurve in Fig. 4.19, which is from the same set, does not have any missing data.

There does not appear to be any significant features in this lightcurve and there is certainly not an 18.7 mmag depth transit.

With such a crowded field, it seemed likely that the reason the KELT survey had tagged this as a possible transit was that a very close neighbour had some periodic variability in it, which was appearing as a transit-like event. Photometry was run on the close neighbours of KS34C047274 to check for variability.
chapter 4. photometric results

(a) The apertures used in multi-aperture photometry where T1 was the target star (KS34C047274) and C2, C3, C4, C5, C6, C7, C8, and C9 were the comparison stars used to find the relative flux of T1.

(b) The apertures used in the multi-aperture photometry where T1 was the target star (USNO-A2 0225-07606886 - neighbour to KELT target KS34C047274) and C2, C3, C4, C5, C6, C7, C8, and C9 were the comparison stars used to find the relative flux of T1.

Figure 4.17: Apertures used in the multi-aperture photometry of KELT target KS34C047274 and its neighbour USNO-A2 0225-07606886 on 2015 September 8.

Photometry, run with the targets and comparison apertures shown in Fig. 4.17b, gave the lightcurve shown in Fig. 4.19. This lightcurve clearly shows a “V” shaped eclipse occurring, and within the time frame of the predicted transit of KS34C047274. The target was later identified as USNO-A2 0225-07606886, which is a 12.2 magnitude star with coordinates RA 10h8m48.85s; Dec -62°1'53.2". This lightcurve shows an approximately 80mmag depth eclipse. It can therefore be concluded that the variations that the KELT-South survey picked up were from a blended eclipsing binary, with the dip in light from the transiting neighbour being diluted by the KELT target into looking like a planetary transit.

Figure 4.18: Lightcurve of KELT target KS34C047274 showing no transit during the predicted time.
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Figure 4.19: Lightcurve of neighbour star to KELT target KS34C047274 (USNO-A2 0225-07606886 at \(10^h08^m48.85^s - 62^\circ01'53.2''\)) showing a 'V' shaped transit during the predicted time.

This target was expired from the KELT candidate list as a false positive caused by a blended stellar binary. However, given the transit seen in this data, a blend between these two stars only accounts for a 31.2 mmag depth.

\[
f_{47274} = 10^{-11.99}/2.5 = 1.600 \times 10^{-5},
\]

where \(f_{47274}\) is the apparent flux of KELT target KS34C047274;

\[
f_{6886} = 10^{-12.2}/2.5 = 1.318 \times 10^{-5},
\]

where \(f_{6886}\) is the apparent flux of USNO-A2 0225-07606886;

\[
f_{6886,t} = 10^{-12.28}/2.5 \approx 1.246 \times 10^{-5},
\]

where \(f_{6886,t}\) is the apparent flux of USNO-A2 0225-07606886 during the middle of the transit.

\[
d_m = 2.5\log_{10}(f_{6886} + f_{47274}) - 2.5\log_{10}(f_{6886,t} + f_{47274}) \approx 0.0141 \text{ mag} = 14.1 \text{ mmag},
\]

where \(d_m\) is the depth (increase of the relative magnitude of the source) of the blended eclipse. This estimate is very close to the predicted transit depth of 18.7 mmag.
The depth seen in the survey data may be the result of the blend of three or more close stars.

### 4.2.2 KS29C07001

![Figure 4.20: Apertures used in the multi-aperture photometry of KELT target KS29C07001 on 2015 August 20. T1 was the target star (KS29C07001) and C2, C3, C4, C5, C6, and C7 were the comparison stars used to find the relative flux of T1.](image)

KS29C07001 (RA $11^h25^m0.27^s$; Dec $-64^\circ 45' 35.9''$) was predicted to have a planetary transit visible from 9:27 UTC (ingress) to 13:35 UTC (egress) on 2015 August 20 (4.07 hour transit duration). The predicted period of this orbit was 11.53 days and the predicted depth was 10.2 mmag. This target is a 10.82 magnitude star. It was planned that the target would be observed 85 times in the V filter with 150 s exposures with the set starting at 8:10 UTC.

The field in Fig. 4.20 shows the density of stars to be comparatively good, with a reasonable number of stars of similar magnitude and spread well across the field that could be used as comparison stars in multi-aperture photometry of the target. The target and comparison stars shown in these images are those used to obtain the lightcurve in Fig. 4.21.

This lightcurve appears like the flat-bottomed ingress of a “U” shaped transit. The phasing looks to have been slightly off resulting in the ingress being about an hour and a half late. The later data in this set could not be obtained due to weather so these are merely conjectures about the overall shape of the lightcurve of this target during transits based on the available information. The depth of this transit was approximately 10 mmag.
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Figure 4.21: Relative lightcurve of KELT target KS29C07001, imaged in V from Mt John on 2015 August 20, corresponding to the target and comparison stars shown in Fig. 4.20, showing the ingress of an eclipse.

Figure 4.22: Relative lightcurves of KELT target KS29C07001 with data from multiple sources including the original KELT data.

These ideas were proven to be largely wrong by the follow-up photometric data obtained from Hazelwood Observatory on 2015 September 12. The results from this set can be seen in the red data in Fig. 4.22. They show this candidate to have a more “V” shaped eclipse. This plot containing both data sets does not seem to have much baseline data, so estimating the depth here becomes particularly inaccurate. The target was added to the list for RV follow-up. If a planet was causing the dip in light, it would be the same depth over all bands. However, if an eclipsing binary was responsible, the dip would likely have varying depths in each band, caused by the difference in temperatures between the two companion stars. Unfortunately, both the KELT collaboration sets of data were obtained in V, so no depth difference between filters can be seen. Given that the field
here is not particularly crowded, it seemed likely that this was a false positive caused by a grazing binary.

It was later found that this target had previously been chased by WASP-South. They determined this to be a blend due to the different depths of the transit in the photometry obtained from different bands.

### 4.3 “U” shaped eclipses

This next section includes some of the most interesting examples of data collected for the purpose of this thesis, in collaboration with the KELT-South follow-up group, with “U” shaped eclipses. The flat-bottomed, “U” shaped eclipses look promising as planetary transits. These results also include models of the planetary systems, fitted with the program described in Chapter 3.

#### 4.3.1 KS26C026700

![Figure 4.23: Apertures used in the multi-aperture photometry of KELT target KS26C026700 on 2015 June 24. T1 was the target star (KS26C026700) and C2, C3, C4, C5, C6, and C7 were the comparison stars used to find the relative flux of T1.](image)

KELT-South target KS26C026700 (RA 15:03:46.2; Dec −29°48′38.5″; $T_{\text{eff}} = 5870K$; $V = 11.46$ mag) was scheduled to have 260 images of 60 s exposures in the V filter taken, starting at 2015 June 24 06:13 UTC. This was meant to cover the predicted transit with ingress at 6:16 UTC and egress at 10:08 UTC and a duration of 3:52 hours (the orbital
Chapter 4. Photometric results

period and transit depth were predicted as 3.418929 days and 21.6 mmag respectively). Unfortunately a drive on the telescope started to slip at about image 236 and weather drastically lowered the signal to noise of the images around the second half of the predicted transit, rendering these parts of the set unusable for photometry. One of the brighter neighbours in the field became saturated for some of the set, but this star was not used in the multi-aperture photometry of KS26C026700.

Using the apertures in 4.23 the multi-aperture photometry of KS26C026700, the lightcurve in Fig. 4.24 and 4.25 was obtained. Figure 4.24 shows the raw data, with most of the ingress visible and some post-egress baseline. A model was able to fit to the data here using the fitting tool in AstroImageJ. This can be seen on the figure as a red curve. The transit in this data has a depth of 20.1 mmag according to the AstroImageJ fit. Given such a small amount of baseline data, another observation to check this depth would be prudent.

Figure 4.25 shows the raw data (labelled "Michael") in a phased global plot with two other follow-up data sets and the survey data. The raw data from Mt John matches the

![Figure 4.24: Relative lightcurve of KELT target KS26C026700, imaged in V from Mt John on 2015 June 24, corresponding to the target and comparison stars shown in Fig. 4.23.](image-url)
results obtained by the other observers. More results are needed before comments can be made about the depth difference between bands. This looks to be a good planetary candidate and has been added to the follow-up RV list.

The MCMC program created will need more development before it can process data sets with such a lack of pre-transit baseline. For this reason, no MCMC fit was obtained for this lightcurve.

### 4.3.2 KS17C06559

KS17C06559 (RA 00$^h$49$^m$5.8$^s$; Dec −52°2′47.5″; $T_{\text{eff}} = 5870\,$K; $V = 10.74\,$mag) was observed on 2015 July 10 starting at 13:00 UTC. This set included 260 images in the V filter with 60s exposures. The set was designed to end at 18:47, which was 20 minutes before nautical twilight (19:02 UTC). The predicted transit on this day had a depth of 12 mmag with a 3:47 hour duration from a 2.65 day orbital period. The predicted ingress was at 14:04 UTC and egress was at 17:50 UTC.

This target had previously been observed in $i'$, $g'$ (on 2014 October 7 and October 13 respectively from LCOGT), and Rc (204 October 23 from the PEST Observatory) bands. The LCOGT sets showed a 12 mmag flat-bottomed eclipse, which agreed with the approximately 12 mmag depth ingress seen by the PEST. These results do not quite agree with the results from the July 10 set from Mt John.
Figure 4.27 shows the lightcurve obtained from photometric analysis of the 2015 July 10 observations from OC61 at Mt John using the target and comparison stars shown in Fig. 4.26. The raw data from this analysis can be seen in purple, with the model fitted blue data having been detrended for airmass. An ingress is only visible here in the detrended data.

Both the raw data and detrended data were able to be fitted with resulting transit depths of 13.8 mmag and 11 mmag, respectively.

This target was added to the RV follow-up list. Despite all the promising photometric results, RV follow-up from ANU showed no variation ($T_{\text{eff}} = 6200\,K$, $\log g = 4.5$, Fe/H = $-0.5$). The notes given to the photometric follow-up group about these spectroscopic results say it looks like there could be two or three sets of spectral lines in the spectrum, suggesting a triple system. More RV observations are needed to confirm or deny this hypothesis.

The lack of pre-transit baseline in this set meant that the MCMC fitting process was settling on somewhat unreasonable parameters. The achieved fit can be seen in Fig. 4.28 with projections of the posterior distribution of the parameters in Fig. 4.29.

![Figure 4.26: Apertures used in the multi-aperture photometry of KELT target KS17C06559 on 2015 July 10. T1 was the target star (KS17C06559) and C2, C3, C4, C5, C6, and C7 were the comparison stars used to find the relative flux of T1.](image)
KS28C05114 is an 11.22 magnitude star at $20^h10^m23.9^s - 51^\circ 48'38.60''$. This KELT target was predicted to have a planetary transit on 2015 July 22 with ingress at 11:16 UTC and egress at 17:36 UTC, giving a total duration of 6:20 hours. The orbital period for this transit was 8.27 days. The predicted depth was 14.0 mmag. This target had been previously observed by SKYNET in the V band on 2014 November 9, where a hint of an egress was seen. If real, the depth of the transit would have been 7 – 8 mmag. The target was observed in the V band in a set of 360 images of 70s exposures, starting at 10:00 UTC and lasting 9 hours, as planned. This set finishes at nautical twilight.
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The multi-aperture photometry was run for this target using the comparison stars that can be seen in 4.30. The resulting lightcurve can be seen in Fig. 4.31. The total normalized counts for the comparison stars in this set make a drastic drop at the very end, coinciding with dawn. Ingress seems to have occurred over an hour late, with egress being on time with the predicted egress. There is a drop in the baseline after egress, which coincided with a repointing of the telescope. Detrending this as a meridian flip gives the lightcurve of Fig. 4.32. This lightcurve is obviously flat-bottomed with a transit depth of 6.3 mmag. With a 6015 K host star and a 6.3 mmag event, this would be about
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Figure 4.30: Apertures used in the multi-aperture photometry of KELT target KS28C05114 on 2015 July 22. T7 was the target star (KS28C05114) and C1, C2, C3, C4, C5, and C6 were the comparison stars used to find the relative flux of T1.

a 0.92R_\odot companion. This target has been added to the RV follow-up list. Photometric follow-up is still needed in different bands.

The fitting program created cannot yet perform the meridian flip detrend possible in AstroImageJ, so the post flip data was excluded from this fit. A depiction of the fitted model can be seen in Fig. 4.33, with projection of the posterior distribution in Fig. 4.34. The fitted parameters are displayed in Table 4.1.

<table>
<thead>
<tr>
<th>R (d)</th>
<th>r (d)</th>
<th>p</th>
<th>t_c (d)</th>
<th>m_0 (mag)</th>
<th>d (mmag)</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.127±0.004</td>
<td>0.007±0.006</td>
<td>0.029±0.006</td>
<td>0.189±0.003</td>
<td>0.299±0.002</td>
<td>0.0075±0.004</td>
<td>0.0080±0.0012</td>
</tr>
</tbody>
</table>

Table 4.1: MCMC fitted parameters of the lightcurve of KS28C05114. Uncertainties used represent the 85% credible intervals of the posterior distributions. t_c values are shifted by the first Julian date of the set.

4.3.4 KS32C06806

KS32C06806 is an 11.16 magnitude star with an effective temperature of 5910 K at right ascension 23^h36^m40.3^s and declination −34°36′40″. KS32C06806 was predicted to have a transit on 2015 August 26 with ingress at 13:51 UTC and egress at 16:05 UTC (2:14 hour duration). This predicted transit has a period of 1.39 days and a depth of 6.86 mmag. The set of observations were planned to start at 12:45 UTC, taking 360 images in the V band with 70s exposures. This set was meant to run for 9 hours, but instead started late, at 13:40, due to cloud.
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FIGURE 4.31: Relative lightcurve of KELT target KS28C05114, imaged in V from Mt John on 2015 July 22, corresponding to the target and comparison stars shown in Figure 4.30.

This lightcurve (4.36) shows an egress occurring at the expected time. With cloud affecting the few existing ingress points, it is hard to determine if this is a flat-bottomed transit, and what the actual depth is. A model was able to be fit to the data using the model fitting tool in AstroImageJ, showing a transit depth of 16.5 mmag. This target was added to the RV reconnaissance list.

KS32C06806 was later observed by KELT-South follow-up member, Chris Stockdales, who saw a 10 mmag full event in V on 2015 September 13 from the Hazelwood Observatory. With T\(_{\text{star}}\) = 5910 K, this corresponds to a 1 R\(_{\text{Jup}}\) companion. The photometric priority increased as lightcurves were needed in different bands so that the depths could be compared. Chris observed this again in I on 2015 September 20 and saw an approximately 10 mmag full event. It was consistent with previous observations in the V-band. On 2015 September 27, he observed in B and saw a transit of consistent depth, however the scatter was too high for the observation to be conclusive. On observing this target again in B on 2015 October 4, with a better signal to noise ratio, an approximately sinusoidal lightcurve, with a slightly earlier than predicted decrease in flux, could be seen.
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**Figure 4.32:** Relative lightcurve of KELT target KS28C05114, imaged in V from Mt John on 2015 July 22, corresponding to the target and comparison stars shown in Figure 4.30, with a meridian flip detrend correcting the drop at the end of the lightcurve.

**Figure 4.33:** MCMC fitted model for KS28C05114.

The priority for this target has therefore been set to 0\(^1\) while RV results are awaited.

---

\(^1\)No photometric follow-up is being made for this target at this time.
Figure 4.34: One and two-dimensional projections of the posterior distribution for the model fitting of KS17C06559.

Figure 4.35: Apertures used in the multi-aperture photometry of KELT target KS32C06806 on 2015 August 26. T1 was the target star (KS32C06806) and C1, C2, C3, C4, C5, C6, and C8 were the comparison stars used to find the relative flux of T1. T7 was removed as a comparison star to reduce the scatter in the relative flux of T1 caused by T7 being a significantly dimmer star than T1 and the other comparison stars.

4.3.5 KS24C007628

Observations of KELT-South target KS24C004628 (CD-34 8618\textsuperscript{2}) were made on 2015 March 24 and 26, coinciding with predicted transits. The transits were predicted to have a period of 2.02 days, a depth of 6.0 mmag, and a duration of 2:17 hours. This

\textsuperscript{2}http://simbad.u-strasbg.fr/simbad/sim-id?Ident=\%402061857\&Name=CD-34\%20\%208618&submit=submit
was the first target observed, and was chosen because it had been previously chased by follow-up members and there was certainly an event of some sort occurring with the predicted period. This seemed like a good target to test the observing and reduction processes that would be used for all future photometric targets. The target was observed both times in the same band to check that the results obtained could be replicated.

Observations of the secondary location (see Chapter 1, Section 1.3 for an explanation of secondary locations) were also attempted but were not managed due to weather and queuing conflicts.

The transit on 2015 March 24 was predicted to ingress at 11:51 UTC and egress at 14:08 UTC. The observations for this predicted transit were planned to include 318 images taken in the V band with 20s exposures, starting at 10:40 UTC. The predicted transit on 2016 March 26 was to ingress at 12:01 UTC and egress at 14:33 UTC. The observations in this set were planned to include 270 images, also taken in the V band, with
40s exposures, starting at 11:00 UTC. Neither of these sets were interrupted, be it by weather or telescope breakdowns (though some slices were removed due to drive slips or low signal to noise), and so the lightcurves from these sets show full transit. The comparison stars chosen for the photometry of each set can be seen in Fig. 4.39. The results of this can be seen in the lightcurves in Figures 4.40 and 4.41.

The lightcurve from the 2015 March 24 set shows a “U” shaped, flat-bottomed eclipse, with an 8 mmag depth. However, the data has a slight upward (decreasing in relative magnitude) trend to it. This is possibly an effect of the changing airmass. Figure 4.41 shows the lightcurve from the March 26 set. This has the same general shape to it (with a 7.3 mmag transit depth) and there is clearly less scatter in the data. This can be
attributed to the increased exposure time at 40s instead of 20s. Given a fixed transit centre, a model was able to be fitted to both the lightcurve using the AstroImageJ fitting tool.

The global fit for this target shows the March 26 set compared to five other sets obtained by different members of the follow-up group. No obvious depth differences can be seen between the sets from varying bands. It appears there may be some difference from the B to I bands for this target but further observations in B did not support this. KS24C007628 having a planetary companion, therefore, looks very promising. This target was added to the RV follow-up list, so details about this companion could be found. However, getting the RV orbit proved rather difficult, due to the rapid rotation and period of near integer days. No conclusive RV results have yet been obtained.

The results of the MCMC fitting model are shown in Figures 3.21 and 3.22 and Table 3.3.

4.4 Summary

The targets discussed in the chapter were sorted depending on the shape of the lightcurves obtained. Neither KS29C10785, KS27C010840 nor KS17C01888 showed signs of a transit of any kind; they all had “flat” lightcurves. The follow-up RV results for KS29C10785 showed no variation, confirming it as a false positive. KS27C010840 is currently being investigated at a new, slightly longer period, to explain the absence of
FIGURE 4.40: Relative lightcurve of KELT target KS24C007628, imaged in V from Mt John on 2015 March 24, corresponding to the target and comparison stars shown in Figure 4.39. The predicted ingress and egress indicated on the plot were the times calculated from the BLS fitted KELT data.

a transit-like event. The results for KS17C01888 were inconclusive, due to the high scatter in the data set, resulting from the comparison stars being much dimmer than the target. All other data showing only “flat” lightcurves can be seen in the Appendix (C Section C.1).

This chapter also included two examples of “V” shaped events in photometric lightcurves. These included the KS34C047274 and KS29C07001 data sets. The lightcurve of target KS34C047274 actually showed no event, but its very close neighbour (USNO-A2 0225-0760688) had an obvious “V” shaped dip in its lightcurve. The combination of these two neighbours is what resulted in a blended eclipsing binary in the survey data, causing
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FIGURE 4.41: Relative lightcurve of KELT target KS24C007628, imaged in V from Mt John on 2015 March 26, corresponding to the target and comparison stars shown in Fig. 4.39. The predicted ingress and egress indicated on the plot were the times calculated from the BLS fitted KELT data.

being the most promising planetary candidates, many of the lightcurves showing convincingly “U” shaped eclipses were discussed in this chapter. The KELT-South targets with “U” shaped transits discussed in this chapter were KS26C026700, KS17C06559, KS28C05114, KS32C06806, and KS24C007628. Photometric data for KS26C026700
Chapter 4. Photometric results

Figure 4.42: Relative lightcurves of KELT target KS24C007628 with sets from multiple collaborative sources, including the original KELT data.

showed a “U” shaped dip, which matched well with the other follow-up lightcurves; this looks to be a good planetary candidate. RV results for this target are being awaited. The periodic event seen in the survey data of KS17C06559 has been confirmed by the data discussed in this chapter and three other mentioned sets of follow-up photometry. Though this transit appears “U” shaped in all sets, the OC61 data is not particularly flat-bottomed. The spectroscopic results for this target suggested a triple system from the number of sets of spectral lines but showed no RV variation. More RV data is needed to clarify exactly what is causing this event. KS28C05114 had a very long set with data covering nine hours. The lightcurve showed an obviously flat-bottomed eclipse. Further photometric results are needed to check for a depth difference between bands, which would suggest some kind of eclipsing binary system. RV results are also being awaited. The lightcurve of KS32C06806 showed the egress of an event occurring at the predicted time. The AstroImageJ fit, given a fixed transit center, appears somewhat “U” shaped, but not flat-bottomed. The scatter from this set was too great to be conclusive. Follow-up photometry with better signal to noise showed this target having a sinusoidal lightcurve. The last “U” shaped lightcurve discussed in this chapter was for target KS24C007628. There was a more-or-less flat bottom to the eclipse and no depth difference between bands was shown. RV is also being awaited for this target.
Spectroscopic results

All of the spectroscopic observations made using the 1 – m telescope with HERCULES are detailed in Appendix A, Table A.2. Two KELT-South planetary candidates were observed: KS17C00302 (HD 113204) and KS17C00596 (HD 9468). Details about the observational method and post-processing pipeline are presented in Chapter 2, Section 2.2. The post-processing pipeline resulted in reduced spectra for each observation.

The resulting spectra were then processed using cross-correlation, for which the code can be found in Appendix D. This computed the cross-correlation between stellar spectra, comparing the first observation with the following observations, to measure the shift in the spectral lines. The spectra used were cropped so that spectral lines from the atmosphere (areas of the spectrum with large amounts of telluric contamination) were not included in the cross-correlation. The region of the stellar spectra that was cross-correlated was the 5000 – 5500 Å range for both targets. The resulting spectra, superimposed onto the comparison spectra, can be seen in Appendix D. A second-order polynomial was fitted to the resulting cross-correlation function to find the peak. For each observation, the spectral line shifts were found from the difference between the peak location and the peak location in the first observation. RV values were calculated from the spectral line shift.

Radial velocities were also found by measuring the shift in the mean line profile of these spectra. A second-order polynomial was fit to the trough of the line profile in order to find the radial velocity shift.

Sinusoidal curves were then fitted to the derived radial velocity values. The curves were of the form

$$v(t) = a_0 + a_1 \sin(2\pi t / T) + b_1 \cos(2\pi t / T), \quad (5.1)$$

where $a_0$, $a_1$, and $b_1$ are the fitted coefficients and $T$ is the period of the orbital systems. From the amplitude ($A = \sqrt{a_1^2 + b_1^2}$) of the fitted RV curve, conclusions about the mass of the predicted companion were made.
The mass ($M$), or rather the projected mass ($M \sin i$), of the predicted planet was found using the following derivation.

If two bodies are in a stable orbit then their momenta (where $P_s$ is the momentum of the star and $P_p$ is the momentum of the planet) about the centre of mass can be equated:

$$P_p = P_s$$

$$M_p \dot{v}_p = M_s \dot{v}_s.$$  \hfill (5.2)

Because the radial velocities are found along the line-of-sight, the Eq. 5.2 needs to be broken down into its line-of-sight components:

$$M_p v_p \sin i = M_s v_s \sin i,$$  \hfill (5.3)

$$M_p \sin i = \frac{M_s v_s \sin i}{v_p}.$$  \hfill (5.4)

where $i$ is the inclination of the orbit to the line-of-sight.

The velocity of the planet can be found by equating the centripetal force with the gravitational force (as is true for orbiting bodies on circular orbits),

$$\frac{M_p v_p^2}{r} = \frac{G M_p M_s}{r^2}$$  \hfill (5.5)

where $r$ is the planet’s orbital radius and $G$ is the gravitational constant. Thus

$$v_p = \sqrt{\frac{GM_s}{r}}.$$  \hfill (5.6)

The unknown radius of the planet’s orbit can be found through the use of Kepler’s third law, assuming a circular orbit for which the semi-major axis is the radius ($a = r$);

$$\frac{T^2}{a^3} = \frac{4\pi^2}{G(M_s + M_p)} = \frac{T^2}{r^3},$$  \hfill (5.7)

where $T$ is the planet’s orbital period. Therefore, the orbital radius is given by

$$r^3 = \frac{T^2 G(M_s + M_p)}{4\pi^2}.$$  \hfill (5.8)
Because $M_p \ll M_s$, the $M_p$ term in Eq. 5.8 is assumed to have negligible impact on the result for the planet’s orbital radius,

$$r \simeq \sqrt[3]{\frac{T^2 G M_s}{4\pi^2}}. \quad (5.9)$$

Substituting Eq. 5.9 into Eq. 5.6 gives the velocity of the planet;

$$v_p \simeq \sqrt{\frac{GM_s}{\left(\frac{T^2 G M_s}{4\pi^2}\right)^{1/3}}} = \sqrt[3]{\frac{G M_s 2\pi}{T}}. \quad (5.10)$$

Further substitution of Eq. 5.10 into Eq. 5.4 results in an equation for the projected mass of a planet.

$$M_p \sin i = v_s \sin i \sqrt[3]{\frac{M_s T}{G 2\pi}} \quad (5.11)$$

where $v_s \sin i$ is the amplitude of the sinusoidal curve fitted to RV data. The period of the fitted curve also gives the orbital period of the system, $T$. The mass of the host star, $M_s$, was found from its spectral type.

### 5.1 HD 113204

HD 113204 (right ascension $13^h 2^m 25.40^s$; declination $-29^\circ 15' 55.9''$) is a $V = 7.071$ star of spectral type A2V C ($T_{\text{eff}} = 8222$ K).

![Figure 5.1: Survey data for KS17C000302 (HD 113204) phased to the BLS period (Pepper, 2016).](image_url)

The photometry results for HD 113204, from the KELT-South survey data, can be seen in Fig. 5.1. These results are plotted according to phase. The KELT-South survey
members find these periods using box least squares (BLS) on the survey data (Kovács et al., 2002). The BLS fit gives the orbital period as 9.66 days. The BLS-determined transit depth is 17.5 mmag, with a calculated companion planet radius of 2.11 $R_\oplus$ and a transit duration of 6.95 hours.

Radial velocities found from the cross-correlation of spectra and shift in line profile are displayed in Fig. 5.2. The RV curve is unconstrained and requires more data for a meaningful analysis. Nevertheless, the fitted RV curves were used to place bounds on the mass of the prospective planet.

The relative radial velocities found using cross-correlation were between -1.6 and 0.0 km/s. The coefficients of the fitted sinusoidal curve (Eq. 5.1) are displayed in the first column of Table 5.1, where the period used was $T = 9.66 \text{d}$. The orbital period for this system is 9.66 days ($T = 834624 \text{s}$) according to the BLS period found from the KELT survey data. Given the small number of observations, the sinusoidal curve fit to this data used a fixed period (9.66 days). This curve has an amplitude of 780 m/s. For the purpose of later mass calculations, this amplitude will be called $A_{\text{spec}}$ ($A_{\text{spec}} = 780 \text{m/s}$). The relative radial velocities (relative to the first radial velocities so that they are comparable...
Table 5.1: Fitted sinusoidal curve (see Eq. 5.1) coefficients for RV data of star HD 113204 found using the BLS-period of $T = 9.66\text{d}$. The first column demonstrates the fit for the RV measurements obtained through cross-correlation of selected regions of the stellar spectra. The second column contains information about the curve fitted to the RV measurement obtained by investigating the shift in the mean line profile.

<table>
<thead>
<tr>
<th></th>
<th>Spectra (m/s)</th>
<th>Line profiles (m/s)</th>
</tr>
</thead>
<tbody>
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<td>$a_0$</td>
<td>$(5.3 \pm 0.9) \times 10^3$</td>
<td>$(3.9 \pm 1.5) \times 10^3$</td>
</tr>
<tr>
<td>$a_1$</td>
<td>$(0.6 \pm 1.2) \times 10^3$</td>
<td>$(3.1 \pm 2.2) \times 10^3$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$(0.5 \pm 0.7) \times 10^3$</td>
<td>$(1.2 \pm 0.8) \times 10^3$</td>
</tr>
<tr>
<td>$A$</td>
<td>$780 \pm 1370$</td>
<td>$3310 \pm 2350$</td>
</tr>
</tbody>
</table>

The amplitudes of the radial velocity functions give the maximum velocity of the star away from the earth, along our line of sight, when corrections have been made to exclude systemic velocity and barycentric movement. The amplitude, $A$, is related to the velocity of the star in the following way:

$$A = v_{\text{star}} \sin i.$$  \hspace{1cm} (5.12)

As an A2V C spectral type star, the host star has a mass of $M_* = 2.5M_\odot = 5 \times 10^{30}\text{kg}$ (Lang, 1991). The mass of the planet, for each amplitude value, was found using the above star-planetary system information and Eq. 5.11. Using the amplitude $A_{\text{spec}} = 780\text{m/s}$, the projected mass of the planet was found to be

$$M_p \sin i = 2.9 \times 10^{28}\text{kg} = 15M_\oplus.$$ \hspace{1cm} (5.13)

However, the amplitude $A_{\text{line}} = 3310\text{m/s}$ resulted in a planet mass of

$$M_p \sin i = 1.2 \times 10^{29}\text{kg} = 64M_\oplus.$$ \hspace{1cm} (5.14)
These projected mass calculations both support the conjecture of a planet in the system and they reiterate the need for more data.

5.2 HD 9468

Spectroscopic target HD 9468 (right ascension $1^h31^m33.8^s$; declination $-59\degree35'33.1''$) has a visual magnitude of 7.975. It is of the F5V C spectral type and has an effective temperature of 6466 K.

![Image](image.png)

**Figure 5.3:** Survey data for KS17C00596 (HD 9468) phased to the BLS period (Pepper, 2016).

Figure 5.3 contains the survey data, phased according to the BLS results. The BLS fit has the orbital period at 1.86 days. The BLS determined transit depth is 2.9 mmag, with a calculated companion planet radius of $0.66 R_J$ and a transit duration of 1.65 hours.

Attempts were made to fit a period to the RV measurements of HD 9468. However, this star is quite dim and, given that the results of this period fitting exercise did not agree with each other or the BLS fitted period from the KELT survey photometry, the fitted period may well be the result of spurious RV data. The Lomb-Scargle periodograms for each set of RV data can be seen in Figures 5.4 and 5.5, while the results of some other attempts to fit a period to the RV data are briefly touched on in Appendix D.1.

The Lomb-Scargle periodograms (??) show the power spectral density (PSD) of different frequencies. The peak of the periodogram from the cropped-spectra-cross-correlation RV measurements (Fig. 5.4) was at $\log_{10}(1/d) = -1$ or rather 10 days. Given that the observations occur over 9 days, this does not seem a likely period for the system and its significance is likely due to the mean RV being non-zero. The peak in the periodogram
Figure 5.4: Lomb periodogram of the cross-correlated cropped spectra RV data for HD 9468. The blue dash line indicates the log frequency correlating to KELT BLS fitted period.

found using the shift-in-line-profile RV measurements occurs at 4.53 days. The is very close to the 2nd highest peak in PSD of the other periodogram, which occurs at a period of 4.39 days. In fact it seems that most of the peaks seen in the periodograms are echoed in by each other. This again may be spurious results, due to the fact that both sets of measurement have the same Julian date. The log frequency corresponding to the BLS period fitted to the KELT survey photometry period is demonstrated on the graphs with a blue dashed line. This matches a local peak in both periodograms, however it is one of the smaller peaks in both instances. The results for a fitted period are, again, rather unconvincing. Given the sheer number of KELT observations, the prudent approach would be to use the BLS fitted KELT period as the period of the system for all further analysis; further analysis on the sets of RV measurements were performed assuming a period of 1.86 days.

RV measurements using both the spectra cross-correlation and mean line profile shift methods are displayed in a phased plot in Fig. 5.6. The radial velocities found from the cross-correlation of cropped spectra are in blue with the corresponding fitted sinusoidal
Figure 5.5: Lomb periodogram of line profile RV data for HD 9468. The blue dash line indicates the log frequency correlating to KELT BLS fitted period.

Table 5.2: Fitted sinusoidal curve (see Eq. 5.1) coefficients for RV data of star HD 9468 found using the BLS-period of $T = 1.86\, \text{d}$. The first column demonstrates the fit for the RV measurements obtained through cross-correlation of selected regions of the stellar spectra. The second column contains information about the curve fitted to the RV measurements obtained by investigating the shift in the mean line profile.

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<tr>
<th></th>
<th>Spectra</th>
<th>Line profiles</th>
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<tr>
<td>$a_0$</td>
<td>$(0.1 \pm 1.9) \times 10^3$</td>
<td>$(-2.4 \pm 8.9) \times 10^3$</td>
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<tr>
<td>$a_1$</td>
<td>$(0.8 \pm 2.1) \times 10^3$</td>
<td>$(1.0 \pm 10.6) \times 10^3$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$(-1.7 \pm 3.9) \times 10^3$</td>
<td>$(15 \pm 15) \times 10^3$</td>
</tr>
<tr>
<td>$A$</td>
<td>1878 m/s</td>
<td>14867 m/s</td>
</tr>
</tbody>
</table>

curve also in blue. This curve is of the form shown in Eq. 5.1 with the coefficients displayed in the first column of Table 5.2. The RV measurements obtained from the shift in minima of the line profiles of each observation are also displayed in the phased figure (Fig. 5.6), but these are in red with the corresponding fitted sinusoidal curve also in red. This curve can be described by the coefficient in the second column of Table 5.2 and is also of the form described in Eq. 5.1. Both fitted sinusoidal curve use the BLS-period of $T = 1.86\, \text{d}$. 
These fits are wildly different with almost opposite phase, and the coefficients of the fits have uncertainties that are often greater than the coefficient value itself. Instead of using one of these likely erroneous curves to find the mass of the planet, an upper mass limit was put on the planet instead. Given that a significant signal was not found in the RV data for this star, the velocity of the star is limited to the spread of the data; the noise in the data must be greater than the RV variations caused by an orbiting companion. The variation has an upper limit, which is the standard deviation of the data. The standard deviations of the RV measurement were 31.81 km/s and 29.01 km/s for the cross-correlated spectra and line profile shifts respectively.

Using these standard deviations as the upper limit for \( v_{\text{star} \sin i} \), the upper mass limit of a planetary companion orbiting this F5 V dwarf star was found.

The mass of a typical F5 V dwarf star is 1.4 solar masses; \( M_\text{st} = 1.4M_\odot = 2.8 \times 10^{30} \text{kg} \) (Lang, 1991). The upper mass limits were found using Eq. 5.11 and for the cross-correlated-spectra RV data \( v \sin i = \sigma_{\text{RV}} = 31.81 \text{km/s} \)

\[
M_p \sin i < 4.59 \times 10^{26} \text{kg}, \quad (5.15)
\]
and for the RV data using the shift in line profiles, $v\sin i = \sigma_{RV} = 29.01\text{km/s}$

$$M_p\sin i < 4.19 \times 10^{26}\text{kg} \quad (5.16)$$

The upper mass limit of a companion orbiting HD 9468 is therefore $4.19 \times 10^{26}\text{kg}$ or rather $0.24M_\odot$.

### 5.3 Summary

The two KELT planetary candidates KS17C000302 (HD 113204) and KS17C00596 (HD 9468) were observed spectroscopically. The raw images were processed to obtain 36 sets of reduced spectra. These spectra were compared using cross-correlation to gain RV measurements, which were then fitted with a sinusoidal curve in an attempt to resolve a varying RV signal.

The photometric KELT survey data for HD 113204 demonstrates a dip in brightness occurring at a BLS determined frequency consistent with a $2.11R_\odot$ companion. The RV data collected for this target tentatively suggests a companion, though more data is needed to confirm this.

A sinusoidal curve could not be fit convincingly to the HD 9468 RV data. Given the spread of the RV measurements obtained, an upper mass limit for the potential planet of $M\sin i = 0.22M_\odot$ was found (using the same assumption previously mentioned). The photometric data for this star from the KELT survey, phased to the BLS determined period, has a dip in brightness which would correspond to a $0.66R_\odot$ companion.

The high scatter on these RV sets is due to both targets, especially HD 9468, being quite dim for targets observed using the 1m, despite being some of the brightest KELT candidates. Collecting data on a larger telescope, such as the South African Large Telescope (SALT), would resolve the high scatter issues. The fitting of future spectroscopic data could be improved by allowing for eccentric orbits. In data such as this, with few point and relatively high scatter, it hardly seems a necessary endeavour.
Chapter 6

Summary

The search for exoplanets is important for understanding the formations and structure of planetary systems. The targets that offer up the most information are transiting planets, due to our ability to find their radii from the lightcurves of their transits, and, in some cases, study their atmospheres through transmission spectroscopy. Conclusions about mass can also be made using spectroscopic techniques to measure radial velocities. In-transit spectroscopy of exoplanets allows the inclination of the planets orbit to be found through use of the Rossiter-McLaughlin effect.

Transit surveys have been used to find more exoplanets than any other detection method. One such transit survey is the KELT (Kilo-degree Extremely Little Telescope) project. All data obtained and discussed in this thesis was done so as part of the KELT-South collaboration.

6.1 Model fitting

A model fitting program was developed, which used MCMC to find the phase and depth of the transits observed as well as finding the radius of the star and planet, and the airmass contribution. The same data set used in development of this program was then fitting using AstroImageJ. Similar results were obtained for ideal data sets, however AstroImageJ drastically out performs this program in any non-ideal situation.

The program demonstrated the benefits of MCMC fitting techniques as well as the importance or proper detrending techniques and parametrisation of a model.
6.2 Photometry

Survey telescope view wide fields, often resulting in densely populated pixels and relatively low signal-to-noise data. Follow-up photometry is a necessary part of narrowing down candidates list and working towards candidate conformation. Follow-up photometry can rule out imposter eclipsing binaries and occasions where candidates have been found only as a result of spurious data.

Seventeen lightcurves were obtained for fifteen KELT-South planetary candidate targets. Of these, four did not show signs of a transit occurring. The reason for this was that, in some extreme cases, the spread of the data was too great to see the small dip in brightness created by the transit. Otherwise, the likely cause of the false positive was spurious data. Five of the lightcurves obtained showed signs of being a blended eclipsing binary or grazing eclipsing binary, be this through the “V” shape of the transit lightcurve or chromaticity during transit (planetary transit have the same transit depth in all filter colours but binary star system eclipses usually have varying depths in the different bands due to the different temperatures of the two stars). This leaves eight targets that have not been ruled out as false positives and are awaiting RV and further spectroscopic results order to be confirmed as having a planetary systems or ruled out as being false-positives.

6.3 Spectroscopy

Two KELT-South planetary candidates were spectroscopically observed. These were HD 113204 and HD 9468. Using cross-correlation (the MATLAB code for this can be found in Appendix D), the radial velocities for each observation were able to be found. A curve was able to be fit to the radial velocity data from HD 113204, but not to the HD 9468 data. The same method of fitting was used for both targets but the resulting fits for HD 9468 were not at all convincing, because ... . From the fitted curve, the mass of HD 113204 was calculated to be ... . The spread of the data from HD 9468 was used to find the upper mass limit as $M \sin i = 0.22 M_\oplus$. These observations were performed to aid with the KELT-South spectroscopic follow-up of targets found during the KELT-South survey.
6.4 Future work

Future work on the modelling aspect of this project could be done to model the movement of the planet in front of the star by an orbit instead of the constant velocity in a straight line currently assumed, to create a more accurate model. Further work on detrending of the data sets would also allow for more exact models to be found with the MCMC process. Applying these adaptations to the model fitting program would open up the opportunity to investigate different limb-darkening “laws”.

Incorporating the KELT-South survey data into the model fitting process, in a weighted manner, may also provide more accurate lightcurves, and resolve issues with partial transits. From this, more decisive conclusions can be made about limb darkening effects.

Photometric data will continue to be collected for this follow-up, with one third of the Optical Craftsman’s telescope time being allocated to this project.

The University of Canterbury will soon be able to request telescope time on the South African Large Telescope (SALT). Spectroscopic data from the SALT telescope may result in high enough signal to noise on the relatively dim KELT-South targets to obtain data demonstrating the Rossiter-McLaughlin effect, so that the inclination of planetary orbits can be found.
Observation record

A.1 Photometry

TABLE A.1: Record of all photometry observations requested on OC61. Large periods spent not requesting observations were due to telescope repairs or upgrades. For example, most of March 2015 was spent upgrading OC61 to an automated telescope.

<table>
<thead>
<tr>
<th>Date</th>
<th>Target ID</th>
<th>Attempt no.</th>
<th>Observed</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
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<td>Yes</td>
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<tr>
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<td>1</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>24-03-2015</td>
<td>KS24C007628</td>
<td>1</td>
<td>Yes</td>
<td></td>
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<tr>
<td>26-03-2015</td>
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<td>Yes</td>
<td></td>
</tr>
<tr>
<td>27-03-2015</td>
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</tr>
<tr>
<td>01-04-2015</td>
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<td>Queued on wrong night</td>
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<tr>
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<td>No</td>
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</tr>
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<td>No</td>
<td></td>
</tr>
<tr>
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<td>No</td>
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<tr>
<td>02-05-2015</td>
<td>KS34C047274</td>
<td>2</td>
<td>Yes</td>
<td>Late to start</td>
</tr>
</tbody>
</table>
Table A.1: Record of all photometry observations requested on OC61. Large periods spent not requesting observations were due to telescope repairs or upgrades. For example, most of March 2015 was spent upgrading OC61 to an automated telescope.

<table>
<thead>
<tr>
<th>Date</th>
<th>Target ID</th>
<th>Attempt no.</th>
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<td>Yes</td>
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</table>
TABLE A.1: Record of all photometry observations requested on OC61. Large periods spent not requesting observations were due to telescope repairs or upgrades. For example, most of March 2015 was spent upgrading OC61 to an automated telescope.

<table>
<thead>
<tr>
<th>Date</th>
<th>Target ID</th>
<th>Attempt no.</th>
<th>Observed</th>
<th>Comment</th>
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Table A.1: Record of all photometry observations requested on OC61. Large periods spent not requesting observations were due to telescope repairs or upgrades. For example, most of March 2015 was spent upgrading OC61 to an automated telescope.

<table>
<thead>
<tr>
<th>Date</th>
<th>Target ID</th>
<th>Attempt no.</th>
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<th>Comment</th>
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<td>Cloud/wind</td>
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</table>
TABLE A.1: Record of all photometry observations requested on OC61. Large periods spent not requesting observations were due to telescope repairs or upgrades. For example, most of March 2015 was spent upgrading OC61 to an automated telescope.

<table>
<thead>
<tr>
<th>Date</th>
<th>Target ID</th>
<th>Attempt no.</th>
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<th>Comment</th>
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A.2 Spectroscopy

TABLE A.2: Record of all spectroscopic observations made. Some observations were made with other observers for training purposes. The RA and Dec mentioned here are those that were displayed on the telescope controls.

<table>
<thead>
<tr>
<th>UTC start</th>
<th>Spectrum type</th>
<th>Assosiated star</th>
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<td>06:30:42</td>
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<td>5</td>
</tr>
<tr>
<td>06:34:20</td>
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<td>HD 113201</td>
<td>1800</td>
</tr>
<tr>
<td>12:13:27</td>
<td>Thorium</td>
<td>HD 113201</td>
<td>5</td>
</tr>
<tr>
<td>12:15:33</td>
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<td>HD 113201</td>
<td>1800</td>
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Table A.2: Record of all spectroscopic observations made. Some observations were made with other observers for training purposes. The RA and Dec mentioned here are those that were displayed on the telescope controls.

<table>
<thead>
<tr>
<th>UTC start</th>
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<th>Exposure (s)</th>
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<td>1800</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>13:03:13 -29:21:00</td>
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<tr>
<td>07:03:24</td>
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</tr>
<tr>
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<td>13:03:11 -29:22:00</td>
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<tr>
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<td>Date: 2015 October 24</td>
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### Table A.2: Record of all spectroscopic observations made. Some observations were made with other observers for training purposes. The RA and Dec mentioned here are those that were displayed on the telescope controls.

<table>
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<th>UTC start</th>
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<th>Exposure (s)</th>
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<td>β Aquarii</td>
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<td>60</td>
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### Table A.2: Record of all spectroscopic observations made. Some observations were made with other observers for training purposes. The RA and Dec mentioned here are those that were displayed on the telescope controls.

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Appendix A. Observation record

Table A.2: Record of all spectroscopic observations made. Some observations were made with other observers for training purposes. The RA and Dec mentioned here are those that were displayed on the telescope controls.

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Date: 2015 November 1  
Observer: Amber Malpas

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### Table A.2: Record of all spectroscopic observations made. Some observations were made with other observers for training purposes. The RA and Dec mentioned here are those that were displayed on the telescope controls.

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Appendix B

Model fitting program

```python
# Basic Fit Model for Transit Data
""" This script is for creating a basic exoplanet transit fit with linear
parameters m_0 and d """

# Importing relevant modules
import numpy as np
from csv import reader
from numpy import linalg as LA
import matplotlib as MATLAB
from matplotlib import pyplot as MAT

# Minimising Xi^2

def LS_matrix_solve(M_, sigma_, t_ing, t_egr, data_reps):
    """ maximises Xi^2 to find the constants m_0 and d for given t_ing and t_egr.
M_ is the flux of the target star
sigma_ is the error on M_
t_ing is the index for ingress in the data
t_egr is the index for egress in the data
data_reps is the length of the data lists (use len(data)) """

    ones_ = np.ones(data_reps)
    ones_ = np.matrix(ones_)
    A_i = np.divide(ones_, np.power(sigma_, 2)) # all values
    if t_egr == data_reps: # just in-transit values
        A_i_in = A_i[:,t_ing:]
    else:
        A_i_in = A_i[:,t_ing:t_egr+1]

    A_11 = -1 * A_i_in.sum()
    A_12 = A_i_in.sum()
    A_21 = -1 * A_i_in.sum()
    A_22 = -1 * A_i_in.sum()

    b_i = np.divide(M_, np.power(sigma_, 2)) # all values
    if t_egr == data_reps: # just in-transit values
        b_i_in = b_i[:,t_ing:]
    else:
        b_i_in = b_i[:,t_ing:t_egr+1]

    b_1 = -1 * b_i_in.sum()
    b_2 = b_i_in.sum()
```

133
\[ A_2 = np.array((A_{21}, A_{22})), \] #these matricies maximise
\[ b_2 = np.array((b_{21}, b_{22})). \] #Chi^2

if LA.det(A) == 0:
    return 0, 0, True
else:
    x = LA.solve(A, b)
    m_0 = x.item(0)
    d = x.item(1)
    return m_0, d, False

#The fit model function (there is surely a better way of doing this)
def build_model(t_ing, t_egd, data_length, m_0, d):
    'Builds the model data given the necessary parameters
    t_ing is the index to the point of ingress in the data
    t_egd is the index to the point of egress in the data
    data_length is the length of the data vectors (use len(data))
    m_0 is the magnitude of the baseline values
    d is the depth of the transit'
    m_t = []
    for t in range(data_length):
        if t < t_ing:
            m_t.append(m_0)
        if t_ing <= t and t <= t_egd:
            m_t.append(m_0 - d)
        if t_egd < t:
            m_t.append(m_0)
    return m_t

#Xi^2
def calc_Xi_sqrd(M, m_t, sigma):
    'Calculates Xi^2 for a given model (m_t) and flux data M with error
    sigma.'
    sigma_sqrd = np.power(sigma, 2)
    Xi_sqrd = np.divide(np.power((M - m_t), 2), sigma_sqrd)
    Xi_sqrd = Xi_sqrd.sum()
    return Xi_sqrd

#Input of file path
file_path_entered = 'No'
while file_path_entered == 'No':
    file_path = raw_input('Enter file path to photometry data (.csv): ')
    #/home/amber/Desktop/Thesis/Data/KS24C007628/26-03-2015/Michael/Measurements.csv

#Shortcut to my Data folder
if file_path == '/Data':
    file_path = '/home/amber/Desktop/Thesis/Data/Measurements.csv
    #/KS24C007628/26-03-2015/Michael/Measurements.csv

#Typical case on my computer
if file_path == 'Amber' or file_path == 'amber':
    target = raw_input('Target:').upper()
    date = raw_input('Date (dd-mm-yyyy): ')
    file_path = '/home/amber/Desktop/Thesis/Data/' + target + '/' + date + '/Measurements.csv'
if file_path.endswith(' .csv') == True:
    file_path_entered = 'Yes'
else:
    print 'Please enter a valid file path'
    file_path_entered = 'No'

# Importing Data
imported_file = open(file_path, 'rb')
read_file = reader(imported_file, delimiter = ',')
labeled_data = [row for row in read_file]
data = labeled_data[1:]
labels = labeled_data[0]
print 'Your data has been imported
Processing data'

# Building empty lists
JD UTC = [] # t
rel_flux_err_T1 = [] # sigma
rel_flux_T1 = [] # M

# Converting data to lists of floats, then vectors
for i in range(len(data)):
    row = data[i]
    JD UTC.append(row[5]) # t
    rel_flux_err_T1.append(row[19]) # sigma
    rel_flux_T1.append(row[11]) # M
JD UTC = map(float, JD UTC)
rel_flux_err_T1 = map(float, rel_flux_err_T1)
sigma_ = np.matrix([rel_flux_err_T1])
rel_flux_T1 = map(float, rel_flux_T1)
M_ = np.matrix([rel_flux_T1])

# Looping over t_in and t_eg
X_i_sqr = np.zeros((len(data), len(data)))
count = [0, 0]
for t_in in range(len(data)):
    for t_eg in range(len(data)):
        if t_in < t_eg:
            m_0, d, singular = LS_matrix_solve(M_, sigma_, t_in, t_eg, len(data))
            if singular == True:
                X_i_sqr[t_in, t_eg] = np.NAN
            else:
                m_t = build_model(t_in, t_eg, len(data), m_0, d)
                X_i_sqr = calc_Xi_sqr(M_, m_t, sigma_)
```python
X_i_sqrd_mat[t_ing, t_egr] = X_i_sqrd
else:
    X_i_sqrd_mat[t_ing, t_egr] = np.NAN
print 'Matrix of Xi^2 has been built:\n', X_i_sqrd_mat

# Finding t_ing and t_egr that minimise Xi^2
NAN = np.NAN
t_ing = 0
t_egr = 0
Xi_min = X_i_sqrd_mat.item(1)

for i in range(len(data)):
    for j in range(len(data)):
        if X_i_sqrd_mat.item((i, j)) != NAN:
            if X_i_sqrd_mat.item((i, j)) <= Xi_min:
                t_ing = i
                t_egr = j
                Xi_min = X_i_sqrd_mat.item((i, j))
            if X_i_sqrd_mat.item((i, j)) == 0.:
                print 'zero found at ', pos
print 'The minimum Xi^2 for this data is: ', Xi_min
print 'The duration of the transit is: ', t_egr - t_ing, ' slices'

# Re-calculating final parameter values
m_0, d, singular = LS_matrix_solve(M, sigma, t_ing, t_egr, len(data))
print 'The base-line flux is: ', m_0
print 'The depth of the transit is: ', d
m_t = build_model(t_ing, t_egr, len(data), m_0, d)

# Graphing data with fit
title = raw_input('Title of graph: ')
MAT.figure(1)
MAT.plot(JDUTC, m_t, 'k-')
MAT.plot(JDUTC, rel_flux_T1, 'b.
MAT.errorbar(JDUTC, rel_flux_T1, rel_flux_err_T1, None, None)
MAT.xlabel('Julian Date (UTC)')
MAT.ylabel('Relative flux of target star')
MAT.title(title)
```

LISTING B.1: Python code for fitting a step function to the transit data using LS.

---

# Basic Fit Model for Transit Data with Airmass Included
'''
This script is for creating a basic exoplanet transit fit with linear parameters m_0, d, and c solved for in MCMC'''

# Importing relevant modules
import numpy as np
from csv import reader
from numpy import linalg as LA
import matplotlib as MATLAB

```
from matplotlib import pyplot as MAT
import emcee
import scipy.optimize as op
import triangle
figno = 0

# Functions
def import_data(file_path):
    imported_file = open(file_path, 'rb')
    read_file = reader(imported_file, delimiter = ',')
labeled_data = [row for row in read_file]
data = labeled_data[1:]  
labels = labeled_data[0]
print labels

JD_index = labels.index('JD UTC')
T1_err_index = labels.index('rel flux err T1')
T1_index = labels.index('rel flux T1')
airmass_index = labels.index('AIRMASS')
exp_index = labels.index('EXPTIME')

print 'DATA IMPORTED'

# Building empty lists
JD.UTC = []  # t
rel_flux.err.T1 = [] # sigma
rel_flux.T1 = []   # M
AIRMASS = []  # airmass
exp = []  # exposure time

# Converting data to lists of floats, then vectors
for i in range(len(data)):
     row = data[i]
     JD.UTC.append(row[JD_index])  # t
     rel_flux.err.T1.append(row[T1_err_index]) # sigma
     rel_flux.T1.append(row[T1_index])   # M
     AIRMASS.append(row[airmass_index])  # airmass
     exp.append(row[exp_index])  # exposure time

print JD.UTC, rel_flux.err.T1, rel_flux.T1, AIRMASS, exp

t_ = mapmat(JD.UTC)
I = mapmat(rel_flux.T1)
M_ = np.multiply(-2.5, np.log10(I))
sigma_ = mapmat(rel_flux.err.T1)
M_max = np.multiply(-2.5, np.log10(I-sigma_))
M_min = np.multiply(-2.5, np.log10(I+sigma_))
sigma_ = np.divide(M_max - M_min, 2)
airmass_ = mapmat(AIRMASS)
exp = map(float, exp)
exp = exp[1]
```python
return JD.UTC, t., I, M, sigma., airmass., exp

def build_model(theta, airmass.):
    """ Builds the model data given the necessary parameters
    t.ing is the index to the point of ingress in the data
    t.eg is the index to the point of egress in the data
    data_length is the length of the data vectors (use (len(data)))
    m0 is the magnitude of the base-line values
    d is the depth of the transit
    """
    m_t = []
t.ing, t.eg, D, m0, d, C = theta

    for t in range(len(airmass_.tolist()[0])):
        m_t.append(m0 + C * airmass_.item(t))
        if t < t.ing or t > t.eg + D:
            # baseline

        if t.ing + D <= t and t <= t.eg:
            m_t.append(m0 + d + C * airmass_.item(t))
            # transit

        if t.ing < t and t <= t.ing + D:
            m_t.append(m0 + d * (t - t.ing) / D + C * airmass_.item(t))
            # ingress

        if t.eg < t and t <= t.eg + D:
            m_t.append(m0 + d * (D - t + t.eg) / D + C * airmass_.item(t))
            # egress

    return m_t[:len(airmass_.tolist()[0])]

def calc_Chi2(M., m_t, sigma.):
    """ Calculates Xi^2 for a given model (m_t) and flux data M. with error
    sigma. """
    sig2_ = np.power(sigma., 2)
    Chi2 = np.divide(np.power((M. - m_t), 2), sig2_)
    Chi2 = Chi2.sum()
    return Chi2

def lnprior(theta, t.f):
    """ Checking prior for lnlike """
    t.ing, t.eg, D, m0, d, C = theta
    t.ing = int(t.ing)
    t.eg = int(t.eg)
    D = int(D)

    print '\nIngress = slice ', int(t.ing), '; Egress = slice ', int(t.eg), ';
    Ingress/Egress duration = ', int(D), ' slices; Transit depth = ', int(d*10000)
    /10.0, ' mmag; Baseline = ', int(m0*1000)/1000.0, ' mag; Airmass contribution
    factor = ', int(C*10000)/10000.0,

    if t.ing + D <= t.eg and 2 * D <= t.f and D>=0.0 and C >= 0.0 and t.eg + D <=
    t.f and d>=0:
        return 0.0
    else:
        print '!
        return -np.inf

def lnlike(theta, M., sigma., airmass.):
    """ Likelihood """
    m_t = build_model(theta, airmass.)
    Chi2 = calc_Chi2(M., m_t, sigma.)
    return -0.5 * Chi2
```

Appendix B. Model fitting program

```python
def lnprob(theta, M_, sigma_, airmass_):
    """ posterior probability """
    t_f = len(M_.tolist()[0])
    lp = lnprior(theta, t_f)
    if np.isfinite(lp):
        return -np.inf
    return lp + llike(theta, M_, sigma_, airmass_)

def MCMC(dim, walkers, iters, args, theta1, burn):
    nll = lambda *args: -llike(*args)
    result = opt.minimize(nll, theta1, args=(M_, sigma_, airmass_))
    print '\n\nMCMC SAMPLES:
'
    pos = [result['x'] + 1e-4 * np.random.rand(dim) for i in range(walkers)]
    sampler = emcee.EnsembleSampler(walkers, dim, lnprob, args=args)
    pos, prob, state = sampler.run_mcmc(pos, iters) # 100)
    samples = sampler.chain[:, burn:, :].reshape((-1, dim))
    print '\n\nMCMC COMPLETE\n'
    return nll, sampler, pos, prob, state, samples

def crop_baseline(Set, t_ing, t_egr, D):
    """ builds a set containing only the predicted baseline """
    A = Set[::, :t_ing]
    a = A.tolist()
    a = a[0]
    B = Set[::, t_egr + D:]
    b = B.tolist()
    b = b[0]
    baseline = np.matrix(a + b)
    return baseline

def mapmat(input_list):
    """ takes list of strings, containing only floats or ints, and converts to a matrix """
    input_list = map(float, input_list)
    output_mat = np.matrix([input_list])
    return output_mat

def vline(JD.UTC, slice_no, y_pos, colour, style, line_width, alpha, label, fontsize):
    """ draws an annotated vertical line """
    x = float(JD.UTC[int(slice_no)])
    MAT.axvline(x=x,
        color=colour,
        linestyle=style,
        lw=line_width,
        alpha=alpha)
    MAT.annotate(label,
        xy=(x, y_pos),
        xycoords='data',
        textcoords='data',
        fontsize=fontsize)
```

Appendix B. Model fitting program

```
arrowprops=None, # arrowprops=dict(arrowstyle="-|>"))
size=font_size,
color=colour)

def vspan(JD, slice_no, duration, colour, alpha):
    '''draws a line of thickness=duration on the graph with a selected opacity (0 >=
    alpha >= 1)'''
x1 = float(JD[int(slice_no)])
x2 = float(JD[int(slice_no + duration)])
MAT.axvspan(x1, x2, facecolor=colour, alpha=alpha)

def plot_model(JD, theta1, theta_mcmc, star, figno, airmass, M, sigma, size):
    '''plots the photometric data with initial guess for MCMC, a selection of MCMC
    lines, and the fit line using the posterior means of the MCMC.'''
    # Unpacking thetas
    t_ing_pred, t_eigr_pred, D_pred, m0_pred, d_pred, C_pred = theta1
    t_ing_mcmc, t_eigr_mcmc, D_mcmc, m0_mcmc, d_mcmc, C_mcmc = theta_mcmc

    # Updating figure number
    figno += 1
    MAT.figure(figno)

    # Predicted
    m_t_pred = build_model(theta1, airmass,)
    vline(JD, (t_ing_pred + D_pred / 2), 1.464, 'r', '—', 1, 1, 'predicted
    ingress',
    'small')
    vline(JD, (t_eigr_pred + D_pred / 2), 1.464, 'r', '—', 1, 1, 'predicted
    egress',
    'small')
    h1, = MAT.plot(JD, m_t_pred, 'r')

    # MCMC
    count = 1
    for t_ing, t_eigr, D, m0, d, C in samples[np.random.randint(len(samples)), size=]
        theta = [t_ing, t_eigr, D, m0, d, C]
        m_t = build_model(theta, airmass,)
        if count:
            h2, = MAT.plot(JD, m_t, 'k', alpha=0.08)
            count = 0
        else:
            MAT.plot(JD, m_t, 'k', alpha=0.08)

    # Posterior means
    m_t_mcmc = build_model(theta_mcmc, airmass,)
    h3, = MAT.plot(JD, m_t_mcmc, 'm', lw=1.5)

    # Ingress
    vline(JD, t_ing_mcmc, 1.462, 'm', '—', 1, 1, 'ingress \n (MCMC)',
    'small')
    vspan(JD, t_ing_mcmc, D_mcmc, 'm', 0.1)
    vline(JD, (t_ing_mcmc + D_mcmc), 1.462, 'm', '—', 1, 1, '', 'small')

    # Egress
    vline(JD, t_eigr_mcmc, 1.462, 'm', '—', 1, 1, 'egress \n (MCMC)',
```
## Uncomment one of these:
`file_path = '/home/amber/Desktop/Thesis/Data/KS24C007628/26-03-2015/Michael/Measurements.csv'`
`file_path = '/home/amber/Desktop/Thesis/Fit Model/Test Data Sets/test.csv'`
`file_path = 'C:\Users\Amber\Desktop\Fit Model\Measurements.csv'`
`file_path = 'C:\Users\Amber\Desktop\Fit Model\Test Data Sets\test.csv'`

```
# Importing Data
JD_UTC, t, I, M, sigma, airmass, exp = import_data(file_path)
```

```
# Predicted values
    d_pred = 10.0/1000 # 10 mmag in mag
Duration_pred = 2.25+0.06 # 2:30 in seconds - Duration of transit
Duration_pred = Duration_pred/(exp + 20) # Duration in slices. Read out time is 20s
D_pred = 6.0 # duration of ingress and egress
```
Listing B.2: Python code for fitting a piece-wise function to the transit data using MCMC. The piece-wise function models a square planet passing in front of the center of a square star of uniform brightness in a straight line at a constant speed.

```python
# Round planet MCMC

# Initial guess

# MCMC

dim = 6 # len(theta1)
walkers = 150
iters = 400
args = (M, sigma, airmass)
burn = 200

nll, sampler, pos, prob, state, samples = MCMC(dim, walkers, iters, args, theta1, burn)

t_ing_mcmc, t_egr_mcmc, D_mcmc, m_0_mcmc, d_mcmc, C_mcmc = map(lambda v: (v[1], v[2] - v[1], v[1] - v[0]), zip(*np.percentile(samples, [16, 50, 84], axis=0)))

theta_mcmc = [t_ing_mcmc[0], t_egr_mcmc[0], D_mcmc[0], m_0_mcmc[0], d_mcmc[0], C_mcmc[0]]

# Triangle plot of MCMC results

tri_labels = ["$t_{ing}$", "$t_{egr}$", "$SDS$", "$Sm_{0}$", "$Sd$", "$SCS$]
sfigno = triplot(samples, tri_labels, theta_mcmc, 'm', sfigno)

# Build final graph

size = 100
sfigno = plot_model(JD_utc, theta1, theta_mcmc, star, sfigno, airmass, M, sigma, size)

print '
PLOTTING COMPLETE'

print '
FINISHED'
```

# Importing relevant modules
import numpy as np
from csv import reader
from numpy import linalg as LA
from transit_modelling import *
import matplotlib.pyplot as MAT

figno = 0
model = 'RPBS' # Round Planet Box Star

# Import data
## Uncomment one of these:
file_path = '/home/amber/Desktop/Thesis/Data/KS24C007628/26−03−2015/Michael/Measurements.csv'
# file_path = '/home/amber/Desktop/Thesis/Fit Model/Test Data Sets/test.csv'
# file_path = 'C:\Users\Amber\Desktop\Fit Model\Measurements.csv'
# file_path = 'C:\Users\Amber\Desktop\Fit Model\Test Data Sets\test.csv'
star = 'KS24C007628'
date = '26−03−2015'

print '−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−'
print star, ':', date
print '−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−'

# Importing Data
JD_utc, t, I, M, sigma, airmass, exp = import_data(file_path)

# Predicted values

### CHANGE THESE!!!
d_pred = 10.0/1000 # 10 mmag in mag
Duration_pred = 2.25∗60∗60 # 2:30 in seconds − Duration of transit
Duration_pred = Duration_pred/(exp + 20) # Duration in slices. Read out time is 20s
D_pred = 10.0 # duration of ingress and egress
t_ing_pred = 30 # Time of ingress in slices
D_egr_pred = t_ing_pred + Duration_pred + D_pred
baseline_pred = crop_baseline(M, t_ing_pred, t_egr_pred, D_pred)
m_0_pred = baseline_pred.mean(1).tolist()

C_pred = 0.0 # maybe use aij value here
# print 'd_pred', d_pred, 'nD_pred', D_pred, 'nt_ing_pred', t_ing_pred, 'nt_egr_pred', t_egr_pred, 'nm_0_pred', m_0_pred, 'nC_pred', C_pred
d_pred = 10.0/1000 # 10 mmag in mag
Duration_pred = 2.25/24 # 2:25 in seconds − Duration of transit
Duration_pred_slice = Duration_pred∗24+60+60/(exp + 20) # Duration in slices. Read out time is 20s

ing_pred = 30 # ingress start slice number
D_pred_slice = 10 # duration of ingress and egress in slices
egr_pred = ing_pred + Duration_pred_slice + D_pred_slice # egress start slice number
D_pred = t[40] − t[30] # duration of ingress and egress
t_ing_pred = t_ing_pred + Duration_pred + D_pred
t_egr_pred = t_ing_pred + Duration_pred + D_pred
baseline_pred = crop_baseline(M, ing_pred, egr_pred, D_pred_slice)
m_0_pred = baseline_pred.mean(1).tolist()
Listing B.3: Python code for fitting a piece-wise function to the transit data using MCMC. The piece-wise function models a round planet passing in front of the center of a square star of uniform brightness in a straight line at a constant speed.
Appendix B. Model fitting program

---

This script models a circle planet transiting in front of a circle star directly through its center. The ideal parameters are found using MCMC. The MCMC posterior distributions of the MCMC parameters are plotted against each other and data is plotted with the model built from the posterior means.

### Importing relevant modules

```python
import numpy as np
from csv import reader
from numpy import linalg as LA
import matplotlib.pyplot as MAT
```

```python
figno = 0
model = 'RPRS' # Round Planet Round Star
```

# Path to data

```python
# Uncomment one of these or add a new one:
file_path = '/home/amber/Desktop/Thesis/Data/KS24C007628/26-03-2015/Measurements.csv'
# file_path = '/home/amber/Desktop/Thesis/Fit Model/Test Data Sets/test.csv'
# file_path = 'C:\Users\Amber\Desktop\Fit Model\Measurements.csv'
# file_path = 'C:\Users\Amber\Desktop\Fit Model\Test Data Sets\test.csv'
```

# Prints

```python
star = 'KS24C007628'
date = '26-03-2015'
```

```python
print '-----------------------------------------------'
print star, ';', date
print '-----------------------------------------------'
```

# Importing Data

```python
JD_UTC, t, I, M, sigma, airmass, exp = import_data(file_path)
```

# Creating the initial guess

```python
# Predicted values
```

```python
d_pred = 10.0/1000 # 10 mmag in mag
Duration_pred = 2.25/24 # 2.25*60*60 # 2:30 in seconds - Duration of transit
Duration_pred_slicer = Duration_pred*24*60*60/(exp + 20) # Duration in slices. Read out time is 20s
ing_pred = 30 # ingress start slice number
```
Appendix B. Model fitting program

D_pred_slice = 10  # duration of ingress and egress in slices
egr_pred = ing_pred + Duration_pred_slice + D_pred_slice  # egress start slice number
D_pred = t[40] - t[30]  # duration of ingress and egress
t_ing_pred = t[30]  # Time of ingress in slices
t_egr_pred = t_ing_pred + Duration_pred + D_pred
baseline_pred = crop_baseline(M, ing_pred, egr_pred, D_pred_slice)
m_0_pred = baseline_pred.mean(1).tolist()
m_0_pred = m_0_pred[0]
C_pred = 0.0  # maybe use aij value here

# Initial guess
theta0 = [t_ing_pred, t_egr_pred, D_pred, m_0_pred, d_pred, C_pred]

# MCMC (Prints model parameters while running)

# MCMC parameters
dim = 6  # len(theta1)
walkers = 150
args = (M, sigma, airmass, model)
burn = 1000
iters = burn + 500
print M

# Running MCMC
all, sampler, pos, prob, state, samples = MCMC(dim, walkers, iters, args, theta0, burn)

# Prints come from MCMC -> lnprob -> lnprior.
# Use if statement in lnprior to adjust acceptable ranges for parameters.
# e.g. t_ing + D <= t_egr, C >= 0.0, t_egr + D <= t_f.
# Parameters will be printed with a '!' if they are not to be accepted.

# Results of MCMC
theta_mcmc = [t_ing_mcmc[0], t_egr_mcmc[0], D_mcmc, m_0_mcmc, d_mcmc, C_mcmc = map(lambda v: (v[1], v[2]-v[1], v[1]-v[0]), zip(*np.percentile(samples, [16, 50, 84], axis=0)))

theta_mcmc = [t_ing_mcmc[0], t_egr_mcmc[0], D_mcmc[0], m_0_mcmc[0], d_mcmc[0], C_mcmc[0]]
theta_15th = [t_ing_mcmc[1], t_egr_mcmc[1], D_mcmc[1], m_0_mcmc[1], d_mcmc[1], C_mcmc[1]]
theta_84th = [t_ing_mcmc[2], t_egr_mcmc[2], D_mcmc[2], m_0_mcmc[2], d_mcmc[2], C_mcmc[2]]
variables = ['t_ing', 't_egr', 'D', 'm_0', 'd', 'C']

for i in range(len(theta_mcmc)):
    print variables[i], ' = ', theta_mcmc[i], '+/- ', theta_15th[i], '/', theta_84th[i]

# -----------------------------
# Plotting
Listing B.4: Python code for fitting a piece-wise function to the transit data using MCMC. The piece-wise function models a round planet passing in front of the center of a round star of uniform brightness in a straight line at a constant speed.
# file_path = '/home/amber/Desktop/Thesis/Data/KS26C026700/24-06-2015/Measurements.csv'
# file_path = '/home/amber/Desktop/Thesis/Data/KS24C007628/26-03-2015/Measurements.csv'
# file_path = '/home/amber/Desktop/Thesis/Data/KS24C007628/26-03-2015/Measurements2.csv'
# file_path = 'C:/Users/Asher/Desktop/Thesis/Fit Model/Test Data Sets/test.csv'
# file_path = 'C:/Users/Asher/Desktop/Thesis/Fit Model/Measurements.csv'
# file_path = 'C:/Users/Asher/Desktop/Thesis/Fit Model/Test Data Sets/test.csv'

# Prints

star = 'KS24C007628'
date = '26-03-2015'

print('-----------------------------------------'
print(star, ' : ', date'
print('-----------------------------------------

# Importing Data

JD.UTC, t., I, M., sigma., airmass., exp = import_data(file_path)

# Creating the initial guess

R, r, p, t.c., m0, d, C = theta

# Predicted values !!!! CHANGE THESE!!!!

d_pred = 15.0/1000 # 10 mmag in mag
Duration_pred = 0.09 # 2:30 in days - Duration of transit #2.25*60*60 in s
Duration_pred_slice = Duration_pred+24*60*60/(exp + 20) # Duration in slices. Read out time is 20s
ing_pred = 50 # ingress start slice number
D_pred_slice = 15 # duration of ingress and egress in slices
egr_pred = ing_pred + Duration_pred_slice + D_pred_slice # egress start slice number
D_pred = t_[ing_pred + D_pred_slice] - t_[ing_pred] # duration of ingress and egress
t_ing_pred = t_[ing_pred] #30 # Time of ingress in slices
t_egr_pred = t_ing_pred + Duration_pred + D_pred
R_pred = Duration_pred/2
r_pred = D_pred/2
p_pred = R_pred/2 # (4*r_pred)
t_c_pred = t_ing_pred + Duration_pred/2 + D_pred
baseline_pred = crop_baseline(M., ing_pred, egr_pred, D_pred_slice)
m0_pred = baseline_pred.mean(1).tolist()
m0_pred = m0_pred[0] ## These repeat is intentional !!!!!
m0_pred = m0_pred[0] ## These repeat is intentional !!!!!
C_pred = 0.01 # use aij value here

# Initial guess

theta0 = [R_pred, r_pred, p_pred, t_c_pred, m0_pred, d_pred, C_pred]
print(theta0)
print(R_pred, r_pred, t_c_pred)
# Appendix B. Model fitting program

```python
# -------------------------------
# MCMC (Prints model parameters while running)
# MCMC parameters
dim = 7 # len(theta1)
walkers = 500
args = (M, sigma, airmass, model)
burn = 100
iters = burn + 50

# Running MCMC
nll, sampler, pos, prob, state, samples = MCMC(dim, walkers, iters, args, theta0, burn )
# Prints come from MCMC -> lnprob -> ln prior.
# Use if statement in lnprior to adjust acceptable ranges for parameters,
# E.g. t_egr + D <= t_egr, C >= 0.0, t_egr + D <= t_f.
# Parameters will be printed with a '!' if they are not to be accepted.

# Results of MCMC
Rmcmc, rmcmc, pmcmc, cmcmc, m0mcmc, dmcmc, Cmcmc = map(lambda v: (v[1], v[2]-v[1], v[1]-v[0]), zip(np.percentile(samples, [16, 50, 84], axis=0)))
theta_mcmc = [Rmcmc[0], rmcmc[0], pmcmc[0], cmcmc[0], m0mcmc[0], dmcmc[0], Cmcmc[0]]
theta_15th = [Rmcmc[1], rmcmc[1], pmcmc[1], cmcmc[1], m0mcmc[1], dmcmc[1], Cmcmc[1]]
theta_84th = [Rmcmc[2], rmcmc[2], pmcmc[2], cmcmc[2], m0mcmc[2], dmcmc[2], Cmcmc[2]]
variables = [f'R', f'r', f'p', f't_{c}', f'm0', f'd', f'C']

for i in range(len(theta_mcmc)):
    print variables[i], '= ', theta_mcmc[i], '+/- ', theta_15th[i], '/', theta_84th[i]

# Plotting

# Triangle plot of MCMC model parameter results
tri_labels = [f'S_{R}', f'S_{r}', f'S_{p}', f'S_{t_{-c}}', f'S_{m_{0}}', f'S_{d}', f'S_{C}']
figno = triplot(samples, tri_labels, theta_mcmc, 'm'. figno)

# Build final graph of data with different fits
size = 100 # no. of MCMC steps to show on graph
figno = plot_model(JD,UTC, theta0, theta_mcmc, star, figno, airmass, M, sigma, size , samples, model)

# Prints
print '\n\nPLOTTING COMPLETE\n'
print '\n' print 'FINISHED
'
```
LISTING B.5: Python code for fitting a piece-wise function to the transit data using MCMC. The piece-wise function models a round planet passing in front of a round star, not necessarily through its center, of uniform brightness in a straight line at a constant speed.

```python
# ----------------- #
###Universal functions for transit modelling
'\''This contains the universal functions for the transit modelling.'\'||
# ---------------------------------------------
#Importing relevant modules
import numpy as np
from math import *
from csv import reader
from numpy import linalg as LA
import matplotlib as MATLAB
from matplotlib import pyplot as MAT
import emcee
import scipy.optimize as op
import triangle

# Universal Functions

##### Round Planet, Box Star

def build_model(theta, airmass, model):
    '''Builds the model data given the necessary parameters
    t_ing is the index to the point of ingress in the data
    t_egr is the index to the point of egress in the data
    data_length is the length of the data vectors (use \(\text{len(data)}\))
    m_0 is the magnitude of the base-line values
    d is the depth of the transit.'''
    m_data = []

    if model == 'RPBS':
        t_ing, t_egr, D, m_0, d, C, = theta
        r = D/2
        A_p = pi*r**2
        for i in range(len(t_data)):
            t = t_data[i]
            if t <= t_ing or t > t_egr + D:  # basal
                m_data.append(m_0 + C * airmass_item(i))
            if t_ing + D <= t and t <= t_egr:
                m_data.append(m_0 + d + C * airmass_item(i))
            if t_ing < t and t <= t_ing + D:
                m_data.append(m_0 + d * A(t-ing, r)/A_p + C * airmass_item(i))
            if t_egr < t and t <= t_egr + D:
                m_data.append(m_0 + d * (1 - A(t-ing, r)/A_p) + C * airmass_item(i))
```

if model == 'RPRS':
    # uses Fin and Egr
    t_ing, t_eg, D, m_0, d, C = theta
    r = D/2
    print t_ing, t_eg, D, m_0, d, C, r
    for i in range(len(airmass_.tolist())[0])):
        t = t_[i]
        if t <= t_ing or t > t_eg + D: # basel
            m_t.append(m_0 + C * airmass_.item(i))
        if t_ing + D <= t and t <= t_eg:
            m_t.append(m_0 + d + C * airmass_.item(i))
        if t_ing < t and t <= t_ing + D: # ing
            m_t.append(m_0 + d * Fr(t, r, t_ing, t_eg) + C * airmass_.item(i))
        if t_eg < t and t <= t_eg + D: # egr
            m_t.append(m_0 + d * Fr(t, r, t_ing, t_eg) + C * airmass_.item(i))

if model == 'RPRSRO':
    R, r, p, t_c, m_0, d, C = theta
    # to avoid rounding errors
    #R = 100000.0*R
    #r = 100000.0*r
    #p = 100000.0*p
    #t_c = 100000.0*t_c
    theta = R, r, p, t_c, m_0, d, C
    t_inge = tinder(t_c, r, R, p)
    ing_start, ing_finish, egr_start, egr_finish = t_inge
    for i in range(len(airmass_.tolist())[0])):
        t = t_[i] # to avoid rounding errors
        if t <= ing_start or t > egr_finish:
            m_t.append(m_0 + C * airmass_.item(i))
        if ing_finish <= t and t <= egr_start:
            m_t.append(m_0 + d + C * airmass_.item(i))
        if ing_start < t and t <= ing_finish:
            m_t.append(m_0 + d * Fr(t, r, t_ing, t_eg) + C * airmass_.item(i))
        if egr_start < t and t <= egr_finish:
            m_t.append(m_0 + d * Fr(t, r, t_ing, t_eg) + C * airmass_.item(i))
    return m_t[:len(airmass_.tolist())[0]]

def crop_baseline(Set, t_ing, t_eg, D):
    """Builds a set containing only the predicted baseline."
    A = Set[::t_ing]
    a = A.tolist()
    a = a[0]
    B = Set[::t_eg + D:] 
    b = B.tolist()
    b = b[0]
    baseline = np.matrix(a + b)
    return baseline
# Importing data

def mapmat(input_list):
    """ Takes list of strings, containing only floats or ints, and converts to a matrix. """
    input_list = map(float, input_list)
    output_mat = np.matrix([input_list])
    return output_mat

def import_data(file_path):
    """ Imports data from a specified .csv file and converts the relevant data into lists. """
    imported_file = open(file_path, 'rb')
    read_file = reader(imported_file, delimiter = ',')
    labeled_data = [row for row in read_file]
    data = labeled_data[1:]
    labels = labeled_data[0]

    JD_index = labels.index('JD.UTC')
    T1_err_index = labels.index('rel.flux.err.T1')
    T1_index = labels.index('rel.flux.T1')
    airmass_index = labels.index('AIRMASS')
    exp_index = labels.index('EXPTIME')

    print 'DATA IMPORTED'

    # Building empty lists
    JD UTC = [] # t
    rel_flux_err_T1 = [] # sigma
    rel_flux_T1 = [] # M
    AIRMASS = [] # airmass
    exp = [] # exposure time

    # Converting data to lists of floats, then vectors
    for i in range(len(data)):
        row = data[i]
        JD UTC.append(row[JD_index]) # t
        rel_flux_err_T1.append(row[T1_err_index]) # sigma
        rel_flux_T1.append(row[T1_index]) # M
        AIRMASS.append(row[airmass_index]) # airmass
        exp.append(row[exp_index]) # exposure time

    global t_
    global shift

    t_ = mapmat(JD.UTC).tolist()
    t_ = t_[0]
    shift = t_[0]
    t_[:] = [x - shift[0] for x in t_]
    l = mapmat(rel_flux_T1)
    M_ = np.multiply(-2.5, np.log10(l))
    sigma_l = mapmat(rel_flux.err.T1)
    M_max = np.multiply(-2.5, np.log10(1-sigma_l))
    M_min = np.multiply(-2.5, np.log10(1+sigma_l))
sigma_ = np.divide(M_max - M_min, 2)
airmass_ = mapmat(AIRMASS)
exp = map(float, exp)
exp = exp[0]

return JD2UTC, t_, I, M_, sigma_, airmass_, exp

#-----------------

#MCMC

def calc_Chi2(M_, m_t, sigma_):
    """calculates Xi^2 for a given model (m_t) and flux data M_ with error
    sigma_.""

    sig2_ = np.power(sigma_, 2)
    # print 'sig2=', sig2_
    Chi2_2 = np.divide(np.power((M_ - m_t), 2), sig2_)
    Chi2 = Chi2_.sum()
    return Chi2

def lnprior(theta, t_f, model):
    """checking prior for lnlike."

    if model == 'RPRSRO':
        R, r, p, t_c, m_0, d, C = theta
        print '\nR =', R, '; r =', r, '; p =', p, '; t_c =', t_c, '; m_0 =', m_0,
        '; d =', d, '; C =', C,
        if R > 0.0 and r > 0.0 and C >= 0.0 and (t_c + R) < t_f and d > 0.0 and abs(p)
        +r < R and p > 0.0:
            return 0.0
        else:
            print '!','
            return -np.inf
    else:
        t_ing, t_egr, D, m_0, d, C = theta
        print '\nIngress = \', t_ing, '; Egress = \', t_egr, '\nIngress/Egress duration = \', D, '\nTransit depth = \', int(d*10000)/10.0, ' mmag ; Baseline = \', int(m_0*1000)/1000.0, ' mag; Airmass contribution factor = \', int(C*10000)/10000.0,
        if t_ing + D <= t_egr and 2 * D <= t_f and D>=0.0 and C >= 0.0 and t_egr + D
        <= t_f and d>=0:
            return 0.0
        else:
            print '!','
            return -np.inf

def lnlike(theta, M_, sigma_, airmass_, model):
    """likelihood."

    m_t = build_model(theta, airmass_, model)
    Chi2 = calc_Chi2(M_, m_t, sigma_)
    return -0.5 * Chi2

def lnprob(theta, M_, sigma_, airmass_, model):

Appendix B. Model fitting program

206 ‘‘posterior probability’’
# uses ln prior and ln like
209 t_f = t_e[-1] # final t
210 lp = ln prior (theta , t_f , model)
211 if not np.isfinite (lp):
212 return -np.inf
213 return lp + ln like (theta , M_, sigma_, airmass_, model)

215 def MCMC (dim , walkers , iters , args , theta1 , burn = None):
216 # uses lnprob
217 nll = lambda *args: -lnlike(*args)
218 result = op.minimize (nll , theta1 , args = args)
219
220 print '\n\nMCMC SAMPLES:
'
221 pos = [ result ['x'] + 1e-4 + np.random.rand (dim) for i in range (walkers) ]
222 sampler = emcee.EnsembleSampler(walkers , dim , lnprob , args = args)
223 pos , prob , state = sampler.run_mcmc (pos , iters ) # 100
224
225 samples = sampler.chain [: , burn : , : ] . reshape ((-1 , dim))
226
227 print '\n\nMCMC COMPLETE
'
228 return nll , sampler , pos , prob , state , samples

# ---
233 # Plotting

235 def vline (JD UTC , x , y_pos , colour , style , line_width , alpha , label , font_size):
236 ‘‘draws an annotated vertical line.’’
237 x += shift
238 MAT. axvline (x=x,
239 color=colour ,
240 linestyle=style ,
241 lw=line_width ,
242 alpha=alpha)
243 MAT. annotate (label ,
244 xy=(x, y_pos) ,
245 xycoords='data' ,
246 textcoords='data' ,
247 arrowprops=None , # arrowprops=dict (arrowstyle="->")
248 size=font_size ,
249 color=colour)

251 def vspan (JD UTC , no , duration , colour , alpha):
252 ‘‘draws a line of thickness=duration on the graph with a selected opacity
(0 >= alpha >= 1).’’
253 x1 = no + shift
254 x2 = no + shift + duration
255 MAT. axvspan (x1 , x2 , facecolor=colour , alpha=alpha)

258 def vspanr (JD UTC , t_initial , t_final , colour , alpha):
259 ‘‘draws a line of thickness=duration on the graph with a selected opacity
(0 >= alpha >= 1).’’
x1 = t_initial + shift
x2 = t_final + shift
MAT.axvspan(x1, x2, facecolor=colour, alpha=alpha)

def plot_model(JD_utc, theta1, theta_mcmc, star, figno, airmass, M, sigma, size, samples, model):
    '''plots the photometric data with initial guess for MCMC, a selection of
MCMC lines, and the fit line using the posterior means of the MCMC.'''
    #uses build_model, vline, and vspan
    if model == 'RPRSRO':
        #Unpacking thetas
        R_pred, r_pred, p_pred, t_c_pred, m_0_pred, d_pred, C_pred = theta1
        R_mcmc, r_mcmc, p_mcmc, t_c_mcmc, m_0_mcmc, d_mcmc, C_mcmc = theta_mcmc

        #Updating figure number
        figno += 1
        MAT.figure(figno)

        #Predicted
        t_ingr_pred = tinder(t_c_pred, r_pred, R_pred, p_pred)
        t_ingr_start_p, t_ingr_end_p, t_egr_start_p, t_egr_end_p = t_ingr_pred
        m_t_pred = build_model(theta1, airmass, model)

        #vline(JD_utc, (t_ingr_start_p + (t_ingr_end_p - t_ingr_start_p)/2) * 1.464, 'r',
        #    '--', 1, 1, 'predicted\n ingress',
        #    # 'small')
        #vline(JD_utc, (t_egr_start_p + (t_egr_end_p - t_egr_start_p)/2) * 1.464, 'r',
        #    '--', 1, 1, 'predicted\n egress',
        #    # 'small')
        h1, = MAT.plot(JD_utc, m_t_pred, 'r')

        #MCMC
        count = 1
        for R, r, p, t_c, m_0, d, C in samples[np.random.randint(len(samples), size=size)]:
            theta = [R, r, p, t_c, m_0, d, C]
            m_t = build_model(theta, airmass, model)

            if count:
                h2, = MAT.plot(JD_utc, m_t, 'k', alpha=0.08)
                count = 0
            else:
                MAT.plot(JD_utc, m_t, 'k', alpha=0.08)

        #Posterior means
        m_t_mcmc = build_model(theta_mcmc, airmass, model)
        h3, = MAT.plot(JD_utc, m_t_mcmc, 'm', lw=1.5)
        t_ingr = tinder(t_c_mcmc, r_mcmc, R_mcmc, p_mcmc)

        tag = ['\n ingress \n (MCMC)', '\n egress \n (MCMC)']

        t_ingr_start, t_ingr_end, t_egr_start, t_egr_end = t_ingr
        print t_ingr
Appendix B. Model fitting program

```python
# Appendix B: Model fitting program

# vspanr(JD.UTC, t.ing_start, t.ingress_end, 'm', 0.1)
# vspanr(JD.UTC, t.egr_start, t.egress_end, 'm', 0.1)

# Data
M_list = M.toList()
sigma_list = sigma.toList()
MAT.errorbar(JD.UTC, M_list[0], sigma_list[0], None, None)

# Asthetics
MAT.xlim(MAT.xlim()[::-1])
MAT.legend([h1, h2, h3], ['Initial guess', 'MCMC lines', 'Final MCMC fit'], fontsize='small')
MAT.xlabel('Julian date (UTC)')
MAT.ylabel('Relative magnitude of target star')
MAT.title('Model fit to photometry of ' + star + ' using MCMC')
MAT.savefig('Model.png')
print('Model plots saved')
return figno

else:
    # Unpacking thetas
    t.ing_pred, t.egr_pred, D_pred, m0_pred, d_pred, C_pred = theta1
    t.ing_mcmc, t.egr_mcmc, D_mcmc, m0_mcmc, d_mcmc, C_mcmc = theta_mcmc

    # Updating figure number
    figno += 1
    MAT.figure(figno)

    # Predicted
    m_t_pred = build_model(theta1, airmass_, model)
    vline(JD.UTC, (t.ing_pred + D_pred / 2), 1.464, 'r', '−−', 1, 1, 'predicted ingress', 'small')
    vline(JD.UTC, (t.egr_pred + D_pred / 2), 1.464, 'r', '−−', 1, 1, 'predicted egress', 'small')
    h1, = MAT.plot(JD.UTC, m_t_pred, 'r')

    # MCMC
    count = 1
    for t.ing, t.egr, D, m0, d, C in samples[np.random.randint(len(samples), size=size)]:
        theta = [t.ing, t.egr, D, m0, d, C]
        m_t = build_model(theta, airmass_, model)
        if count:
            h2, = MAT.plot(JD.UTC, m_t, 'k', alpha=0.08)
            count = 0
        else:
            MAT.plot(JD.UTC, m_t, 'k', alpha=0.08)

    # Posterior means
    m_t_mcmc = build_model(theta_mcmc, airmass_, model)
    h3, = MAT.plot(JD.UTC, m_t_mcmc, 'm', lw=1.5)

    # Ingress
    vline(JD.UTC, t.ing_mcmc, 1.462, 'm', '−−', 1, 1, 'ingress (MCMC)', 'small')
```

# Appendix B. Model fitting program

## 'small'

```python
vspan(JDUTC, t_Ing_mcmc, D_mcmc, 'm', 0.1)
vline(JDUTC, (t_Ing_mcmc + D_mcmc), 1.462, 'm', '—', 1, 1, '', 'small')

# Egress
vline(JDUTC, t_egr_mcmc, 1.462, 'm', '—', 1, 1, 'egress \n (MCMC)', 'small')
vspan(JDUTC, t_egr_mcmc, D_mcmc, 'm', 0.1)
vline(JDUTC, (t_egr_mcmc + D_mcmc), 1.462, 'm', '—', 1, 1, '', 'small')

# Data
M_list = M_.tolist()
sigma_list = sigma_.tolist()
MAT.errorbar(JDUTC, M_list[0], sigma_list[0], None, None)

# Aesthetic
MAT.ylim(MAT ylim()[:−1])
MAT.legend([h1, h2, h3], ['Initial guess', 'MCMC lines', 'Final MCMC fit'], fontsize = 'small')
MAT.xlabel('Julian date (UTC)')
MAT.ylabel('Relative magnitude of target star')
MAT.title('Model fit to photometry of ' + star + ' using MCMC')
MAT.savefig('Model.png')
print 'Model plots saved'
return figno
```

```python
def triplot(samples, tri_labels, theta, colour, figno):
    """plots samples from MCMC showing posterior means in magenta."
    fig = triangle.corner(samples, labels=tri_labels,
                          verbose=True,
                          truths=theta,
                          truth_color=colour)
    fig.savefig("triangle.png")
    print 'Tri-plot saved'
    figno += 1
    return figno
```

```python
# Round Planet, Box Star

def A(t, r):
    """function for the fraction of the round planet that is blocking the square
    star at some time during ingress or egress."
    if 2*r == t:
        area = pi*r**2
    elif t == 0:
        area = 0
    else:
        area = (2*(2*r**2*sqrt(t)*sqrt(2*r-t)*np.arctan(sqrt(t)/sqrt(2*r-t))-t*(2*r**2-3*r*t+t**2))/((2 * sqrt(t*(2*r-t)))))
    return area
```
Appendix B. Model fitting program

#------------------------------------------------------------
# Round planet, round star, no radial
#
# ### Intercept: Round planet, round star, no radial offset
# def intercept(t_in, t_eg, r, t):
#     """finding the intercept between the planet and star function at varying t values."""
#     R = (t_eg - t_in) / 2
#     s = (t_eg - R) - (t - r)
#     t1 = sqrt((r**2 - R**2)/(2*s) - s/2 + R) # intercept with origin at back of star, O_1
#     t2 = sqrt((r**2 - R**2)/(2*s) + s/2 + r) # intercept with origin at back of planet, O_2
#     return t1, t2
#
# ### Round planet, round star, no radial offset
# def A1(t, r, t_in, t_eg, t1):
#     """finding the area of the star that is in transit."""
#     if t_in <= t and t < t_in:
#         area = A(t1, R)
#     if t_eg <= t:
#         area = A_p - A(t1, R)
#     return area
#
# ### Round planet, round star, no radial offset
# def A2(t, r, t_in, t_eg, t2):
#     """finding the area of the planet that is in transit."""
#     A_p = pi*r**2
#     if t_in <= t and t < t_eg:
#         area = A(t2, r)
#     if t_eg <= t:
#         area = A(t2, r)
#     return area
#
# def F(t, r, t_in, t_eg):
#     """finding the fraction of the star covered during ingress and egress of the transit."""
#     # uses intercept, A1, and A2
#     t1, t2 = intercept(t_in, t_eg, r, t)
#     A1 = A1(t, r, t_in, t_eg, t1)
#     A2 = A2(t, r, t_in, t_eg, t2)
#     A_p = pi*r**2
#     f = (A1 + A2) / A_p
#     return f
# -------------------
#Round planet, round star, radial

### Intercept: Round planet, round star, radial offset

def intercept(t_c, r, R, p, t):
    '''finding the t intercept bewteen the planet and star function at varying t_i values.'''
    s = (t_c + r - t)
    a = p**2 + s**2
    b = s*(R**2 - p**2 - r**2 - s**2)
    c = ((s**2 + p**2 + r**2 - R**2)**2)/4 - (p**2)*(r**2)
    k = b**2 - 4*a*c
    if abs(k) < 1e-8:
        k = 0.0

    t_p1 = -b/(2*a) + sqrt(k) / (2*a) # intercept with origin at center of planet, O_2
    t_p2 = -b/(2*a) - sqrt(k) / (2*a) # intercept with origin at center of planet, O_2
    t_s1 = t_p1 - s # intercept with origin at center of star, O_1
    t_s2 = t_p2 - s # intercept with origin at center of star, O_1

    y_p11 = sqrt(r**2 - t_p1**2)
    y_p12 = -sqrt(r**2 - t_p1**2)
    y_p21 = sqrt(r**2 - t_p2**2)
    y_p22 = -sqrt(r**2 - t_p2**2)
    y_s11 = y_p11 + p
    y_s12 = y_p12 + p
    y_s21 = y_p21 + p
    y_s22 = y_p22 + p

    if abs((t_s1**2 + y_s11**2) - R**2) < abs((t_s1**2 + y_s12**2) - R**2):
        y_s1 = y_s11
        y_p1 = y_p11
    else:
        y_s1 = y_s12
        y_p1 = y_p12

    if abs((t_s2**2 + y_s21**2) - R**2) < abs((t_s2**2 + y_s22**2) - R**2):
        y_s2 = y_s21
        y_p2 = y_p21
    else:
        y_s2 = y_s22
        y_p2 = y_p22

    #print 'y_s1, y_s2, y_p1, y_p2 = ', y_s1, y_s2, y_p1, y_p2
    #print 'y_s11, y_s21, y_s12, y_s22, y_p11, y_p21, y_p12, y_p22 = ', y_s11, y_s21, y_s12, y_s22, y_p11, y_p21, y_p12, y_p22
    t_intercepts = [t_s1, t_s2, t_p1, t_p2]
    y_intercepts = [y_s1, y_s2, y_p1, y_p2]

    return t_intercepts, y_intercepts #=intercept(t_c, r, R, p, t)
def tinder(t_c, r, R, p):
    ''' finds start and finish times of ingress and egress. '''
    t_1 = sqrt(((r+R)**2-p**2) + t_c + r)
    t_2 = -sqrt(((r+R)**2-p**2) + t_c + r)
    t_3 = sqrt(((R-r)**2-p**2) + t_c + r)
    t_4 = -sqrt(((R-r)**2-p**2) + t_c + r)
    t_inge = [t_1, t_2, t_3, t_4]
    t_inge.sort()
    return t_inge

def Fr(t, theta, t_inge):
    ''' finding the fraction of the star covered during ingress and egress of the transit... '''
    # uses intercepts, A1, and A2
    R, r, p, t_c, m_0, d, C = theta
    ing_start, ing_finish, egr_start, egr_finish = t_inge
    A = pi*r**2
    area_s, area_p = Ar(t, theta, t_inge)
    f = 1 - (area_s + area_p)/A
    return f

def Ar(t, theta, t_inge):
    ''' finding the area of the planet that is in transit... '''
    R, r, p, t_c, m_0, d, C = theta
    s = t_c + r - t
    ing_start, ing_finish, egr_start, egr_finish = t_inge
    t_intercepts, y_intercepts = intercept(t_c, r, R, p, t)
    t_s1, t_s2, t_p1, t_p2 = t_intercepts
    y_s1, y_s2, y_p1, y_p2 = y_intercepts
    phi_ss = [bound(t_s1, y_s1, R), bound(t_s2, y_s2, R)]
    phi_ps = [bound(t_p1, y_p1, r), bound(t_p2, y_p2, r)]
    #phi_ss.sort()
    phi_s1 = phi_ss[1]
    phi_s2 = phi_ss[0]
    phi_p1 = phi_ps[1]
    phi_p2 = phi_ps[0]
    phi_diff = ((phi_p1 + phi_p2) % pi + pi)/2
    if t <= ing_finish:
        phi_p1 = (phi_p2 - phi_p1)/2 % pi
        phi_s1 = (phi_s1 - phi_s2)/2 % pi
        seg_p = r**2*phi_p1
        seg_s = R**2*phi_s1
if ((phi_p1) < pi/2) : # case 1
    tri_p = cos(phi_p1) * r**2 * sin(phi_p1)
    area_p = pi*r**2 - seg_p + tri_p
    case = 1
else:
    tri_p = cos(pi - phi_p1) * r**2 * sin(pi - phi_p1)
    area_p = pi*r**2 - seg_p - tri_p
    case = 2
else:
    phi_p1 = (phi_p1 - phi_p2)/2 % pi
    phi_s1 = (phi_s1 - phi_s2)/2 % pi
    seg_p = r**2*phi_p1
    seg_s = R**2*phi_s1

if ((phi_p1) < pi/2) : # case 1
    tri_p = cos(phi_p1) * r**2 * sin(phi_p1)
    area_p = seg_p - tri_p
    case = 3
else:
    tri_p = cos(pi - phi_p1) * r**2 * sin(pi - phi_p1)
    area_p = seg_p + tri_p
    case = 4

tri_s = cos(phi_s1) * R**2 * sin(phi_s1)
area_s = seg_s - tri_s

if area_p<0:
    print area_s, area_p, case
return area_s, area_p

def bound(t, y, r):
    """takes t and y intercept coordinates and produces an angle for use as a bound in integration for area""

    if (t > 0.0) and (y > 0.0):
        phi = np.arccos(abs(t)/abs(r))
    elif t < 0.0 and y > 0.0:
        phi = pi/2.0 + np.arcsin(abs(t)/abs(r))
    elif t < 0.0 and y < 0.0:
        phi = pi + np.arccos(abs(t)/abs(r))
    elif t > 0.0 and y <0.0:
        phi = 3.0*pi/2.0 + np.arcsin(abs(t)/abs(r))
    else:
        phi = 0.0
    return phi

Appendix C

Photometric results

C.1 “Flat” lightcurves

C.1.1 KS28C00737

Target KS28C00737\(^1\) ($22^h15^m37.7^s−54^\circ13′26.6″$, $T_{\text{eff}} = 7604$ K, and $V = 9.02$ mag) was observed on 2015 August 22. The BLS fitted period for this target was 2.59 days, with a transit depth of 2.6 mmag and a transit durations of 1:52 hours.

This target was observed 210 times using the V with 30 s exposures. The resulting 2:55 covered the predicted transit.

![Figure C.1: Apertures used in the multi-aperture photometry of KELT target KS28C00737 on 2015 August 22. T1 was the target star (KS28C00737) and C1, C2, C3, C4, C5, C6, and C7 were the comparison stars used to find the relative flux of T1.](image)

Multi-aperture photometry (comparison stars used are shown in Fig. C.1) of this target resulted in a “flat” lightcurve (Fig. C.2). KS28C00737 was expired as spurious.

\(^1\)HD 211013 with spectral type Fm
Appendix C. Photometric results

C.1.2 KS24C007628 Secondary

This was the secondary location to the transit in Section 4.3.5. This set was observed in V on 2015 March 23. 318 images were taken over 3.5 hr, starting at 10:45 UTC. The exposure time for these was 20s.

Multi-aperture photometry was run using the apertures selected in Fig. C.3. The resulting lightcurve can be seen in Fig. C.4. This relatively featureless lightcurve is the result hoped for, as an event at this location in the orbit would mean the companion of KS24C007628 was a star, not an exoplanet.
C.1.3 KS27C026665

KS27C026665 (18\textsuperscript{h}31\textsuperscript{m}7.4\textsuperscript{s} − 54° 53′13.9′′, $T_{\text{eff}} = 5483$ K, and $V = 11.52$ mag) has been found to have a BLS fitted period of 0.59 days with a transit depth of 8 mmag and a transit duration of 1:25 hours.

This candidate was observed on 2015 August 11.

Multi-aperture photometry was run on KS27C026665 with the aperture selection shown in Fig. C.5. The resulting lightcurve is shown in Fig. C.6.

Given the rather featureless lightcurve and supporting the featureless lightcurves from TG, this target was expired as spurious.
Appendix C. Photometric results

C.1.4 KS29C03238

KS29C03238 (23h13m23.8s − 64° 45′21.8″) was found to have a 2.94 day BLS fitted period, with a predicted transit duration of about 2:30 hours.

This target was queued for 280 observations of 40 s exposures with the V filter. This set was to start at 2015 July 13 10:25 UTC and continue for 4:40, covering the predicted transit. The weather conditions on this night were not optimal and this is reflected in the total comparison star counts plotted in pink in Fig. C.8.

The multi-aperture photometry performed to achieve this lightcurve (Fig. C.8) used the comparison stars shown in Fig. C.7.

The variation in this lightcurve seems to coincide with a dip in the total counts of the comparison star. The survey lightcurves from this exoplanet have not made it through recent winnowing processes, but the small dip in this curve has stopped it from being expired until further follow-up data is obtained.

C.2 “U” shaped eclipses
C.2.1 KS24C030627

KELT candidate KS24C030627 ($12^h33^m17.0^s -20^\circ 50'33.7''$, $V = 12.42$ mag) has a predicted transit with a BLS fitted period of 4.44 days. This predicted transit has a duration of 5:01 hours and a depth of 18.7 mmag.

KS24C030627 was observed on 2015 May 3. The observation set was queued to start at 07:00 UTC and continue for 8:00 hours, completely covering the predicted transit. This observation set included 410 images with 50s exposures, taken using the V filter.

Figure C.9 shows the comparison stars that were chosen for the multi-aperture photometry of this target. It also shows ring artefacts on the images that were not removed during flat-fielding.

Many follow-up lightcurves were obtained by KELT collaborators, as can be seen in Fig. C.11.
Appendix C. Photometric results

Figure C.7: Apertures used in the multi-aperture photometry of KELT target KS29C03238 on 2015 July 13. T1 was the target star (KS29C03238) and C1, C2, C3, C4, C5, and C6 were the comparison stars used to find the relative flux of T1.

Figure C.8: Relative lightcurve of KELT target KS, imaged in V from Mt John on 2015 July 13, corresponding to the target and comparison stars shown in Fig. C.7.

Though the results in Fig. C.11 look promising as an exoplanetary transit, RV observations from TRES expired this as an eclipsing binary.

C.2.2 KS27C013482

KS27C013482 ($18^h49^m54.7^s -47^\circ 8'17''$) has a possible transit occurring with BLS predicted period of 5.9 days. The depth of this predicted transit is 7.6mmag, with a
Appendix C. Photometric results

Figure C.9: Apertures used in the multi-aperture photometry of KELT target KS24C030627 on 2015 May 3. T1 was the target star (KS24C030627) and C1, C2, C3, C4, C5, C6, and C7 were the comparison stars used to find the relative flux of T1. Image contains artefacts from dust.

duration of 6:40 hours.

This target was observed on 2015 August 25, for 7:05 hours, starting at 6:30 UTC. This constituted a total of 150 observations made using the V filter with 150s exposures.

Multi-aperture differential photometry was performed using the comparison stars selected in Fig. C.12. The resulting lightcurve is shown in Fig. C.13.

This lightcurve has a transit depth of approximately 8mmag. This corresponds to a $1.1R_\oplus$ companion.
Figure C.10: Relative lightcurve of KELT target KS24C030627, imaged in V from Mt John on 2015 May 3, corresponding to the target and comparison stars shown in Fig. C.9.

Figure C.11: Relative magnitude lightcurve of KELT target KS24C030627, imaged by KELT follow-up partners.
Appendix C. Photometric results

Figure C.12: Apertures used in the multi-aperture photometry of KELT target KS27C013482 on 2015 August 25. T1 was the target star (KS27C013482) and C1, C2, C3, C4, C5, C6, and C7 were the comparison stars used to find the relative flux of T1.

Figure C.13: Relative lightcurve of KELT target KS27C013482, imaged in V from Mt John on 2015 August 25, corresponding to the target and comparison stars shown in Fig. C.12.
Appendix D

Cross-correlation program

D.1 Fitting a period to HD 9468 RV data

Some attempts were made to fit a period to the RV data of HD 9468. Below are examples of attempts that were made to fit a period to the RV data obtained from the cross-correlation of cropped spectra. These results did not agree with each other or the Lomb-Scargle results from Chapter 5, Section 5.1 and were largely unconvincing. For this reason the KELT survey period was used when fitting a sinusoidal curve to the RV data.

![Figure D.1: RV measurement for HD 113204 phased and fitted with a sinusoidal curve found by searching over period values from an initial guess (the BLS KELT period was used as the initial guess), using the period value and LS to find the coefficients of the sinusoidal curve and then minimising the $\chi^2$ values to find the ideal period.](image-url)
Radial velocities found from the cross-correlation of cropped spectra, phased according to a fitted period, can be seen in Fig. D.1. The red dashed line shows a sinusoidal curve fitted using an LS method. The period was found using the \textit{fminsearch} function in MATLAB, where the “best” period was the one that provided the smallest $\chi^2$ value. The fitted curve found using this method was

$$v(t) = (0.1 \pm 1.9) \times 10^3 + (3.0 \pm 5.3) \times 10^3 \sin(\omega t) + (-1.1 \pm 3.2) \times 10^3 \cos(\omega t),$$

where $\omega = \frac{2\pi}{T}$ and $T = 1.9551$ d. The red dashed line in Fig. D.2 shows the same data as Fig. D.1, with a curve of the same form as the previous curve, but with coefficients and a period (for which the data was phased) found by minimising $\chi^2$ using the \textit{fminsearch} function in MATLAB. This RV function has the form

$$v(t) = (-5.2) \times 10^3 + (5.2) \times 10^3 \sin(\omega t) + (15.7) \times 10^3 \cos(\omega t),$$
where $\omega = \frac{2\pi}{T}$ and $T = 1.3294$ d. The initial guess here was

$$v(t) = (-5) \times 10^3 + (5) \times 10^3 \sin(\omega t) + (15) \times 10^3 \cos(\omega t), \quad (D.3)$$

where $\omega = \frac{2\pi}{T}$ and $T = 1.48$ d. The `fminsearch` function requires a good first guess to find a minimum. It would seem that, in these cases, using the `fminsearch` function has resulted in local minima being found, otherwise one would expect the results to agree. Further efforts could have been made to resolve this issue by manually searching over $T$ values and finding a $\chi^2$ minima to use as the initial guess when using this function. However, the lack of data or the lack of a signal from a planetary companion seems to be the likely cause of all this disagreement (especially considering the Lomb-Scargle results) and so the search for a period was abandoned in favour of the BLS fitted KELT period.

### D.2 MATLAB code

This section contains MATLAB code for the cross-correlation and line profile minima search used to obtain RV measurement from the reduced spectra of HD 9468. This code was largely written by Assoc Prof Michael Albrw, but was modified and extended by Amber Malpas (author of this thesis). The code for HD 113204 is very similar, but does not include the Lomb-Scargle analysis.

**Listing D.1:** Function for using `fminsearch` to find a period, fitting the coefficients of the sin curve using LS in `fitsin`.  

```matlab
function chi = chil(T)
% for using fminsearch to find a period, fitting the coefficients of the sin curve using LS in fitsin.
%global drvel rvelshift jd
A = fitsin(jd-7320,rvelshift(1:30),drvel(1:30),T);
a = A(1:3);
a = [a,T];
chi = sum((rvelshift(1:30)-model(a,jd')).^2./drvel(1:30).^2):
```

**Listing D.2:** Function for a $\chi^2$ value for given model parameters.  

```matlab
function chi = chif(a)
%global drvel rvelshift jd
chi = sum((rvelshift(1:30)-model(a,jd')).^2./drvel(1:30).^2):
```
function A = fitsin(t,y,sigma,p)

% Demonstratation script to fit a sum of sinusoids to some data.
% Michael Albrow Feb 2012
%

x = 2*pi*t./p;
var = numel(x);
%xx = min(x):0.01:max(x);  % x vector to use for plotting

% plot the data points
%
figure()
clf
errorbar(x,y,sigma,'r.')
hold on

% Define the basis functions
%
bf = zeros(3,n);
bf(1,:) = ones(1,n);
bf(2,:) = sin(x);
bf(3,:) = cos(x);

% create and fill the alpha and beta matrices
alpha = zeros(3,3);
beta = zeros(3,1);
for k = 1:3,
    for j = 1:3,
        alpha(k,j) = sum(bf(j,:).*bf(k,:)./sigma.^2);
    end
    beta(k) = sum(y.*bf(k,:)./sigma.^2);
end
alpha;
beta;

c = inv(alpha);
a = c*beta;
unc_a = sqrt(diag(c));
%A = [a unca];

%yy = a(1) + a(2)*sin(xx) + a(3)*cos(xx);
A = [a, unc_a];

plot(xx,yy,'b-')
xlabel('X')
ylabel('Y')

LISTING D.3: Function for fitting a sum of sinusoids to data using LS method.
Appendix X. Cross-correlation program

function m = model(a, jd)
% change weather or not a(4) or global period is used here depending on
% which version of test.m is run
m = a(1) + a(2) * sin(2 * pi * jd / a(4)) + a(3) * cos(2 * pi * jd / a(4));

LISTING D.4: Function for building a sinusoidal wave given four coefficients as input parameters.

function [Pn, Prob] = lomb(t, y, freq)
% [Pn, Prob] = lomb(t, y, freq)
% Uses Lomb’s method to compute normalized
% periodogram values “Pn” as a function of
% supplied vector of frequencies “freq” for
% input vectors “t” (time) and “y” (observations).
% Also returned is probability “Prob” of same
% length as Pn (and freq) that the null hypothesis
% is valid.
% x and y must be the same length.
% function [Pn, Prob] = lomb(t, y, f)
% check inputs
if length(t) ~= length(y); error('t and y not same length'); exit; end;
% subtract mean, compute variance, initialize Pn
z = y - mean(y);
var = std(y);
N = length(freq);
Pn = zeros(size(f));

% now do main loop for all frequencies
for i = 1:length(f)
    w = 2 * pi * f(i);
    if w > 0
        twt = 2 * w * t;
        tau = atan2(sum(sin(twt)), sum(cos(twt))) / 2 / w;
        wtmt = w * (t - tau);
        Pn(i) = (sum(z.*cos(wtmt)) .* 2) / sum(cos(wtmt) .* 2) + ...
            (sum(z.*sin(wtmt)) .* 2) / sum(sin(wtmt) .* 2);
    else
        Pn(i) = (sum(z.*t).* 2) / sum(t.^2);
    end
end
% and normalize by variance, compute probs
Pn = Pn / (2 / var.^2);
Prob = 1 - (1 - exp(-Pn)).^N;
for i = 1:length(Pn)  % accomodate possible roundoff error
    if Prob(i) < .001
        Prob(i) = N * exp(-Pn(i));
    end
end
LISTING D.5: Uses Lomb’s method to compute normalised periodogram values, P_n, as a function of supplied vector of frequencies for input vectors of time observations. Also returned is probability of same length as P_n that the null hypothesis is valid.

```matlab
% Original author: Assoc Prof Michael Albrow
% Adapted by Amber Malpas

% HD 9468
% 30 spectroscopic observations

clear all
clc

d = load('hd9468-reduced.csv');
period = 1.8620273;
tt = 7319:0.001:7330;
ttt = 0:0.001:2;

% Plots full spectra
close all

for i = 2:31
    fig = figure(1);
    plot(d(:,1),d(:,i),'b-')
    hold on
    xaxis('Wavelength (\AA)','Interpreter','latex');
    yaxis('Relative Flux','Interpreter','latex');
    set(gca,'LineWidth',1,'FontSize',14);
    plot(d(:,1),d(:,i),'r-')
    saveas(fig,strcat('Full_spec_',int2str(i),'.png'))
    close(fig)
end

% Rebin to log wavelength scale
npts = numel(d(:,1));
logwave = linspace(log10(d(1,1)),log10(d(npts,1)),npts);
wave = 10.0.^logwave;
for i = 2:31
d(:,i) = pchip(d(:,1),d(:,i),wave);
end
d(:,1) = wave;

% Cross-correlate against first spectrum

% Cropping the spectra:
```
Appendix X. Cross-correlation program

% p = find ((d(:,1)>4820) & (d(:,1)<4900));
% p = find ((d(:,1)>5000) & (d(:,1)<5500));
% p = find ((d(:,1)>1) & (d(:,1)<100000));
% p = find ((d(:,1)>6275) & (d(:,1)<6315));
% for i = 2:31
% fig2 = figure(2);
% plot(d(p,1),d(p,2),'b-')
% hold on
% plot(d(p,1),d(p,i),'r-')
% xlabel('Wavelength (\AA)', 'Interpreter','latex');
% ylabel('Relative Flux', 'Interpreter','latex');
% set(gca,'LineWidth',1,'FontSize',14);
% saveas(fig2,strcat('Cropped_spec_','int2str(i),'.'png'))
% close(fig2)
% end
% Cross-correlating cropped spectra:
% for i = 1:30
% fig3 = figure(3);
% c = xcorr(d(p,2)-1.0,d(p,i+1)-1.0,20);
% dw = -(length(c)-1)/2:(length(c)-1)/2;
% mw(i+1) = sum(dw.*(c-min(c)))/sum(c-min(c));
% vel = dw*(d(p(2),1)-d(p(1),1))*3e5/mean(d(p,1));
% plot(vel,c,'r-')
% hold on
% grid on
% qmax = find(c==max(c));
% q = qmax-2:qmax+2;
% plot(vel(q),c(q),'c.','MarkerSize',10)
% f = fit(vel(q),c(q),'poly2');
% coeffs = coeffvalues(f);
% rvel(i) = -coeffs(2)/(2*coeffs(1));
% ci = confint(f);
% dc = coeffs - ci(1,:);
% dvel(i) = sqrt((dc(2)^2/(2*coeffs(1))^2 + coeffs(2)^2*dc(1)^2/(2*coeffs(1))^2));
% yrange = get(gca,'ylim');
% plot(f,'b-')
% set(gca,'ylim',yrange,'LineWidth',1,'FontSize',14);
% xlabel('Velocity (km/s)', 'Interpreter','latex');
% ylabel('CCF', 'Interpreter','latex');
% saveas(fig3,strcat('Xcorr_spec_','int2str(i)','.'png'))
% close(fig3)
% end
% RV results from cross-correlation:
% rv = mw*(d(p(2),1)-d(p(1),1))*3e8/mean(d(p,1));
% rvel = rvel*1000; % km/s
% dvel = dvel*1000; % km/s
% std1 = std(rvel(1:30))
% mvel = sum(-rvel(1:30).'/dvel(1:30).^2)/sum(1./dvel(1:30).^2);
% rvelshift = -rvel - mvel;
% Plotting RV results:
load('jd.txt')

fig4 = figure(4);

errorbar(jd(2:30)-7320+0.05,-rvel(2:30)-mvel1,drvel(2:30),'b-','MarkerSize',10)

hold on
xlabel('JD-2457320','Interpreter','latex')
ylabel('RV (km/s)','Interpreter','latex')

% Searching for a period:

% guessT = period;
% fitT = fminsearch(@chi1,guessT);
% fitT
% A = fitsin(jd-7320,-rvel(1:30)-mvel1,drvel(1:30),fitT);
% A
% a = A(1:3)
% unc_a = A(4:6)
% guessfit = [-5, 5, 15, 1.48];
% b = fminsearch(@chi2, guessfit);
% b
% yy = model(b, tt-7320);
% % Goodness of fit (want 26) not useful if errors are not estimated well
% chi_a = chi1(fitT)%for chi^2 minimisation
% chi_b = chi2(b)

% Fixed period:

A = fitsin(jd-7320,-rvel(1:30)-mvel1,drvel(1:30),period);
A
a = A(1:3)
unc_a = A(4:6)
amplitude_a = sqrt(a(2)^2 + a(3)^2)
c=a;
% guess = [-5, 5, 15]; %for chi^2 minimisation
% best_fit = fminsearch(@chi2, guess); %for chi^2 minimisation
% yy = model(best_fit, tt-7320); %for chi^2 minimisation

% Plotting fitted sinusoidal curve with RV results:

figure(4)
plot(tt-7320,a(1) + a(2)*sin(2*pi*tt/period) + a(3)*cos(2*pi*tt/period), 'b--')
%plot(tt-7320,a(1) + a(2)*sin(2*pi*tt/fiT) + a(3)*cos(2*pi*tt/fiT), 'b--')
%plot(tt-7320, yy, 'k--')
set(gca,'LineWidth',2,'FontSize',14);
saveas(fig4,'RV_sin_fits.png')
close(fig4)
Cross-correlation program

% Plotting phased data with LS fitted curve and fitted period:
fig5 = figure(5);

cycle = (jd-7320)/fitT;
phase = cycle - floor(cycle);
plot((ttt,a(1)) + a(2)*sin(2*pi*ttt) + a(3)*cos(2*pi*ttt),'r--')
axis([0 2 -150 150])
hold on
errorbar([phase phase+1],([rvel(1:30)’-mvel1 -rvel(1:30)’-mvel1],[drvel(1:30)’ drvel (1:30)’],[b,’,’Markersize’,10])
xlabel(’Phase’,’Interpreter’,’latex’);
ylabel(’Radial velocity (km/s)’,’Interpreter’,’latex’);
set(gca,’LineWidth’,2,’FontSize’,14);
saveas(fig5,’Phased_LS.png’)
close(fig5)

fig6 = figure(6);
cycle = (jd-7320)/b(4);
phase = cycle - floor(cycle);
plot((ttt,b(1)) + b(2)*sin(2*pi*ttt) + b(3)*cos(2*pi*ttt),'r--')
axis([0 2 -150 150])
hold on
errorbar([phase phase+1],([rvel(1:30)’-mvel1 -rvel(1:30)’-mvel1],[drvel(1:30)’ drvel (1:30)’],[b,’,’Markersize’,10])
xlabel(’Phase’,’Interpreter’,’latex’);
ylabel(’Radial velocity (km/s)’,’Interpreter’,’latex’);
set(gca,’LineWidth’,2,’FontSize’,14);
saveas(fig6,’Phased_ch.png’)
close(fig6)

mvel1

%
% Period search - Lomb-Scargle:

% first create a vector of frequency bins, 1 per Hz
logper = 0.17:0.0001:1;
per = 10.^logper;
f=1./per;
[Pn Prob]=lomb(jd-7320+0.05,[-rvel(1:30)’-mvel1’,f]);
t = jd-7320+0.05;
y = -rvel(1:30)’-mvel1;
fig7 = figure(7);
h=plot(log10(f),Pn,’r’); set(h,’LineWidth’,1);
hold on
plot([-0.27 -0.27],[0 3.5],’b--’)
xlabel(’log$_{10}$ Frequency (1/d)’,’Interpreter’,’latex’);
ylabel(’Normalized PSD’,’Interpreter’,’latex’);
title(’Lomb Periodogram’,’Interpreter’,’latex’);
set(gca,’LineWidth’,2,’FontSize’,14);
saveas(fig7,’Lomb_periodogram_Xcorr.png’)

appendix X. cross-correlation program

% then sort for smallest values first
% (ie. those points least likely to be random)
[p, ind] = sort(Prob);
most = ind(1:5); % just the first 5 values
ANS = [f(most)’ 1/f(most)’ Pn(most)’ Prob(most)’]

% plot the phased lightcurve
per = 1/f(ind(1));
cycle = t./per;
phase = cycle – floor(cycle);

fig8 = figure(8);
plot([phase phase + 1], [y y], ’b∗’)
xlabel(’Phase’, ’Interpreter’, ’latex’)
ylabel(’$\Delta f/f$’, ’Interpreter’, ’latex’)
set(gca, ’LineWidth’, 1, ’FontSize’, 14);
saveas(fig8, ’Phased_delta_Xcorr.png’)
close(fig8)

% Using the line profile shit to Find RV values

for i = 1:30
a = load(strcat(’Data/hd_9468_obs_’, num2str(i), ’.dat’));

fig9 = figure(9);
plot(a(:, 1), a(:, 2), ’r−’)
set(gca, ’LineWidth’, 2, ’FontSize’, 14);
hold on
q = find((a(:, 1) < 6) & (a(:, 1) > −5));
nq = numel(q);

plot(a(q), a(q), ’c. ’, ’MarkerSize’, 10)
f = fit(a(q), a(q, 2), ’poly2’);
coeffs = coeffvalues(f);
rvel2(i) = −coeffs(2)/(2*coeffs(1));
cc = confint(f);
dc = coeffs – ci(1,:);

rvel2(i) = sqrt(dc(2)^2/(2 * coeffs(1))^2 + coeffs(2)^2 * dc(1)^2/(2 * coeffs(1))^2);

rvel2(i) = rvel2(1:30) * 1000; % km/s

std2 = std(rvel2(1:30))

mvel2 = sum(rvel2(1:30).’/drvel2(1:30).’^2) / sum(1./drvel2(1:30).’^2)

rvelshift = rvel2 − mvel2;
% Plotting unphased data with other RV data:

figure(4);
errorbar(jd−7320, rvel2(1:30)−mvel2, drvel2(1:30), 'r.', 'MarkerSize', 10)

B = fitsin(jd−7320, rvel2(1:30)−mvel2, drvel2(1:30), period);

b = B(1:3);

unc_b = B(4:6);
amplitude_b = sqrt(b(2)^2 + b(3)^2)

figure(4)
plot(tt−7320, b(1) + b(2)∗sin(2∗pi∗tt/period) + b(3)∗cos(2∗pi∗tt/period), 'r−−')
saveas(fig4, 'RV_sinfits.png')

% Lomb−Scargle Period search
%
% first create a vector of frequency bins, 1 per Hz
logper = 0.17:0.0001:1;
per = 10.^logper;
f = 1./per;
[Prob, Prob] = lomb(jd−7320+0.05,−rvel2(1:30)−mvel2, f);

t = jd−7320+0.05;
y = −rvel2(1:30)−mvel2;

fig10 = figure(10);
hold on
plot([−0.27 −0.27], [0 2.5], 'b−−')
xlabel('log_10 Frequency (1/d)', 'Interpreter', 'latex');
ylabel('Normalized PSD', 'Interpreter', 'latex');
title('Lomb Periodogram', 'Interpreter', 'latex');
set(gca, 'LineWidth', 2, 'FontSize', 14);
saveas(fig10, 'Lomb_periodogram_line.png')

% then sort for smallest values first
% (ie. those points least likely to be random)
%
[p, ind] = sort(Prob);
most = ind(1:5);

ANS = [f(most)∗1./f(most)∗Pn(most)∗Prob(most)]

% plot the phased data
%
per = 1/f(ind(1));
cycle = 1./per;
phase = cycle − floor(cycle);

fig11 = figure(11);
plot([phase phase+1], [y y], 'b∗')
xlabel('Phase', 'Interpreter', 'latex');
ylabel('$\Delta f/\Delta f$', 'Interpreter', 'latex')
LISTING D.6: Calls the aforementioned functions in order to cross-correlate spectra and measure the line profile shifts in order to obtain RV measurements. The two RV data sets are fitted, searched for a period using Lomb-Scargle method, and plotted for comparison.
References


References


J. Pepper. KELT North & South candidate selection page. Access to the KELT North and South candidate selection page ("KELT Voting") is restricted to members of the KELT project., 2016.


References


