IN THE SHADOWS OF GIANTS: A TOMOGRAPHIC METHOD FOR ANALYSING THE ORBITS OF TRANSITING EXOPLANETS

Grant Robert MacKinnon Miller

A Thesis Submitted for the Degree of PhD at the University of St Andrews

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In the Shadows of Giants
A tomographic method for analysing the orbits of transiting exoplanets

by

Grant Robert MacKinnon Miller

University of St Andrews

600 YEARS

Submitted for the degree of Doctor of Philosophy in Astrophysics

26th September 2012
Declaration

I, Grant Robert MacKinnon Miller, hereby certify that this thesis, which is approximately 30,000 words in length, has been written by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

Date Signature of candidate

I was admitted as a research student in September 2008 and as a candidate for the degree of PhD in September 2008; the higher study for which this is a record was carried out in the University of St Andrews between 2008 and 2012.

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Abstract

The radial velocity anomaly which affects spectroscopic observations of stars undergoing transit by a companion body is known as the Rossiter-McLaughlin effect. This effect can be used to measure the obliquities of the orbits of transiting planets. In this thesis I present a tomographic method for analysing the effect, which manifests itself in stellar spectral line-profiles. I implement this method on seven systems known to host transiting planets, and some systems with early-type host stars, for which the transit events have not yet been shown to be the result of planetary companions.

Despite being well-suited to examining systems with early-type, rapidly-rotating host stars which have a more pronounced Rossiter-McLaughlin effect, I find the tomographic method is able to produce reasonable results for the system parameters of planets orbiting relatively slowly-rotating stars. I show that the method provides a significant increase in the accuracy of determinations of the stellar rotation rate and is able to better constrain values for the transit impact parameter.

Though I do not confirm the existence of any new planets around early-type stars, I do use the tomographic method to reject one candidate as a stellar eclipsing binary system, and also reveal that one of the candidate host stars is a non-radial pulsator. I show that the method is able to examine systems involving stars with a range of spectral types and rotation rates.
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Firstly I would like to thank my supervisor Professor Andrew Collier Cameron for his help and advice on all matters over the past few years. His infectious enthusiasm for the field of astrophysics has been an inspiration to me. Thanks to Rim for helping me with the reduction of my data and to David for being a cracking office-mate and for producing some lovely plots for me.

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Lastly I would like to dedicate this thesis to my amazing family. Especially my parents, who have always supported me in everything I have ever done. No-one could possibly wish for a more loving and caring Mum and Dad. Also to my sister Fiona for being a superb sibling and role model who I really look up to, and my nephew Finn, who was born at the very start of my postgraduate degree, and who, like me, is only just starting to understand what is out there in the night sky.
“This space we declare to be infinite, since neither reason, convenience, possibility, sense-perception nor nature assign to it a limit. In it are an infinity of worlds of the same kind as our own.”

Giordano Bruno, De l'infinito universo et mondi (1584)
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Introduction

1.1 A brief history

The idea of other worlds existing in orbit around distant stars is not a new one. It stretches at least as far back as the 16th century when Italian philosopher Giordano Bruno was burnt at the stake for his astronomical beliefs. Bruno’s then-controversial views included the belief that the other stars in the night sky were just like our Sun and would be surrounded by planets like those already known to exist in our Solar System. However, in terms of modern astrophysical research, the study of extrasolar planets (exoplanets) is a fledgling field. It was not until 1992 that the detection of the first planet orbiting another star was confirmed \cite{WolszczanFrail1992}. Interestingly though, this planet was orbiting a pulsar, and it wasn’t until even later, in
1995, that the first planet orbiting a Main Sequence star (similar to our Sun) was discovered (Mayor & Queloz, 1995).

Since then, the discovery rate of exoplanets has increased exponentially. There have been over one hundred ground and space-based planet-search projects (many still operating and some proposed for the future) utilising several different scientific methods in order to confirm the detection of planets orbiting distant stars. To date over 800 exoplanets have been discovered, with a wide range of masses, residing in almost 700 planetary systems, all (so far) within our own galaxy.

The driving aims of the search for exoplanets are learning about the distribution of planetary characteristics in our galaxy (is our planet, or indeed Solar System typical or a relatively unusual configuration?), refining our models of how planets and planetary systems form and evolve, and the ever-intriguing possibility of discovering small, Earth-like planets around main sequence stars capable of harbouring life.

1.2 Methods for detecting exoplanets

There are a number of different scientific methods that can be implemented in order to detect and confirm the existence of exoplanets. Most of these techniques involve observing the effect the planet has on its host star, as the planet is too small and faint (compared to its nearby star) to be resolved directly with current instruments. Each method has its own advantages and disadvantages, and sensitivity to different regions of the planet parameter space. The following is an overview of each of the detection methods which have been successfully implemented in the search for exoplanets to date.

1.2.1 The radial velocity method

The idea of using the radial velocity variations of stars to detect planets dates as far back as 1952 (Struve 1952), though it was not until Latham et al. (1989) used it to discover a substellar companion to the solar-type star HD 114762, with a minimum mass of \(11M_{\text{Jup}}\), that it was shown to be possible. The method involves measuring the 'Doppler wobble' in the
stellar spectrum due to the changing radial velocity of the star. The stellar wobble is caused by the gravitational pull of an orbiting planet. The more massive the planet the larger the radial-velocity shift. The Doppler shift of the light in the stellar spectrum is usually measured by taking an average of the star’s spectral lines and measuring how the centroid of this average line profile moves over a period of time. The shifting spectrum gives information on the period of the planet’s orbit and a lower limit for the mass of the planet. The true mass cannot be found using this method alone, as the inclination, \( i \), of the planet’s orbital axis to our line-of-sight is not known. Therefore the planet masses derived from radial velocity measurements are always stated as \( M_P \sin i \).

At the moment the radial velocity method is by far the most productive method for discovering extrasolar planets, with over half of the known extrasolar planets having been discovered from radial velocity measurements alone. The radial velocity method is well suited to detecting large planets around relatively nearby stars, as the brighter the star and the larger the Doppler shift the easier it is to measure. Younger hot stars earlier than around F5 on the main sequence pose a problem for radial velocity searches due to their lack of spectral lines and increased chance of rotational broadening.

The amplitude of the stellar radial velocity variation, \( K_* \), is related to the mass of the orbiting companion by the equation:

\[
K_* = \frac{2 \pi a M_P \sin i}{(M_P + M_*) P \sqrt{1 - e^2}} \tag{1.1}
\]

where \( a \) is the orbital semi-major axis, \( P \) is the period of orbit and \( e \) is the orbital eccentricity. Therefore by estimating \( M_\text{s} \) from the spectral type and assuming a circular orbit and \( M_\text{s} \gg M_P \), \( M_P \sin i \) can be measured directly from the maximum radial velocity shift.

Figure 1.1 shows an example of the sinusoidal curve that is produced from radial velocity measurements. This particular set of data was used to confirm the existence of the planet WASP-2b (Collier Cameron et al. 2007a).

### 1.2.2 Gravitational microlensing

When a foreground star passes directly between the Earth and a background star it can magnify the light from the background star (see Figure 1.2). This effect is known as gravitational
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Figure 1.1: Plot of the radial velocity data for WASP-2b. The top panel shows the data over multiple orbits and the bottom panel shows the phase-folded plot. Plot taken from Collier Cameron et al. (2007a).
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microlensing. If the foreground star (known as the 'lens star') has a planet orbiting it there is a chance that its gravitational field may cause a noticeable addition to the microlensing event (Gould & Loeb 1992). This method allows good measurement of the mass of the planet and is also capable of detecting low mass Earth-like planets (Beaulieu et al., 2006). One major disadvantage of microlensing as a planet searching method is that observations of each object can only be performed once, as it relies on the chance alignment of two stars separated by a large distance. This means there is no possibility of follow-up observations and all the analysis has to be done on one single event. However, gravitational microlensing is capable of detecting planets at much larger distances than the other detection methods which are limited to bright, nearby stars. It can be used to discover small planets as far away as the galactic bulge and is the only method capable of detecting free-floating planets (Gaudi et al., 2009).

![Figure 1.2: A lightcurve for object showing the increase in brightness observed by multiple telescopes as the lens stars passes in front of the background star. Plot taken from Bozza et al. (2012)](image_url)
1.2.3 Astrometry

Similar to the radial velocity method, astrometry involves observing the effect of the gravitational pull of a planet on its host star. Instead of dealing with the Doppler shift of the spectrum the astrometry method involves accurately measuring the position on the sky of the host star as a function of time (Combrinck, 1983). To date this method has not been used to detect any previously undiscovered extrasolar planets, however it has been used at least once to measure the mass of a known extrasolar planet (Benedict et al., 2002). Progress will be made in the field of astrometry with the launch of the Gaia mission in 2013 (Cacciari, 2009) and the proposed Near Earth Astrometric Telescope (NEAT) mission (Malbet et al., 2012).

1.2.4 Pulse timing

The period of a pulsar can be measured to an extremely high level of accuracy (Kaspi, 1995). Planets can be detected around pulsars due to the changes in arrival time of the pulses they cause via their gravitational pull on the pulsar (Wolszczan & Frail, 1992). The level of accuracy possible with pulsar timing means it is a good method for finding low mass planets, however it is often overlooked as it does not involve main sequence stars.

1.2.5 Transit-timing variations

The existence of some exoplanets has been confirmed by precise measurements of the small variations they cause in the transit timings of other known planets, or in the eclipse timings of binary star systems which have a planet in a circumbinary orbit (Nesvorný et al., 2012; Qian et al., 2011). Recently results from the Kepler Mission have shown how successful transit-timing variation measurements can be in confirming the existence of transiting planets in multi-planet systems (Ford et al., 2011; Fabrycky et al., 2012; Steffen et al., 2012). By showing that the transit timing variations are anti-correlated they are able to prove that the objects are dynamically perturbing each other and therefore are in the same system. By imposing dynamical stability over astronomical timescales they show the objects must have masses in the planetary regime.
1.2.6 Direct imaging

As mentioned in the introduction to this section, direct imaging of extrasolar planets is very difficult as they are extremely faint compared to their host stars. This means that so far detections have been restricted to massive Jupiter-like planets at large distances from their host stars (tens or even hundreds of AU). The first proposed image of an extrasolar planet was announced in 2004 (Chauvin et al., 2004). Since then there have been a handful of successful attempts (Marois et al., 2008; Kalas et al., 2008; Neuhäuser & Schmidt, 2012). Figure 1.3 from Marois et al. (2008) shows the high-contrast near infrared imaging of 4 planets orbiting HR 8799. As only the radius of the planet and not the mass can be estimated from this method there is often debate as to whether these large stellar companions are actually brown dwarfs.

Figure 1.3: Direct imaging of the four planets discovered orbiting HR 8799. Image from Marois et al. (2010).
1.2.7 The transit method

This method involves photometrically measuring the drop-off in brightness observed when a planet crosses the stellar photosphere of its host star and blocks a small portion of the emitted light as seen from the Earth’s viewpoint, just as occasionally happens with the transits of Venus and Mercury in our own solar system [Deeg 1998]. Even for a large, Jupiter-sized planet the dip in brightness is still only very small (∼1%). The radius of the eclipsing object can be estimated from the magnitude of the dip in light. Photometric transit observations also provide information on the inclination of the planet’s orbit, therefore combining transit observations with radial velocity measurements is an ideal way to reveal the true mass and density of the planet. One disadvantage of this method is that only a small fraction of stars have planets orbiting at inclinations that would cause a transit event as seen from Earth. The fraction also decreases as a function of the planet’s distance from its host star. The probability of a planet’s orbit being aligned so that it is seen to transit decreases as a function of its orbital separation from its host star [Horne 2003]:

\[ P_t \approx \frac{R_*}{a}, \] (1.2)

where \( R_* \) is the stellar radius and \( a \) is the orbital semi-major axis of the planet. Therefore if it were our Solar System being observed, the probability of the Earth transiting the Sun would be roughly 0.5%. For Jupiter, even though it is much larger than the Earth, the probability drops to 0.1% due to its larger separation from the Sun. Larger planets cause greater dips in the brightness of their host star making them easier to detect compared to small, Earth-like planets. There is also more chance of detecting a planet with a short orbital period (∼1 – 5 days) as the fraction of time it spends in-transit is higher and multiple transit observations can be made in a short space of time. Putting all of these factors into consideration it becomes clear that transit surveys are very good at finding large, gas-giant planets which orbit very close to their host stars (< 0.1AU) with short orbital periods. These planets are known as ‘hot Jupiters’ due to their physical similarity to our planet Jupiter and their close proximity to their stars.

To maximise planet detection rate, transit searches tend to be wide-field surveys which target a large number of relatively bright, nearby stars at the same time. These bright systems are amenable to radial-velocity follow-up observations, which are required to confirm
the mass of the transiting object. These wide-field, ground-based transit surveys have major
difficulties detecting smaller, Earth-like planets, which exist in the habitable zone around their
star, with orbital separations $10 - 100$ greater than those of hot Jupiters. This is due to their
long periods, minute transit depths ($\sim 0.1\%$) and low probability that the inclination of the sys-
tem allows their transits to be visible from Earth.

Transit searches also suffer from false-positive detections. These are cases where the pres-
ence of a planet-mass object is mimicked by some other type of astrophysical object. Examples
of this include grazing eclipsing binary stars where only a fraction of the stellar companion is
transiting the target star leading to a planet-sized dip in light; stellar companions with radii
similar to planets, such as brown dwarfs and low-mass red dwarfs; and background eclipsing
binary systems which have their light diluted by that of the target star, resulting in a planet-
sized dip in the total light from both systems (Seager & Mallén-Ornelas, 2003). These last
systems are known as blended eclipsing binaries. There are various ways to eliminate these
false-positives by performing follow-up observations. As mentioned previously, radial velocity
measurements provide a measure of the mass of the companion object, so in conjunction with
photometric transit measurements a precise measure of the mass and density can be made,
and one can rule out objects such as brown dwarfs which are too massive to be planets. The
shape of the lightcurve helps rule out grazing eclipsing binary detections. Due to the limb
darkening of the host star a grazing object will produce a more V-shaped lightcurve than the
typical U-shaped one produced by a planet. Blended eclipsing binaries can be ruled out by
performing follow-up photometric observations with larger telescopes which can resolve all of
the stars in the original field of view. Torres et al. (2011) developed a sophisticated procedure
called BLENDER which models the photometry in terms of a 'blend' rather than transiting
planet signature, in order to eliminate these false-positives from a photometric dataset. Trans-
sit surveys can also suffer from false-alarms. Unlike false-positive detections, false-alarms do
not involve a genuine eclipse by an astrophysical object. One source of false-alarms is cor-
related noise, or "red noise" (Pont et al., 2006) which can create underlying fluctuations in
the transit lightcurve on the order of $\sim 1$mmag which is the same as the drop in brightness
caused by a transiting planet. Figure 1.4 illustrates how a mixture of white and red noise
can produce a lightcurve with dips on the same order of those which would be caused by a
transiting planet.
Figure 1.4: The top panel shows a lightcurve with uncorrelated ("white noise") only. The middle panel shows red noise only. The bottom panel shows the result of combining the red and white noise. The bottom lightcurve has features which resemble transit lightcurves produced from high precision, wide-field surveys. [Pont et al., 2006].
1.2. Methods for detecting exoplanets

There are many system parameters which can be measured through photometric observations of the star. Kepler’s third law means that by measuring the period $P$ of the transiting planet (i.e. the interval between successive transits), and estimating the stellar mass $M_\star$ from its spectral type, one can calculate a value for the orbital separation of the planet, $a$:

$$a^3 = \frac{G(M_\star + M_P)}{4\pi^2} P^2,$$  \hspace{1cm} (1.3)

where $M_P$ can be neglected if we assume that $M_\star \gg M_P$.

Values for other system parameters can be gained by analysing the shape of the transit lightcurve, which is a plot of how a target star’s brightness drops as a planet passes in front of its disc. It is the characteristics of the transit lightcurve (width, depth, duration of ingress/egress) that are the key to determining the major parameters of the system such as the radius of the planet $R_P$, the orbital inclination $i$ and the impact parameter (how close to the centre of the stellar disc the transiting object crosses) $b$.

Figure 1.5 shows the measurable components of a transit lightcurve. The transit duration $l$, the ingress and egress duration $w$, the transit depth $d$ and the central curvature $C$. The reason that the transit lightcurve is not exactly box-shaped and rather has sloped edges and a curved base is due to stellar limb-darkening. The stellar radius can be calculated from the transit duration $l$, impact parameter $b$ and transit depth $d$ using the relation

$$R_\star \frac{a}{l} = \frac{\pi}{P} \left(1 + \sqrt{d} \right)^2 - b^2,$$  \hspace{1cm} (1.4)

where the impact parameter $b$ is a value between 0 and 1 representing how close to the centre of the stellar disc the planet is during mid transit (Collier Cameron et al., 2007b). It is related to the orbital inclination via the relation $b = a \cos \frac{i}{R_\star}$. Neglecting limb darkening, Seager & Mallén-Ornelas (2003) show that the transit depth $d$ provides an estimate for the radius ratio of the star and planet:

$$d \equiv \frac{F_{\text{out of transit}} - F_{\text{in transit}}}{F_{\text{out of transit}}}. \hspace{1cm} (1.5)$$

The flux $F$ from the star is emitted from an area $A_\star$ and the flux blocked by the planet during transit is is equivalent to the area of the planet $A_P$. So substituting we get
Figure 1.5: Schematic of an ideal transit lightcurve from Brown et al. (2001).
1.2. Methods for detecting exoplanets

\[ d = \frac{A_s - (A_s - A_p)}{A_s} = \frac{A_p}{A_s}, \quad (1.6) \]

and substituting in the radii of the star and planet we get

\[ d = \frac{\pi R_p^2}{\pi R_s^2} = \left( \frac{R_p}{R_s} \right)^2, \quad (1.7) \]

So if an estimate of the stellar radius can be made from the spectral type we can measure the radius of the planet from the depth of the transit. Tingley & Sackett (2005) find that to account for limb darkening, the right hand side of this equation should be multiplied factor of roughly 1.3. Mandel & Agol (2002) presented useful analytic formulae for modelling transit lightcurves using limb-darkening coefficients from model atmospheres.
The first successful detection of an extrasolar planet using the transit method was made by Charbonneau et al. (2000). They observed two transits of HD 209458b for which radial velocity variations had already been reported by Henry et al. (1999). The observations were taken using the STARE project’s Schmidt camera which has a 6° field-of-view and a 2048x2048 pixel CCD. The observations suggested values $R_P = 1.27 \pm 0.02 R_J$ for the radius of the planet and $i = 87.1° \pm 0.2°$ for the inclination of its orbit to the line-of-sight. Using the results from the previous radial-velocity measurements combined with their value for the orbital inclination, Charbonneau et al. calculated a value for the planet’s mass of $M_P = 0.63 M_J$. Using the values for the radius and mass of the planet they were also able to calculate its average density, surface gravity and escape velocity. A high-precision photometric lightcurve of HD 209458 taken using the Hubble Space Telescope can be seen in Figure 1.6.

Since this first detection by Charbonneau et al. many transit surveys have monitored the brightness of millions of stars in our galaxy in the hope of detecting the tell-tale periodic dips in flux. To date there have been 285 planets discovered using this method (roughly one third of all known planets). Among the surveys that have been the most successful are the ground-based TrES, OGLE-TR, HATNet, XO and SuperWASP surveys (Alonso et al. 2004).

Figure 1.6: Lightcurve of HD 209458 taken with the STIS spectrograph on the Hubble Space Telescope (Brown et al., 2001).

http://exoplanet.eu/catalog-transit.php
The SuperWASP Project

The work in this thesis is based on observations of planets and planet candidates detected through the SuperWASP project. In the following section the project, its goals and success will be outlined.

1.2.8 Other possible methods for exoplanet detection

Other detection methods which have been proposed include using a polarimeter to detect the polarized light that the planet is reflecting, looking for features in circumstellar discs which are caused by the presence of planets and measuring light variations caused by the changing orbital phase of a planet.

A plot showing mass vs semi-major axis for all exoplanets discovered by all the methods described above can be seen in Figure 1.7. It nicely highlights which regions of the parameter space each detection technique is sensitive to.

1.3 The SuperWASP Project

The SuperWASP (Super Wide Angle Search for Planets [Pollacco et al., 2006a]) project is the world’s leading ground-based search for transiting extrasolar planets. It is operated by eight academic institutions in the UK and the Canary Islands, namely: Queens University Belfast, the University of St Andrews, Keele University, the University of Leicester, the Isaac Newton Group of telescopes, the University of Cambridge, the Open University and the Instituto de Astrofísica de Canarias. It involves two remotely operated observatories, one in each hemisphere so as to observe the whole sky. SuperWASP-North, which experienced first light in 2004, is located amongst the Isaac Newton Group of telescopes at the Observatorio del Roque de los Muchachos on the island of La Palma in the Canary Islands. SuperWASP-South is located at the South African Astronomical Observatory station in Sutherland, South Africa and made its first observations in 2006.

The predecessor of SuperWASP was the WASP0 camera which operated on La Palma in 2000 and in Greece in 2001. It consisted of a Nikon 200mm f/2.8 telephoto lens and an Apogee AP10 CCD. WASP0 was shown to be capable of detecting variable stars and managed to detect
Figure 1.7: Plot of mass vs semi-major axis for all planets discovered as of December 2011. Exoplanets discovered via the transit method are denoted by blue circles, radial velocity method by black wedges, microlensing by red stars, timing by grey squares, and direct imaging by orange triangles. Plot courtesy of Keith Horne (http://star-www.st-and.ac.uk/kdh1).
the transit of the known planet HD 209458 (Kane et al., 2004).

1.3. The SuperWASP Project

1.3.1 The Telescopes

Each observatory consists of a robotic equatorial fork mount which holds 8 Canon 200mm f/1.8 lenses backed with high quality 2048x2048 pixel CCDs (see Figure 1.8). The entire assembly is housed in a small enclosure with a retractable roof. The opening/closing of the roof, pointing of the cameras and data taking are all fully automated. Each camera has a 7.8° × 7.8° field-of-view meaning the total FOV is almost 500 square degrees (30 degrees in declination by 1 hour in right ascension (Pollacco et al., 2006a). Initially the set-up did not include any optical filters, however infrared blocking filters, which allow light in the range 400nm - 700nm to be transmitted, were installed on both the northern and southern facilities before the start of regular operations in early 2006.

1.3.2 Data Pipeline and Archive

During an average night’s observing session, the SuperWASP cameras take almost 1000 frames. Each frame is an 8.4MB FITS file (Street & SuperWASP Consortium, 2004). Bias, dark-current and flat-field exposures are taken at dusk before each observing session and at dawn at the end of the night. Each frame is checked and ones with any irregularities are rejected before the master bias, dark and flat files are created. The data is processed using a customised data reduction pipeline written by the SuperWASP project members. It creates a photometric input catalogue of all objects within the CCD boundary using the USNO-B1.0 catalogue. It then performs aperture photometry on each object that is brighter than a certain magnitude. The aperture photometry is performed for 3 apertures of 2.5, 3.5 and 4.5 pixel radius (1 pixel is 13.7 arcseconds on the sky) centered on each qualifying object. The sky background is calculated using an annulus of 13 pixel inner and 17 pixel outer radius making it ten times greater in area than the 3.5 pixel aperture (Pollacco et al., 2006c). The processed data is then stored in an archive along with the raw images. Before being searched for transits using the code developed by Collier Cameron et al. (2007c), the data is run through the SysRem and TFA decorrelation algorithms in order to remove some of the systematic errors (Mazeh et al., 2007; Kovács et al., 2005). The archive contains a catalogue of objects with each individual object having its own page which can be added to by members of the project as they analyse
Chapter 1. Introduction

Figure 1.8: The SuperWASP-North assembly on the island of La Palma (from www.superwasp.org/).

Figure 1.8: The SuperWASP-North assembly on the island of La Palma (from www.superwasp.org/).
1.3.1 The SuperWASP Project

The data.

1.3.3 The WASP Planets

SuperWASP detected its first planet (WASP-1b) in 2006 [Cameron et al., 2007]. WASP-1b is a hot Jupiter with a radius of $1.33-2.53 R_J$ and a mass of $0.80-0.98 M_J$. It was first detected as a photometric transit in the 2004 season of SuperWASP data and was later confirmed as a planet using the SOPHIE spectrograph at the Observatoire de Haute-Provence. Since then the SuperWASP project has become the most successful ground-based transiting planet survey and has discovered over 80 transiting extrasolar planets to date[3]. The planets discovered by the survey are all hot gas-giants, ranging from the Saturn-sized WASP-29b to the $10 M_J$ planet WASP-18b.

1.3.4 Follow-up observations

The SuperWASP project also performs follow-up photometry and radial velocity measurements using several telescopes in different locations around the world. These follow-ups are performed on the best candidates, from the initial photometric observations from the WASP cameras, to confirm whether or not a planet is causing the observed brightness variation. There are many telescopes across the globe which are used to perform follow-up observations of candidates first detected in the data from La Palma and Sutherland. The main instruments used for radial velocity follow-up observations are the Coralie spectrograph ($R = 50,000$) on the 1.2 m Swiss Euler Telescope at La Silla in Chile, and the Sophie spectrograph ($R = 75,000$) on the 1.93 m telescope at Haute-Provence Observatory in the south of France. Multiple telescopes are used to perform photometric follow-up observations of SuperWASP targets, including the UK's largest optical telescope, the 1 m James Gregory Telescope (JGT) housed at the University of St Andrews observatory.

During the course of my doctorate degree I have spent over one hundred nights observing on the JGT, the results of which have lead to the rejection of multiple SuperWASP candidates as astrophysical false-positives, and I have also helped in the confirmation of multiple WASP planets. Figure 1.9 shows a comparison of follow-up photometry of the planet Qatar-1b (the first planet announced by the Qatar Exoplanet Survey, QES [Alsubai et al., 2011]) from 3 ground-based telescopes at different locations in the northern hemisphere. The data for

Chapter 1. Introduction

the two curves in the middle of this figure were taken by myself from the JGT and were subsequently used to confirm that the transiting companion was of planetary radius.

I have also been on one radial velocity follow-up run on the Nordic Optical Telescope (NOT) located at the Roque de los Muchachos Observatory on La Palma in the Canary Islands, and two separate observing runs on the 1.93-m telescope at the Haute-Provence Observatory. The data taken from these runs has lead to the mass confirmation of multiple WASP planets.

![Figure 1.9: The top lightcurve was taken using the 60 cm telescope at Keele University. The middle two lightcurves were taken by the author using the James Gregory Telescope at St Andrews, and the bottom lightcurve was taken using KeplerCam on the 1.2 m telescope at the Fred Lawrence Whipple Observatory in Arizona. The figure is taken from the discovery paper Alsubai et al. (2011).](image)

1.4 Planet formation and orbital evolution

When they were first discovered, hot Jupiters provided a puzzle for planet formation and evolution theorists. Before the discovery of 51 Peg in 1995, not many astrophysicists considered the idea that gas giants could exist in orbits much smaller than those observed in our own
Solar System. It can be shown that in the core-accretion scenario of gas giant formation (Pollack et al., 1996), which is currently the most widely accepted formation model, these planets must form beyond a certain distance from their host star known as the ‘snow line’, where temperatures are low enough (~150 K) for ice to form on dust grains therefore allowing them to clump together (Sasselov & Lecar, 2000). This point occurs around 4 AU from a Sun-like star. The existence of gas giants at orbital separations smaller than 0.1 AU therefore means that instead of forming in-situ they must migrate inwards through the system towards their host stars after they form. There is no clear consensus on how these planets undergo migration, however there are a few leading theories. The initial view of planet migration involves the planet undergoing gravitational interactions with a protoplanetary disc causing the planet to lose angular momentum and move inwards through the disc (Goldreich & Tremaine, 1980).

Assuming the protoplanetary disc is aligned with the stellar spin axis, this process would lead to planets in well-aligned orbits around the equator of their host star. However, there have more recently been several observations of planets confirmed to be on highly misaligned orbits (Triaud et al., 2010; Albrecht et al., 2012a; Anderson et al., 2010). This has lead to processes such as planet-planet scattering and the Kozai mechanism with tidal dampening being viewed as the most likely methods for transporting gas giant planets inwards through their systems (Weidenschilling & Marzari, 1996; Fabrycky & Tremaine, 2007; Nagasawa et al., 2008; Winn, 2011).

The Kozai mechanism requires there to be another massive perturbing body, such as a nearby stellar companion, in a more distant orbit around the star. Kozai (1962) found that if the orbit of the outer companion is inclined above a critical angle (~40°), the inclination, I, and eccentricity, e, of the inner companion (in our case the hot Jupiter) will vary cyclically, with the value of \((1 - e^2) \cos I\) being conserved. As the orbital eccentricity of the gas giant increases it will experience strong tidal interactions with its host star while at periastron. These tidal interactions will serve to shrink and circularise the orbit. The inclination of the orbit once it has become circularised is essentially random, and there is no reason to expect it to be well-aligned such as is the case with disc migration.

In a recent paper expanding on the work by Winn et al. (2010), who observed a relation between the level of spin-orbit misalignment and stellar effective temperature, Albrecht et al. (2012a) present evidence that the orbits of all hot Jupiters may initially be randomly aligned, due to planet-planet interaction and/or the Kozai mechanism, and that some of them realign.
via tidal interactions. They present Rossiter-McLaughlin analysis of 14 hot Jupiter systems and their results show that those which are well-aligned appear to have short tidal timescales, with the misaligned systems having longer timescales for tidal interactions.

It is worth pointing out the possibility that disc migration could actually lead to misaligned systems if, for some reason, the stellar spin axis and protoplanetary disc plane were out of alignment before the planet migrated inwards. In a recent study [Watson et al. (2011)] were able to estimate the stellar rotation axis of a number of stars with spatially resolved debris discs. Their results showed no evidence of misalignment between the debris disc plane and the axis of rotation of the host star.

1.5 The Rossiter-McLaughlin Effect

The alignment of orbital planes is of high relevance to planet migration models. Extrasolar planet searches have yielded a large number of gas giant planets orbiting close (< 1AU) to their host stars. These planets are known as 'hot Jupiters' and, as mentioned in the previous section, current theories suggest they would have to form at greater distances and then migrate inwards to their current observed separations. Measurements of the distribution of \( \lambda \) will help to inform us which of the different theories of migration are the most plausible, as some migration mechanisms would conserve coplanar orbits and others would effectively randomise \( \lambda \).

One way to test migration theories is to measure the distribution of obliquities in the orbits of the current dataset of planets. The degree of misalignment of the stellar spin axis and planet orbital axis can be determined via the Rossiter-McLaughlin (RM) effect. The RM effect is the name given to the anomalous variation in radial velocity of a star caused by an opaque object passing over the stellar disc. The effect is observed due to stellar rotation. The rotation of the star causes one half of its disc to appear blue-shifted and the other half to appear red-shifted. Now imagine a smaller body, such as a planet, transiting the stellar disc. When over the approaching side of the disc, the planet blocks some of the blue-shifted light making the starlight appear slightly red-shifted. The opposite happens when the planet is over the receding half of the disc. When the planet is in front of the stellar rotation axis it causes no anomalous shift. The effect was first described separately by Rossiter and McLaughlin in 1924, who observed the anomaly in eclipsing binary star systems [Rossiter 1924, McLaughlin]
1.5. The Rossiter-McLaughlin Effect

The two main parameters of a system that can be calculated using the RM effect are the projected stellar rotation rate, \( V \sin i \), and the projected spin-orbit misalignment angle (\( \lambda \)) of the stellar rotation axis and planet orbital axis. \( V \sin i \) is related to the amplitude of the anomalous radial velocity signal, and \( \lambda \) can be derived from the symmetry of the RM feature. For example if the planet was orbiting in a plane perpendicular to the axis of stellar rotation the amount of red-shifted and blue-shifted light would be equal. This case is defined as \( \lambda = 0^\circ \) for a planet orbiting in the same direction as the stellar rotation, and \( \lambda = 180^\circ \) for a planet in a retrograde orbit. Values of \( \lambda \) can range from \(-180^\circ\) to \(+180^\circ\) with positive values representing a planet moving towards the stellar north pole as it transits. Figure 1.10 shows the radial velocity anomaly produced via the RM effect in three different scenarios, each with the same impact parameter but with different spin-orbit misalignment angles. The bottom panel in Figure 1.11 shows the full radial velocity curve for the planet WASP-13b, with the predicted RM effect anomaly at transit (phase 1).

Queloz et al. (2000) were the first to successfully detect the spectroscopic transit of an exoplanet when they used the ELODIE spectrograph on the 1.93 m telescope at Haute-Provence Observatory to observe the RM effect caused by HD 209458b. They found the planet to be in a well-aligned orbit, with \( \lambda = 3.9^{+18}_{-20}^\circ \).

Winn et al. (2010) show an observed relationship between the degree of misalignment and the stellar effective temperature, with orbits being preferentially misaligned around stars with \( T_{\text{eff}} > 6250 \) K. In a follow-up study Albrecht et al. (2012a) expand on this result by defining a 'tidal timescale', based on orbital separation, stellar effective temperature and planet-star mass ratio, on which a hot Jupiter can realign with its host star. Both studies suggest that hot-Jupiters initially have a random distribution of obliquities and then some fraction become re-aligned due to tidal interactions. More measurements of \( \lambda \) for a broader range of planetary systems will help to refine these observed relationships and, in turn, inform theories of planetary evolution and migration.

The next chapter of this thesis presents a description of the methods used to analyse the RM effect and goes on to introduce a new method for analysing RM observations which can access a new region of the planet parameter space. In chapter 3 this new method is applied to the planet WASP-3b, which is well-suited to this type of analysis as a case study to showcase
Figure 1.10: The RM waveforms for three different planet trajectories. Notice all three have identical impact parameter so therefore would have identical photometric transit signatures. The solid lines include the effect of limb darkening [Gaudi & Winn, 2007].
1.5. The Rossiter-McLaughlin Effect

The Rossiter-McLaughlin (RM) effect is a characteristic of binary systems where the absorption of light from one star is modulated by the silhouette of the other star. This effect is often used to determine the orbital inclination of close binary systems.

The power of the new technique. In chapter 4, RM data for multiple WASP planets which present more of a challenge to the technique are examined to show how the new method performs on stars with slower rotation rates. In chapter 5 the new method is applied to candidate planets from the SuperWASP survey around hot, rapidly-rotating stars in an attempt to examine a sparsely populated region of the parameter space and add valuable data which will help answer the question of which migration mechanism for hot Jupiters is dominant.

Chapter 6 is a discussion and summary of the various conclusions reached throughout, and finally the future prospects for the work are outlined.
Chapter 1. Introduction
In this chapter we describe how the Rossiter-McLaughlin (RM) effect can be analysed in order to reveal the orbital dynamics of a transiting system, along with other stellar and planetary parameters. We discuss the previous methods used to analyse the effect, and also the problems inherent in these methods. Finally, we present a new tomographic method for analysing the RM effect which is not affected by the same issues.
2.1 Introduction

Measuring the distribution of spin-orbit alignments of known planetary systems helps to shed some light on the hot Jupiter migration process (or processes) and to refine models of system evolution. The projected spin-orbit misalignment angle between the planet's orbital axis and the rotation axis of the host star can be determined via the Rossiter-McLaughlin effect. As described in Chapter 1, the RM effect is the radial velocity anomaly observed during transit due to the Doppler shadow of the companion moving across the stellar photosphere. For example, a planet in a prograde orbit will first block some blue-shifted light, from the half of the stellar photosphere which is rotating towards us, causing an anomalous red-shift in the star's radial velocity. Then once it has crossed the stellar rotation axis it will block light from the receding half of the stellar disc causing an anomalous blue-shift. Conversely, a planet orbiting in the retrograde direction will first cause an anomalous blue-shift followed by an anomalous red-shift in the radial velocity measurement of the host star. The form of the observed RM effect is therefore determined by the projected stellar rotation velocity $v \sin I$, the projected spin-orbit misalignment angle $\lambda$, the impact parameter $b$ and the radii of the star and planet. We use $I$ to denote the inclination of the stellar spin axis to the line-of-sight, and it is not to be mistaken with $i$, which is the inclination of the planet's orbital plane to the line-of-sight.

2.2 Methods for analysing the Rossiter-McLaughlin effect

Despite the RM effect first being measured for a binary star system in 1924 (Rossiter, 1924; McLaughlin, 1924), it was not until 74 years later that Queloz et al. (2000) observed the effect caused by a transiting exoplanet. They created a model of the system, splitting the stellar disc into 90,000 sections for which they calculated individual surface brightness and spectral line-profiles. They then simulated the in-transit spectrum by summing all the individual sections not obscured by the planet and then calculated the Doppler shift of the simulated spectrum and compared it to their observations in order to measure $\lambda$ and $v \sin I$. Ohta et al. (2005) and Giménez (2006) derived detailed analytic expressions for measuring the anomalous radial velocity shift in the centroid of the average line-profile during transit. Using the radial velocity shift to determine the parameters related to the Rossiter-McLaughlin effect can be a problem when the spectrograph used to take the observations can resolve the stellar line...
2.2. Methods for analysing the Rossiter-McLaughlin effect

profile. The data reduction pipelines for instruments such as SOPHIE and HARPS calculate radial-velocities by fitting a Gaussian profile to the cross-correlation function (CCF) in order to measure the shift in line centroid. However, as the planet is blocking some of the light from the star this shows up on the line profile as a travelling ‘bump’ of width equal to that of the local non-rotating intrinsic line profile. This means that the spectral line profile is now asymmetric and time-varying during transit, introducing a systematic deviation to measurements of the radial velocity. Winn et al. (2005) showed that the formula of Ohta et al. (2005) leads to an over-estimation of the magnitude of the anomalous radial-velocity shift. This problem is especially noticeable in the resulting measurements of $v \sin I$, with Gaussian-fitting RM analyses consistently producing artificially high values when compared with results from spectral-synthesis. The degree of error becomes greater for more rapidly rotating host stars as their line profiles exhibit higher degrees of rotational broadening and the bump produced by the planet’s Doppler shadow becomes more pronounced (Hirano et al. 2009).

In more recent studies Winn et al. (2005, 2006, 2007) have employed a similar technique to that of Queloz et al. (2000) by building a grid of stellar surface brightness and velocity, simulating the transit spectrum and then comparing the model to their data. Winn et al. (2007) used an empirical template spectrum of the star, rather than a theoretical spectrum. This approach should do well to account for the systematic error present when just using the shift in line centroid and formulae from Ohta et al. (2005) to calculate the RM parameters. However, their method does not account for the problem entirely as their analysis of HD 189733b shows a clear pattern of correlated residuals in the radial velocities during transit (Winn et al. 2006). A similar pattern in the radial velocity residuals of HD 189733b was found by Triaud et al. (2009) who discuss their cause in detail. Simpson et al. (2010) also found a similar correlation pattern when analysing the WASP-3 system using the expressions from Ohta et al. (2005) with corrections developed by Hirano et al. (2009). An improved analytic formula for calculating the anomalous radial velocity shift due to the RM effect was presented by Hirano et al. (2011), taking into account effects thermal, instrumental and pressure broadening, and macroturbulence to better describe the stellar line-profile.

In order to eliminate the need for empirical corrections or complex analytic formulae Collier Cameron et al. (2010a) developed a new method that involves decomposing the stellar line profile into its various components, namely the limb-darkened rotation profile, Gaussian average line profile and the travelling signature caused by the transiting planet. By modeling
Chapter 2. The Rossiter-McLaughlin Effect

Each component of the deformed Gaussian line-profile, the trajectory of the bump can be tracked as it crosses the spectral line, leading to accurate measurements of $\lambda$, $v \sin I$, the width of the intrinsic stellar line-profile $v_g$ and $b$.

2.3 A new tomographic method for analysing the Rossiter-McLaughlin effect

The following methodology was first described in detail in Collier Cameron et al. (2010a).

As discussed previously, during a transit the stellar spectral lines are deformed by a time-variable feature moving across them, caused by the planet blocking a small portion of the emitted light from the star. In order to analyse this effect we first build a model of the average out-of-transit line-profile. This is done by convolving a Gaussian representing the the local line profile at any point on the surface of the star with a limb-darkened rotation profile. For the local line profile we use

$$g(x) = \frac{1}{\sqrt{2\pi s}} e^{-\frac{x^2}{2s^2}}, \quad (2.1)$$

where $x = \frac{v}{v \sin I}$ and $s = \frac{\sigma}{\sqrt{2}v \sin I}$

For the limb-darkened rotation profile we use the equation

$$f(x) = \frac{6[(1-u)\sqrt{1-x^2} - \pi u(x^2-1)/4]}{\pi(3-u)} \quad (2.2)$$

This expression is derived by assuming a linear limb-darkening model $B(\mu) = B(1)(1-u+u\mu)$ where $u$ is the limb-darkening coefficient and $\mu = \cos \theta$ is the direction cosine of the surface normal in relation to the line-of-sight at any particular point on the surface of the star ($\theta = 0$ at the centre of the stellar disc). We then substitute in $\mu = \sqrt{1-x^2-y^2}$ and integrate between $y = \pm \sqrt{1-x^2}$. Next we integrate the resulting equation over the range $-1 < x < 1$ in order to normalise it.

Both the functions for the local line profile and the limb-darkened rotation profile are normalised such that

30
\[
\int_{-\infty}^{\infty} g(x)dx = \int_{-1}^{1} f(x)dx = 1 \quad (2.3)
\]

To model the observed rotation profile we take the convolution of functions \(g(x)\) and \(f(x)\):

\[
h(x) = \int_{-1}^{1} f(z)g(x-z)dz \quad (2.4)
\]

which is calculated by numerical integration. We need to shift the model to account for the fact that the average line profiles are computed in the velocity frame of the Solar System barycentre. To do this we compute

\[
x_{ij} = v_{ij} - [K(e \cos \omega + \cos(v_j + \omega))] + \gamma \quad (2.5)
\]

where \(v_{ij}\) is the velocity of pixel \(i\) in the barycentric frame, \(v_j\) is the true anomaly at the time of the \(j\)th observation, \(\omega\) is the argument of periastron, \(e\) is the orbital eccentricity, \(K\) is the radial velocity amplitude and \(\gamma\) is the systemic centre-of-mass velocity.

At any particular moment in time, the position of the planet on the plane of the sky is given by the co-ordinates

\[
x_p = r \sin(v + \omega - \pi/2), \quad (2.6)
\]

\[
z_p = r \cos(v + \omega - \pi/2) \cos i, \quad (2.7)
\]

where \(r\) is the instantaneous distance of the planet from the star and \(i\) is the inclination of the orbital axis to the line-of-sight (see Figure 2.1). The perpendicular distance of the planet from the stellar rotation axis in units of \(R_*\) is now

\[
u_p = x_p \cos \lambda - z_p \sin \lambda, \quad (2.8)
\]

where \(\lambda = \phi_{\text{spin}} - \phi_{\text{orbit}}\) and \(\phi\) is the position angle in the plane of the sky (Winn et al., 2005).
Chapter 2. The Rossiter-McLaughlin Effect

The radial velocity of the missing starlight at any given point is therefore \( v_p = u_p v \sin I \) where \( v \sin I \) is the equatorial projected stellar rotation velocity. Combining the model out-of-transit line profile with the model of the missing starlight gives us

\[
p_{ij} = h(x_{ij}) + \beta g(x_{ij} - u_p).
\] (2.9)

Here the term \( h(x_{ij}) \) is the model of the out-of-transit stellar line profile. The term \( \beta g(x_{ij} - u_p) \) represents the travelling Gaussian planet signature caused by the missing starlight, where \( \beta \) is the fraction of starlight blocked by the planet during the total part of the eclipse and is expressed as

\[
\beta = \frac{R_p^2}{R_*^2} \frac{1 - u + u\mu}{1 - u/3}
\] (2.10)

![Diagram showing the various co-ordinates involved in modeling the RM effect. \( x_p \) and \( z_p \) are the co-ordinates of the planet on the plane of the sky, \( u_p \) is the projected distance of the planet from the stellar rotation axis, \( b \) is the impact parameter of the transit, and \( \lambda \) is the projected angle between the stellar rotation axis and the orbital axis of the planet. Diagram courtesy of Andrew Collier Cameron.](image)

Figure 2.1: Diagram showing the various co-ordinates involved in modeling the RM effect. \( x_p \) and \( z_p \) are the co-ordinates of the planet on the plane of the sky, \( u_p \) is the projected distance of the planet from the stellar rotation axis, \( b \) is the impact parameter of the transit, and \( \lambda \) is the projected angle between the stellar rotation axis and the orbital axis of the planet. Diagram courtesy of Andrew Collier Cameron.
2.3. A new tomographic method for analysing the Rossiter-McLaughlin effect

The co-ordinates described above can be seen in the context of a model transit in Figure 2.1.

2.3.1 Fitting the model

In order to orthogonalise the data $d_{ij}'$ and the model $p_{ij}'$ we subtract their optimal mean values using inverse-variance weights $w_{ij} = 1/\sigma_{ij}^2$:

$$d_{ij}' = d_{ij} - \frac{\sum_{ij} d_{ij} w_{ij}}{\sum_{ij} w_{ij}}, \quad (2.11)$$

$$p_{ij}' = p_{ij} - \frac{\sum_{ij} p_{ij} w_{ij}}{\sum_{ij} w_{ij}}. \quad (2.12)$$

The goodness of fit of the model to the observed data is then calculated using the $\chi^2$ statistic

$$\chi^2 = \sum_{i=1}^{n} \left( d_{ij}' - \hat{A} p_{ij}' - \alpha_i \right)^2 \omega_{ij} \quad (2.13)$$

where $\alpha_i$ is the optimal average of the residual spectra and $\hat{A}$ is a multiplicative constant calculated via optimal scaling:

$$\hat{A} = \frac{\sum_{ij} d_{ij}' p_{ij}' w_{ij}}{\sum_{ij} p_{ij}'^2 w_{ij}}. \quad (2.14)$$

If the spectral resolving power ($R = \lambda / \Delta \lambda$) of the spectrograph leads to a velocity resolution lower (numerically higher) than the minimum velocity increments used when producing the average line profile this will mean that the errors on the data from neighbouring pixels are correlated. In order to make sure our data points are statistically independent we bin them by a factor

$$\text{binfac} = \frac{\text{velocity resolution}}{\text{minimum velocity increment}} \quad (2.15)$$

before computing the $\chi^2$ statistic.
2.3.2 Markov chain Monte Carlo technique

Finally, the model parameters are calculated using a Markov chain Monte Carlo (MCMC) method using the Metropolis-Hastings algorithm to fit the model through $\chi^2$-minimisation \cite{Tegmark2004}. This method of MCMC was preferred over other such $\chi^2$-minimisation techniques as it does not get stuck in local minima as often, and the uncertainties on the parameters are calculated directly from the distribution of values produced as the chain searches for the global minimum. The MCMC code used for this study is a hybrid of the code previously used to calculate the parameters of the WASP systems from photometric and spectroscopic data sets \cite{CollierCameron2007}, and a new code developed by Collier Cameron et al. \cite{CollierCameron2010} specifically for tomographic RM analysis. Therefore at the same time as calculating the parameters from the RM effect we recalculate all the MCMC fitting parameters for the system.

The code includes the mass and radius calibration \cite{Torres2010} which was recently implemented in the MCMC analysis by Enoch et al. \cite{Enoch2010}. The method described by Torres et al. \cite{Torres2010} is used to derive the stellar mass and radius from polynomial functions of $T_{\text{eff}}$, $\log g$, and $[\text{Fe}/\text{H}]$. As in Collier Cameron et al. \cite{CollierCameron2010}, we replaced the width of the local non-rotating profile $s$ with $v_{\text{CCF}}$, the FWHM of the CCF in an attempt to avoid correlated pairs of jump parameters,

$$v_{\text{CCF}} = \sqrt{(v \sin I)^2 + v_g^2}, \quad (2.16)$$

where $v_g$ is the FWHM of the Gaussian representing the local stellar and instrumental line profile:

$$v_g = 2sv \sin I \sqrt{\ln 2}. \quad (2.17)$$

At each step in the chain the current values of the free parameters are altered by a Gaussian perturbation and then the goodness-of-fit is then recalculated. For example, the proposed next step for $\lambda$ is

$$\lambda_k = \lambda_{k-1} + f \sigma_{\lambda} G(0, 1), \quad (2.18)$$
2.3. A new tomographic method for analysing the Rossiter-McLaughlin effect

where \( f \) is a scale factor of order unity and \( G(0,1) \) is a random number drawn from a Gaussian distribution of zero mean and unit variance. Steps are accepted or rejected in accordance with the Metropolis-Hastings algorithm. After each proposed step \( \Delta \chi^2 = \chi_k^2 - \chi_{k-1}^2 \) is calculated. If \( \Delta \chi^2 < 0 \) then the proposed step is accepted. If \( \Delta \chi^2 > 0 \) then the step is accepted with a probability of \( e^{-\Delta \chi^2/2} \). Each successful step is recorded to the MCMC output. If a step is rejected by the code, the previous accepted step is recorded again. Varying the scale factor \( f \) changes the acceptance rate of the MCMC. Typically we find a suitable value for \( f \) of order unity.

For all datasets analysed we run the MCMC with an initial burn-in phase of around 500 steps. This allows the chain to settle down and find the region of the parameter space containing the minimum. After the first burn-in period we re-evaluate our estimates of the variances on the binned CCF data. We then run the chain for another 100 steps in order to re-evaluate the variances on the four RM fitting parameters from the chains. This is followed by a final production run of 10,000 steps from which we will obtain our final values and uncertainties for the free parameters, where \( f \) is fixed at a certain value, found by trial and error, to return the desired acceptance rate of 25%.

2.3.3 Implementation of the new method

The tomographic Rossiter-McLaughlin analysis method described above was first successfully implemented on a transiting planetary system by Collier Cameron et al. (2010a), who used it to confirm and improve upon the parameters for the planet transiting the star HD 189733. They found the planet to be in a very well-aligned orbit with a spin-orbit misalignment angle consistent with zero. It was then used by Collier Cameron et al. (2010b) to confirm the existence of the first planet transiting an A-type star (WASP-33b). They also used it to show that WASP-33b is in a highly-inclined, retrograde orbit with \( \lambda \approx 250^\circ \). It was subsequently used by Miller et al. (2010) to analyse the WASP-3 system, the results of which are discussed in detail in Chapter 3 of this thesis.

More recently it has been used by Gandolfi et al. (2012) to analyse the orbit of the hot Jupiter CoRoT-11b, and has been implemented in the analysis of WASP-32 and WASP-38 by Brown et al. (2012b). Chapter 4 of this thesis is based on a paper submitted to Monthly Notices of the Royal Astronomical Society by Miller et al. (2012) in which the method is used to analyse confirmed SuperWASP planetary systems with slower stellar rotation rates.
than most previous systems examined via the tomographic approach. A similar method was previously used to analyse the RM effect in the binary star systems V1143 Cyg and DI Herculis (Albrecht et al., 2007, 2009).

Unlike methods commonly used to constrain the parameters of transiting exoplanets, the tomographic method does not rely on high precision radial velocity measurements, making it uniquely useful for detecting planets orbiting rapidly-rotating early-type stars, such as WASP-33b. Many of these stars, which have reliable photometric data, have been dropped from radial velocity follow-up observations due to their rotational broadening and line-poor spectra which make it impossible to accurately measure the shift in the line centroid. The tomographic method is well-suited to analysing the time-varying radial velocity anomaly present in the spectroscopic observations of rapidly-rotating stars for which the magnitude of the effect is somewhat greater than that observed in more slowly-rotating Sun-like stars. This also gives it an advantage over any method which measures shifts in the line centroid in order to examine the RM effect, as these will experience large over-estimates of the radial-velocity shift during transit, leading to artificially high values for $v \sin I$, when looking at rapidly-rotating stars.

Chapter 5 is based on a paper (in preparation), also by the author, in which the method is used to try and confirm the existence of more planets orbiting younger, hotter stars.

This method involves analysing the the average line-profile of the multiple stellar spectral lines found in each spectral observation. The different spectrographs used to carry out the observations implement different methods for producing this average line-profile in their data reduction pipelines. The HARPS (Pepe et al., 2000) and Sophie (Bouchy & The Sophie Team, 2006) spectrographs, used to obtain the data analysed in Chapters 3 & 4, both produced average line-profiles as cross-correlation functions (CCF). The Narval spectrograph (Aurière, 2003), used to obtain the data presented in Chapter 5, produces average line-profiles via a least-squares deconvolution (LSD) method. We had no preference for either method, as our analysis just requires the average line-profiles to be input. The reason for using both methods was down to the fact that the data were not reduced by us. The average line-profiles are produced via the automated data reduction pipelines at the telescopes. The CCF and LSD methods for producing average line-profiles are not too different from each other. They both involves cross-correlating the observed spectrum with a line mask corresponding to a star of similar spectral type.
A case study: WASP-3b


In this chapter we implement the new tomographic method of Rossiter-McLaughlin analysis outlined in Chapter 2. Our target is the known hot Jupiter planet WASP-3b. We use this analysis of the WASP-3b RM dataset as a case study of the new method and to compare it to other methods of RM analysis which have been performed on the same system and data, making it a fair test of the power of transit tomography.
Chapter 3. A case study: WASP-3b

3.1 Introduction

To gain information on the distribution of spin-orbit misalignment angles, the WASP (Wide Angle Search for Planets) consortium has been performing follow-up spectrographic observations of the transits of the known WASP planets. Observations have been made using the HARPS spectrograph on the ESO 3.6m telescope at La Silla and the SOPHIE spectrograph on the 1.93m telescope at the Observatoire de Haute-Provence. In this study we implement the tomographic analysis method described in Chapter 2 to remove the inherent error present in results for stellar rotation rate when using the Gaussian-fitting method, by instead focusing on the light removed by the planet. We model all the components of the line-spread function and fit to spectral observations of WASP-3b in order to track the trajectory of the missing light component as it crosses the line profile during transit. A model of the out-of-transit profile is subtracted from the data leaving only the signature of the blocked light. The trajectory of this feature is used to derive values for the projected stellar rotation rate, the impact parameter and the spin-orbit misalignment.

WASP-3b is the third planet to be discovered by the SuperWASP survey (Pollacco et al., 2008). It is a hot Jupiter of mass $M_P = 1.76^{+0.08}_{-0.14} M_{\text{Jup}}$ and radius $R_P = 1.31^{+0.07}_{-0.14} R_{\text{Jup}}$. It is in a 1.85-day orbit around a main sequence star of spectral type F7-8V with effective temperature $T_{\text{eff}} = 6400 \pm 100$ K. The WASP-3 system is an ideal candidate for this study as, with a projected stellar rotation rate of $v \sin i = 13.4 \pm 1.5$ km s$^{-1}$ measured from spectroscopic analysis, it is one of the fastest-rotating host stars to harbour a WASP planet. As mentioned in the previous chapter, the tomographic analysis of the RM effect is well-suited to systems with rapidly-rotating host stars with their broader spectral lines and easily resolvable anomalies caused by the transiting planet.

Two previous studies (Simpson et al., 2010; Tripathi et al., 2010) have performed RM analysis of the WASP-3 system using non-tomographic techniques, one on the same observations as analysed here, and another on separate observations. This provides us with a good way to compare and contrast the separate methods of RM analysis and show the strengths of the tomographic technique.
3.2 Observations and analysis

We reanalyse data presented in Simpson et al. (2010), who used the SOPHIE echelle spectrograph (Bouchy et al., 2009) on the 1.93m telescope at the Observatoire de Haute-Provence to take 26 observations before, during and after the transit of WASP-3b on the night of September 30th 2008. A major advantage of this new method is that it does not require high precision radial velocity measurements, therefore the spectrograph was used in high efficiency mode ($R = 40000$). The exposure times for the observations ranged from 300 - 1800 seconds to ensure a constant signal-to-noise ratio of 35 under changing atmospheric conditions. In total, 137 minutes of observations were taken during transit and 130 minutes out of transit. CCFs were computed using the automated SOPHIE data-reduction pipeline which is adapted from the HARPS data-reduction software. WASP-3 is of spectral type F7-8V, so the weighted mask function used for the cross-correlation was for a G2V star as this was the closest type offered by the pipeline. For a more detailed explanation of the observations and data reduction procedure see Simpson et al. (2010).

All parameters in Table 3.1 and Table 3.2 are free to be fitted by the model during the MCMC analysis. They are each given an initial starting value, which is calculated to be close to the true value, in order to assist the MCMC in finding the global minimum. The only value which is fixed is the stellar limb-darkening $u$, which is chosen from the tables of Claret (2004)(ATLAS models) and input manually at the start. As is the case here, the orbital eccentricity $e$ can be set to zero at the start of the MCMC run if it appears that that planet is in a circular orbit.

3.2.1 Photometric and spectroscopic datasets

In total we used 8 photometric and 2 radial velocity datasets in the MCMC analysis. In addition to the photometric datasets analysed in the discovery paper we included 2 additional sets of photometry taken with the RISE instrument on the 2m Liverpool Telescope at Observatorio del Roque de Los Muchachos, La Palma (Gibson et al., 2008). The radial velocity data comprised the 26 observations described earlier to target the RM effect, and the 6 out-of-transit observations taken in July and August 2007 also using the SOPHIE spectrograph as described by Pollacco et al. (2008). Figure 3.1 shows phase-folded plots of the photometric data and the out-of-transit radial velocity measurements.
**Figure 3.1**: Upper panel: Phase-folded plot of the 6 out-of-transit radial velocity measurements which are not affected by any time-varying asymmetry of the line-profile. The out-of-transit RV fit was calculated by adjusting the velocity semi-amplitude, orbital eccentricity, argument of periastron and true anomaly. The position of the planet over the stellar disc, ratio of star/planet radii, impact parameter and non-linear limb darkening coefficients were used to model the RM anomaly during transit. Lower panel: Phase-folded plot of all 8 sets of photometric data analysed in this study.
3.2. Observations and analysis

Figure 3.2: Top: Residual map of time series CCFs with the model spectrum subtracted leaving the bright time-variable feature due to the light blocked by the planet. Bottom: Here the best-fit model for the time-variable feature has also been removed to show the overall residual. The horizontal dotted line marks the phase and radial-velocity of mid-transit. The shift of this line from zero shows the underlying systemic radial-velocity. The two vertical dashed lines are at ±v sin I from the systemic radial velocity (marked by the vertical dotted line). The crosses on the vertical dotted line denote the two points of contact at both ingress and egress.
Table 3.1: Results of MCMC analysis compared to those presented in the literature.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Pollacco et al. (2007)</th>
<th>Gibson et al. (2008)</th>
<th>This study</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit epoch (JD-2450000)</td>
<td>$T_0$</td>
<td>$4143.8503^{+0.0004}_{-0.0003}$</td>
<td>$4605.5592^{+0.0002}_{-0.0002}$</td>
<td>$3992.4101^{+0.0004}_{-0.0004}$</td>
<td>days</td>
</tr>
<tr>
<td>Orbital period</td>
<td>$P$</td>
<td>$1.846834^{+0.000002}_{-0.000002}$</td>
<td>$1.846835^{+0.000002}_{-0.000002}$</td>
<td>$1.846837^{+0.000001}_{-0.000001}$</td>
<td>days</td>
</tr>
<tr>
<td>Planet/star radius ratio</td>
<td>$(R_p/R_*)^2$</td>
<td>$0.0105^{+0.0002}_{-0.00004}$</td>
<td>$0.0103^{+0.0002}_{-0.00004}$</td>
<td>$0.0105^{+0.0002}_{-0.00004}$</td>
<td>days</td>
</tr>
<tr>
<td>Transit duration</td>
<td>$t_T$</td>
<td>$0.1110^{+0.0018}_{-0.0004}$</td>
<td>$0.1147^{+0.0008}_{-0.0005}$</td>
<td>$0.1126^{+0.0006}_{-0.0006}$</td>
<td>days</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>$b$</td>
<td>$0.505^{+0.051}_{-0.166}$</td>
<td>$0.448^{+0.014}_{-0.014}$</td>
<td>$0.45^{+0.11}_{-0.07}$</td>
<td>$R_*$</td>
</tr>
<tr>
<td>Stellar reflex velocity</td>
<td>$K_s$</td>
<td>$0.2512^{+0.0079}_{-0.0108}$</td>
<td>$0.2782^{+0.0138}_{-0.0134}$</td>
<td>$0.5499^{+0.0037}_{-0.0036}$</td>
<td>$km\ s^{-1}$</td>
</tr>
<tr>
<td>Centre-of-mass velocity</td>
<td>$\gamma$</td>
<td>$-5.4887^{+0.0013}_{-0.0018}$</td>
<td>$-5.4599^{+0.0037}_{-0.0036}$</td>
<td>$-5.4599^{+0.0037}_{-0.0036}$</td>
<td>$km\ s^{-1}$</td>
</tr>
<tr>
<td>Orbital semi-major axis</td>
<td>$a$</td>
<td>$0.0317^{+0.0005}_{-0.0010}$</td>
<td>$0.0313^{+0.0001}_{-0.0001}$</td>
<td>$0.0313^{+0.0001}_{-0.0001}$</td>
<td>AU</td>
</tr>
<tr>
<td>Orbital inclination</td>
<td>$i$</td>
<td>$84.4^{+2.1}_{-0.8}$</td>
<td>$85.06^{+0.16}_{-0.15}$</td>
<td>$87.0^{+1.0}_{-1.1}$</td>
<td>degrees</td>
</tr>
<tr>
<td>Stellar mass</td>
<td>$M_*$</td>
<td>$1.24^{+0.06}_{-0.11}$</td>
<td>$1.20^{+0.01}_{-0.01}$</td>
<td>$1.20^{+0.01}_{-0.01}$</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Stellar radius</td>
<td>$R_*$</td>
<td>$1.31^{+0.05}_{-0.12}$</td>
<td>$1.21^{+0.04}_{-0.04}$</td>
<td>$1.21^{+0.04}_{-0.04}$</td>
<td>$R_\odot$</td>
</tr>
<tr>
<td>Stellar surface gravity</td>
<td>$\log g_*$</td>
<td>$4.30^{+0.07}_{-0.03}$</td>
<td>$4.33^{+0.03}_{-0.03}$</td>
<td>$4.33^{+0.03}_{-0.03}$</td>
<td>[cgs]</td>
</tr>
<tr>
<td>Stellar density</td>
<td>$\rho_*$</td>
<td>$0.55^{+0.03}_{-0.05}$</td>
<td>$0.67^{+0.05}_{-0.06}$</td>
<td>$0.67^{+0.05}_{-0.06}$</td>
<td>$\rho_\odot$</td>
</tr>
<tr>
<td>Planet mass</td>
<td>$M_p$</td>
<td>$1.76^{+0.08}_{-0.14}$</td>
<td>$1.76^{+0.08}_{-0.14}$</td>
<td>$1.90^{+0.10}_{-0.09}$</td>
<td>$M_J$</td>
</tr>
<tr>
<td>Planet radius</td>
<td>$R_p$</td>
<td>$1.31^{+0.07}_{-0.14}$</td>
<td>$1.29^{+0.05}_{-0.12}$</td>
<td>$1.20^{+0.03}_{-0.03}$</td>
<td>$R_J$</td>
</tr>
<tr>
<td>Planetary surface gravity</td>
<td>$\log g_p$</td>
<td>$3.37^{+0.04}_{-0.04}$</td>
<td>$3.42^{+0.04}_{-0.04}$</td>
<td>$3.47^{+0.04}_{-0.04}$</td>
<td>[cgs]</td>
</tr>
<tr>
<td>Planet density</td>
<td>$\rho_p$</td>
<td>$0.78^{+0.28}_{-0.13}$</td>
<td>$0.82^{+0.14}_{-0.09}$</td>
<td>$1.08^{+0.11}_{-0.09}$</td>
<td>$\rho_J$</td>
</tr>
<tr>
<td>Planet temp</td>
<td>$T_{eql}$</td>
<td>$1960^{+76}_{-76}$</td>
<td>$1920^{+22}_{-22}$</td>
<td>$1920^{+22}_{-22}$</td>
<td>$K$</td>
</tr>
</tbody>
</table>
3.3. Results

The resulting values for the system parameters can be seen in Table 3.1 alongside those taken from the discovery paper, both with their 1σ errors. With the exception of the impact parameter, all values are in agreement within their 1σ uncertainty ranges. Through examination of its relation with the stellar surface gravity, Pollacco et al. (2008) suggest that the impact parameter should lie between 0.4 and 0.6 which is in good agreement with the value found in this study of $b = 0.38^{+0.11}_{-0.07}$. Using our method the impact parameter can be more closely constrained, as the properties of the streak of ‘missing light’ also give us a measure of the latitudes of ingress and egress. The streak can be seen in Figure 3.2 where the average line-profile has been removed from each observation and they have then been stacked on top of each other to make a trailed spectrum.

One major success of this study is that sensible values in agreement with previous work are produced without having to fix any of the system parameters in place. Pollacco et al. (2008) showed that in order to reconcile the MCMC analysis with spectroscopic diagnostics, $\log g_*$ must be between 4.25 and 4.35. Recently Enoch et al. (2010) attempted to reproduce the results from the WASP-3 discovery paper incorporating the Torres mass calibration into the MCMC analysis and found they also needed to fix $\log g_*$ to the value determined by spectroscopic analysis. In this study we left $\log g_*$ as a floating variable and found its value to be $\log g_* = 4.33^{+0.03}_{-0.03}$ which lies within the range suggested in the discovery paper.

The results produced for the RM parameters are presented in Table 3.2 along with their one sigma errors. Correlation plots showing the MCMC output for the four RM parameters
are shown in Figure ??. The value we obtained for the projected stellar rotation rate $v \sin I = 13.90 \pm 0.03$ km s$^{-1}$ is in good agreement with the value of $v \sin I = 13.4 \pm 1.5$ km s$^{-1}$ derived by the analysis of the SOPHIE spectroscopy presented in the WASP-3 discovery paper (Pollacco et al., 2008). However, our result shows a much greater level of precision. This is because uncertainties on previous estimates of $v \sin I$ are removed by the fact that we can measure the FWHM of the intrinsic profile directly. Our analysis finds the projected spin-orbit misalignment angle to be $\lambda = 5^{+6}_{-3}$, which is almost indistinguishable from zero.

Simpson et al. (2010) recently performed a Rossiter-McLaughlin effect analysis of the WASP-3 system with the same data used in this study. They used the method of Hirano et al. (2009) to account for the aforementioned systematic error encountered when trying to calculate $v \sin I$ by applying the Ohta et al. (2005) method. Their value for $v \sin I$ of $15.7^{+1.3}_{-1.4}$ km s$^{-1}$ is slightly larger than our value. For $\lambda$ they derived a value of $13^{+9}_{-7}$ which agrees with our result. In addition to this Tripathi et al. (2010), implementing the RM calibration procedure of Winn et al. (2005), analysed a separate set of data on WASP-3 and retrieved values that are in good agreement with those found in this study, as can be seen in Table 3.2.

### 3.3.1 Age from evolutionary tracks

Using our new, more accurate values for the system parameters we can to plot the position of WASP-3 on the $R/M^{1/3}$ vs $T_{eff}$ plane (see Figure 3.4). From the MCMC analysis we obtained a value for the stellar effective temperature of $T_{eff} = 6332 \pm 105$ K. Comparing this temperature range with the evolutionary tracks from Girardi et al. (2000) we can get a separate mass estimate for the star of $M_\star = 1.23 \pm 0.04$ M$_\odot$. This is in good agreement with our previous value of $M_\star = 1.24^{+0.06}_{-0.11}$ M$_\odot$ obtained from the MCMC analysis. From the maximum error range we can put an upper limit on the stellar age of around 2 Gyr. This is an improvement on the value presented in Pollacco et al. (2008) which suggested an upper limit of 3.5 Gyr. We cannot put a lower limit on the age of the star using Figure 3.4 as the lower range of the errors lie on or beyond the zero-age main sequence. The evolutionary tracks of Siess et al. (2000) suggest a pre-main sequence lifetime of 0.13 Gyr for a 1.2 M$_\odot$ star. WASP-3 is a main sequence star, so we can impose this value as an extreme lower age limit. In the discovery paper a lower age estimate of 0.7 Gyr is presented.

Figure 3.5 shows the updated position of the WASP-3b system in a mass-radius plot using our new values for $M_P$ and $R_P$. 

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Figure 3.3: Correlation plots for the four parameters calculated from the RM effect. The distribution of points shows each accepted step on the Markov chain.
Figure 3.4: The new position of WASP-3 in the $T_{\text{eff}}$ vs $R/M^{1/3}$ plane. The larger of the two boxes shows the data from the discovery paper. The smaller box shows the error range from this study. The lines show evolutionary tracks from Girardi et al. (2000) for 1.2, 1.3 and 1.4 solar masses and isochrones at 0.1, 0.5, 1, 1.5, 2, 2.5 and 3 billion years. The tracks and isochrones here are for stars with solar metallicity, $[M/H] = 0$. 
3.3.2 Age from gyrochronology

We can also determine an age estimate from gyrochronology. If we assume that the spin axis of WASP-3 is nearly perpendicular to the line of sight, then $v \sin I = 13.9 \text{ km s}^{-1}$ and $R_s = 1.21 R_\odot$ yields a spin period of $4.5 \sin i$ days. The period will be shorter than 4.5 days if the inclination is substantially less than 90 degrees.

WASP-3 has 2MASS colour $J-K = 0.242$. The fastest rotators at the same colour in the 590-Myr-old Coma Berenices open cluster have periods of order 6 days (Collier Cameron et al., 2009). Hyades stars of similar colour also have periods in the range 5-6 days at age 625 Myr (Radick et al., 1987), as is also found to be the case in the Praesepe cluster (age 580 Myr) by Delorme et al. (2010).

If we assume that WASP-3 is spinning down because of angular momentum loss in a hot, magnetically-channelled stellar wind, its spin period should increase with time as the square root of its age. From their calibration of the period-colour relation in Hyades and Praesepe, Delorme et al. (2010) find

$$ t = 625 \left( \frac{P_{\text{rot}}}{11.401 + 12.652(J - K - 0.631)} \right)^2 \text{ Myr}, $$

yielding a gyrochronological age of 300 Myr for WASP-3, with an uncertainty of order 10 percent. We caution, however, that this relation is only applicable once the spin rate has converged to the asymptotic period-colour relation. While convergence is probably complete for most stars of this mass by the age of 300 Myr, there remains a small possibility that the star could have been born as a relatively slow rotator, leading to over-estimation of the gyrochronological age. We can, however, state with confidence that the gyrochronological age of WASP-3 is substantially less than that of the Hyades and Praesepe.

3.4 Conclusions

The Rossiter-McLaughlin effect present in the WASP-3 system was analysed from observations made using the SOPHIE spectrograph on the 1.93m telescope at the Observatoire de Haute-Provence (Simpson et al., 2010). We analysed the observations using a new method developed by Collier Cameron et al. (2010a) which involves decomposing the CCF into its various components and directly tracking the trajectory of the missing starlight across the line.
Figure 3.5: Mass-radius plot for known transiting planets. The two black dots indicate the previous position of WASP-3b from the results in the discovery paper (Pollacco et al., 2008) and its updated position from the mass and radius values determined in this study.
3.4. Conclusions

profile. This method was incorporated into an MCMC analysis of all photometric and spectroscopic data available for the WASP-3 system and was found to produce good results for the system parameters, helping further constrain the values of the spin-orbit misalignment angle, projected stellar rotation rate and the impact parameter. The value we obtained for the projected spin-orbit misalignment angle $\lambda = 9^{+6}_{-5}^\circ$ is close to zero and agrees with the previous results found by Simpson et al. (2010) and Tripathi et al. (2010). Our value of $v \sin I = 13.90 \pm 0.03 \text{ km s}^{-1}$ is in agreement with the value obtained from the spectroscopic broadening but determined to a much higher level of precision. We conclude that this new method of analysing the Rossiter-McLaughlin effect successfully retrieves a more accurate and precise value for the projected stellar spin rate compared with previous measurements, and in doing so it is not vulnerable to the systematic error present in previous methods that require fitting of Gaussians to non-Gaussian CCFs in order to calculate the velocity shifts. It also finds a value for the spin-orbit misalignment angle that agrees with all previous measurements and is of a similar precision. The fact that we clearly detect the signature of the missing light after subtracting the model out-of-transit profile shows that the method works well for stellar rotation rates where the line-broadening is not much greater than the intrinsic line width. In fact, Collier Cameron et al. (2010a) showed that this method can be successful when $v \sin I$ is as low as half the value of the intrinsic stellar line width.

We find the orbit of WASP-3b to be well-aligned with the stellar spin axis however, this does not necessarily suggest that WASP-3b must have migrated through the protoplanetary disc via gravitational interactions. As described in Section 1.4, results from Albrecht et al. (2012a) show that hot Jupiters may start out life on a random distribution of orbits, and that the ones we now see in aligned orbits are the systems with short ‘tidal timescales’. These timescales depend on the orbital separation, planet-star mass ratio and the effective temperature of the star. Stars with convecting envelopes have shorter tidal timescales as tidal dissipation is stronger in convective shells rather than radiative outer layers. Both Winn et al. (2010) and Albrecht et al. (2012a) consider the boundary between these to be at $T_{\text{eff}} = 6250$ K. Though with a relatively young age of 2 Gyr, $T_{\text{eff}} > 6250$ K and small planet-star mass ratio of 0.0013, the low obliquity of WASP-3b’s orbit is not easily explained by the idea of a short tidal timescale.

Many transit candidates are rejected from radial-velocity follow-up observations if they are found to be rotating too fast for high-precision determination of the radial-velocity shift.
This is especially true for stars of spectral type earlier than F5 which tend to be line-poor rapid rotators. It has already been shown (Collier Cameron et al., 2010c) that using this new method we can successfully confirm the existence of a planet-sized object around rapidly-rotating stars by measuring the size of the ‘bump’ on the stellar line profile, opening up a way for establishing the existence of close-orbiting planets around rapidly-rotating stars previously inaccessible to planet hunters using the RV method. With this new information we will also be able to investigate any differences in planet formation between solar-type and early-type stars. Chapter 5 of this thesis discusses in detail the implementation of the tomographic RM technique on systems with early-type host stars.
Rossiter-McLaughlin analyses of five transiting systems


In this chapter we implement the tomographic Rossiter-Mclaughlin analysis method on five planets, discovered via the SuperWASP survey. These planets are WASP-16b (Lister et al. 2009), WASP-17b (Anderson et al. 2010), WASP-18b (Hellier et al. 2009), WASP-23b (Triaud et al. 2011), and WASP-31b (Anderson et al. 2011). Each of the five systems has a significantly slower projected stellar rotation rate ($v \sin I$) than three of the four systems for
which the results from tomographic analysis have been previously published, namely WASP-33 (Collier Cameron et al., 2010c), WASP-3 (Miller et al., 2010) and CoroT-11 (Gandolfi et al., 2012). We therefore use these analyses to test and compare how the new method performs when slower rotation rates are involved.

4.1 Introduction

The tomographic RM method has been shown to successfully remove some of the problems present in the previous standard radial velocity method used to analyse the RM effect, especially when analysing systems with a rapidly-rotating host star for which the systematic affecting the measurements of the stellar rotation rate are greater. Three of the four systems with published tomographic RM analyses to date, WASP-33 (\(v \sin I \sim 90\) km s\(^{-1}\)), WASP-3 (\(v \sin I \sim 14\) km s\(^{-1}\)) and CoRoT-11 (\(v \sin I \sim 40\) km s\(^{-1}\)), have relatively fast rotation velocities. In this chapter we investigate how the method performs on stars with lower projected stellar rotation rates. The fastest rotator of the five systems measured in this chapter is WASP-18 with \(v \sin I \sim 11\) km s\(^{-1}\) and the slowest is WASP-23 with \(v \sin I \sim 1\) km s\(^{-1}\). The only previous system with relatively slow rotation to be measured via this technique is HD 189733 (\(v \sin I \sim 3\) km s\(^{-1}\)) which has the observational advantage of being much brighter than any of the stars studied in this chapter.

4.2 Observations

The WASP project (Pollacco et al., 2006b) employs a system of photometric and radial velocity follow-up observations utilising multiple telescopes in the northern and southern hemispheres. Photometric observations are used to constrain the the orbital period and the geometry of the transit, while the radial velocity data allows us to measure the mass of the transiting body. A larger amount of good quality observational data leads to more accurate values from the resulting analysis, therefore all available radial velocity and photometric data were included in the analysis of each of the five planetary systems in this chapter. The following section briefly presents the observational data for each object, and describes the various instruments that were used to obtain them.
4.2.1 Photometry

In addition to the original observations obtained using the SuperWASP instruments in La Palma, Canary Islands and Sutherland, South Africa, follow-up photometry of each planetary transit was obtained using the EulerCam instrument on the 1.2m Leonhard Euler Telescope at La Silla Observatory. Photometry was also obtained using the 2m Faulkes Telescope South (FTS) and Faulkes Telescope North (FTN) found at the Siding Spring Observatory, Australia and the Haleakala Observatory, Hawaii respectively, and the 1.54m Danish Telescope at ESO La Silla, Chile.

4.2.2 Spectroscopy

Each of the in-transit spectra used for the Rossiter-McLaughlin analysis were obtained using HARPS, which is a high-resolution ($R = 115000$) echelle spectrograph mounted on the 3.6m telescope at La Silla Observatory, Chile (Mayor et al., 2003). HARPS is stable within 1 ms$^{-1}$ across a full night of observations, so the data were obtained with the instrument in OBJO mode without simultaneous Thorium-Argon calibration. Instead there were calibrations performed at the start and end of the observing session. All out-of-transit radial velocity measurements were taken using HARPS and CORALIE, which is another high resolution echelle spectrograph mounted on the 1.2m Leonhard Euler Telescope (Queloz et al., 2001).

The spectra were extracted and cross-correlated against a weighted line mask representing the spectrum of a star of similar spectral type to that of the host using the HARPS Data Reduction System (DRS); (Baranne et al., 1996; Pepe et al., 2000).

4.2.3 WASP-16b

In total 40 out-of-transit radial velocity measurements were taken of WASP-16 by CORALIE and HARPS between 2008 and 2011. The spectroscopic transit was observed by HARPS on the 21st March 2010 and comprises 32 data points. The initial photometry for WASP-16b came from the WASP-South telescope. Follow-up photometry was obtained in the I-band using the EulerCam instrument on the 1.2m Leonhard Euler Telescope. The photometric observations of WASP-16b are described in the discovery paper (Lister et al., 2009).
4.2.4 WASP-17b

Multiple out-of-transit data points were taken of WASP-17b using CORALIE and HARPS between 2007 and 2009. In order to measure the RM effect, a spectroscopic transit consisting of 42 separate spectral observations was observed on 5th July 2009 by HARPS. Follow-up photometry in the I-band was taken using EulerCam. The photometry and out-of-transit radial-velocity observations are outlined in the discovery paper (Anderson et al., 2010).

4.2.5 WASP-18b

Out-of-transit radial-velocity observations of WASP-18b were taken by CORALIE and HARPS between 2007 and 2009. A transit was observed by HARPS on 21th August 2008, consisting of 19 spectral observations. EulerCam was used to observe two photometric transits, one in I-band and the other in B-band. A third photometric lightcurve was obtained in the R-band using the 1.54m Danish Telescope.

4.2.6 WASP-23b

CORALIE was used to make multiple RV observations of WASP-23b between 2008 and 2010. 28 spectra were taken through transit by HARPS on 19th December 2009 (Triaud et al., 2011). Photometric lightcurves were obtained in the Z & R-bands by EulerCam and in the Z-band by FTS.

4.2.7 WASP-31b

The radial velocity of WASP-31b was observed multiple times by CORALIE between 2009 and 2010. The spectroscopic transit was observed on the 15th April 2010 during which 17 data points were taken. In addition to the original WASP-South data, follow-up photometry was performed using EulerCam (R-band) and FTN (Z-band). A more detailed description of the photometry is presented in the discovery paper (Anderson et al., 2011).

4.3 Results

4.3.1 WASP-16b

WASP-16b is a Jupiter-mass planet in a 3.12 day orbit around a star similar to our Sun with $T_{\text{eff}} = 5700 \pm 150$ K and spectral type G3V (Lister et al., 2009). The slow rotation rate of
the host star makes Rossiter-McLaughlin analysis quite problematic, as the anomalous radial velocity signal is very weak. However, despite its extremely low rotation rate we still see a ‘bump’ in the trailed spectra when the average line-profile is removed (see Figure 4.1), and we find a value for the misalignment of $\lambda = -36 \pm 45^\circ$. The uncertainty on this value is large but still does not seem to suggest that the system has a high degree of misalignment, which is in agreement with the results presented by Brown et al. (2012a) who find $\lambda = -4.2^{+11.0}_{-13.9}^\circ$, and Albrecht et al. (2012b) who present a value of $\lambda = 11^{+26}_{-19}^\circ$. Our value has a larger degree of uncertainty than the results from these previous studies. This is most likely because we only analysed one set of HARPS data from the night of 21st March 2010 which was partially affected by cloud cover, whereas Brown et al. (2012a) analysed an additional set of HARPS observations taken on 12th May 2011 and Albrecht et al. (2012b) performed their analysis on a spectroscopic transit observed using the High Resolution Echelle Spectrometer (HIRES) on the 10-m Keck telescope in Hawaii, thereby we find a value for the projected stellar rotation rate of $v \sin I = 2.48^{+0.03}_{-0.06}$ km s$^{-1}$, which agrees with the results from Brown et al. (2012a), Albrecht et al. (2012b) and the discovery paper (Lister et al., 2009). However, using the tomographic method, we obtain independent measurements of $v \sin I$ from the shape of the out-of-transit line-profile and the range of the velocities spanned by the Doppler shadow of the transiting body. This allows us to place a smaller uncertainty range on our final $v \sin I$ value. Results from the MCMC analysis of all system parameters are shown in Table 4.1. In order to calculate an age, and separate mass estimate, for the star the results for stellar density and effective temperature were compared with evolutionary tracks and isochrone models. The values were compared with Padova (Marigo et al., 2008), Teramo (Pietrinferni et al., 2004), Victoria-Regina (VandenBerg et al., 2006) and Yonsei-Yale (Demarque et al., 2004) isochrone models and the resulting age and mass estimates can be seen in Table 4.2. The mean value gives an age estimate of 4.2 Gyr, however the Teramo models give a noticeably older age estimate than the three other models. For the mass estimate we get $M_\star = 1.01M_\odot$, which is slightly lower than the resulting value from MCMC analysis, however the uncertainty range places them in agreement. Figure 4.2 shows the resulting position of WASP-16 on a plot of stellar density versus stellar effective temperature with evolutionary tracks and isochrones from the Yonsei-Yale models.
Table 4.1: System parameters from the MCMC analysis for WASP-16b.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit epoch</td>
<td>$T_0$</td>
<td>4593.7788 ± 0.0011</td>
<td>days</td>
</tr>
<tr>
<td>Orbital period</td>
<td>$P$</td>
<td>3.118623$^{+0.000016}_{-0.000014}$</td>
<td>days</td>
</tr>
<tr>
<td>Planet/star radius ratio</td>
<td>$(R_p/R_*)^2$</td>
<td>0.006567 ± 0.00035</td>
<td></td>
</tr>
<tr>
<td>Transit duration</td>
<td>$T_{14}$</td>
<td>0.0824$^{+0.0031}_{-0.0027}$</td>
<td>days</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>$b$</td>
<td>0.770$^{+0.041}_{-0.027}$</td>
<td></td>
</tr>
<tr>
<td>Eccentricity</td>
<td>$e$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Orbital separation</td>
<td>$a$</td>
<td>0.0423 ± 0.0003</td>
<td>AU</td>
</tr>
<tr>
<td>Orbital inclination</td>
<td>$i$</td>
<td>85.2 ± 0.4 degrees</td>
<td></td>
</tr>
<tr>
<td>Projected stellar rotation rate</td>
<td>$v\sin I$</td>
<td>2.48$^{+0.03}_{-0.06}$</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Projected alignment angle</td>
<td>$\lambda$</td>
<td>−36 ± 45</td>
<td>degrees</td>
</tr>
<tr>
<td>Intrinsic v(FWHM)</td>
<td>$v_g$</td>
<td>6.63 ± 0.05</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>RM centre-of-mass velocity</td>
<td>$\gamma$</td>
<td>−1.78 ± 0.01</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Stellar density</td>
<td>$\rho_*$</td>
<td>1.04$^{+0.13}_{-0.12}$</td>
<td>$\rho_\odot$</td>
</tr>
<tr>
<td>Stellar effective temperature</td>
<td>$T_{\text{eff}}$</td>
<td>5758$^{+110}_{-100}$</td>
<td>K</td>
</tr>
<tr>
<td>Stellar mass</td>
<td>$M_*$</td>
<td>1.04 ± 0.03</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Stellar radius</td>
<td>$R_*$</td>
<td>1.00$^{+0.05}_{-0.04}$</td>
<td>$R_\odot$</td>
</tr>
<tr>
<td>Planet mass</td>
<td>$M_p$</td>
<td>0.89 ± 0.02</td>
<td>$M_J$</td>
</tr>
<tr>
<td>Planet radius</td>
<td>$R_p$</td>
<td>0.79 ± 0.05</td>
<td>$R_J$</td>
</tr>
</tbody>
</table>

Table 4.2: Age and mass values for WASP-16 from comparison with various isochrone models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Age estimate (Gyr)</th>
<th>Mass estimate ($M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Padova</td>
<td>$3.1^{+3.2}_{-3.1}$</td>
<td>$1.64^{+0.06}_{-0.65}$</td>
</tr>
<tr>
<td>Teramo</td>
<td>$6.5^{+4.1}_{-3.8}$</td>
<td>$0.95^{+0.05}_{-0.18}$</td>
</tr>
<tr>
<td>Victoria-Regina</td>
<td>$3.8^{+4.2}_{-2.3}$</td>
<td>$1.00^{+0.10}_{-0.03}$</td>
</tr>
<tr>
<td>Yonsei-Yale</td>
<td>$3.5^{+2.2}_{-2.4}$</td>
<td>$1.06^{+0.04}_{-0.05}$</td>
</tr>
</tbody>
</table>
4.3. Results

Figure 4.1: Top: Residual map of WASP-16 time series CCFs with the model average line profile subtracted. Despite the slow rotation rate of the star, a noticeable time-variable feature is still left behind due to the light blocked by the planet. Bottom: Here the best-fit model for the time-variable feature has also been removed to show the overall residual. The horizontal dotted line marks the phase of mid-transit. The shift of the vertical dotted line from zero shows the underlying systemic radial velocity. The two vertical dashed lines are at \( \pm v \sin I \) from the systemic radial velocity. The crosses on the vertical dotted line denote the two points of contact at both ingress and egress. The light and dark vertical features arise due to crosstalk between overlapping spectral lines in the wings of the CCF.
Chapter 4. Rossiter-McLaughlin analyses of five transiting systems

Figure 4.2: Modified Hertzsprung-Russell diagram showing the updated position of WASP-16 in the density-effective temperature plane. The isochrones for the ages 0.1, 0.6, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 Gyr (left to right, shown by black curves) and the evolutionary mass tracks for masses 0.9, 1.0, 1.1 and 1.2 $M_\odot$ (right to left, red dashed lines) are from Demarque et al. (2004) who used Yonsei-Yale models.
4.3.2 WASP-17b

WASP-17b is a planet with extremely low density which has already been shown to be in a highly-misaligned and retrograde orbit, with a projected spin-orbit misalignment angle of $\lambda \approx -150^\circ$ and an orbital period of 3.74 days (Anderson et al., 2010). Its host star has an effective temperature of $T_{\text{eff}} = 6350$ K meaning it is in agreement with the proposal of Winn et al. (2010) that hotter systems are more likely to be misaligned. The retrograde motion shows-up clearly in the trailed spectra as the anomalous streak moves from the blue to the red side of the line (Figure 4.3). Our value of $\lambda = -168 \pm 18^\circ$ agrees well with the result presented by Bayliss et al. (2010) who found $\lambda = -167 \pm 11^\circ$ by modelling the RM effect using the analytic formula of Hirano et al. (2011), and shows a slightly higher degree of misalignment than the three solutions presented in the discovery paper (Anderson et al., 2010) which suggest $\lambda \approx -150^\circ$, however there is overlap in the 1$\sigma$ error ranges. Again we find a much more accurate value for the stellar rotation rate of $v \sin I = 8.37^{+0.07}_{-0.08}$ km s$^{-1}$, compared to the previously accepted value of $9.0 \pm 1.5$ km s$^{-1}$. Results from the MCMC analysis of all system parameters are shown in Table 4.3. Comparison with isochrones gives a mean age estimate of 1.4 Gyr and value of $M_* = 1.30 M_\odot$ for the mass of the host star. Our age estimate agrees well with a similar analysis by Anderson et al. (2010) who found a value of $1.2^{+2.8}_{-1.2}$ Gyr. The full list of values calculated for age and mass of the star can be seen in Table 4.4. An example isochrone plot is shown in Figure 4.4 using the models from Demarque et al. (2004).

4.3.3 WASP-18b

WASP-18b is a planet with a very short period of just 0.94 days and a mass ten times that of Jupiter, orbiting a star of spectral type F6V (Hellier et al., 2009). The system is of unique interest to planetary scientists as the planet may be in the final stages of spiralling into its host star. We find that the orbit of WASP-18b is well aligned with the rotation axis of its host star, with a resulting value of $\lambda = -1 \pm 4^\circ$. Using the same data set and the RM analysis method discussed in Section 2.2, Triaud et al. (2010) obtained a value of $\lambda = 4 \pm 5^\circ$. Using data from the Carnegie Planet Finder Spectrograph (PFS) on the 6.5 m Magellan II telescope located at Las Campanas Observatory in Chile, Albrecht et al. (2012b) find a value of $\lambda = 13 \pm 7^\circ$. All results shows the system to be well-aligned, however there is no overlap in the 1$\sigma$ error ranges between our study and that of Albrecht et al. (2012b). Once a model
### Table 4.3: System parameters from the MCMC analysis for WASP-17.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit epoch</td>
<td>$T_0$</td>
<td>6964.5500 $\pm$ 0.0019</td>
<td>days</td>
</tr>
<tr>
<td>Orbital period</td>
<td>$P$</td>
<td>3.735489$^{+0.00016}_{-0.00014}$</td>
<td>days</td>
</tr>
<tr>
<td>Planet/star radius ratio</td>
<td>$(R_p/R_\ast)^2$</td>
<td>0.009611 $\pm$ 0.00035</td>
<td></td>
</tr>
<tr>
<td>Transit duration</td>
<td>$T_{14}$</td>
<td>0.1625$^{+0.0031}_{-0.0027}$</td>
<td>days</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>$b$</td>
<td>0.097$^{+0.056}_{-0.060}$</td>
<td></td>
</tr>
<tr>
<td>Eccentricity</td>
<td>$e$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Orbital separation</td>
<td>$a$</td>
<td>0.0509 $\pm$ 0.0005</td>
<td>AU</td>
</tr>
<tr>
<td>Orbital inclination</td>
<td>$i$</td>
<td>89.3 $\pm$ 0.4</td>
<td>degrees</td>
</tr>
<tr>
<td>Projected stellar rotation rate</td>
<td>$v \sin I$</td>
<td>8.37$^{+0.07}_{-0.08}$</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Projected alignment angle</td>
<td>$\lambda$</td>
<td>$-168 \pm 18$</td>
<td>degrees</td>
</tr>
<tr>
<td>Intrinsic v(FWHM)</td>
<td>$v_g$</td>
<td>10.5 $\pm$ 0.1</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>RM centre-of-mass velocity</td>
<td>$\gamma$</td>
<td>$-49.34 \pm 0.01$</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Stellar density</td>
<td>$\rho_\ast$</td>
<td>$0.49^{+0.02}_{-0.02}$</td>
<td>$\rho_\odot$</td>
</tr>
<tr>
<td>Stellar effective temperature</td>
<td>$T_{\text{eff}}$</td>
<td>6452$^{+100}_{-100}$</td>
<td>K</td>
</tr>
<tr>
<td>Stellar mass</td>
<td>$M_\ast$</td>
<td>1.25 $\pm$ 0.03</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Stellar radius</td>
<td>$R_\ast$</td>
<td>1.36 $\pm$ 0.03</td>
<td>$R_\odot$</td>
</tr>
<tr>
<td>Planet mass</td>
<td>$M_p$</td>
<td>0.47 $\pm$ 0.03</td>
<td>$M_J$</td>
</tr>
<tr>
<td>Planet radius</td>
<td>$R_p$</td>
<td>1.32 $\pm$ 0.03</td>
<td>$R_J$</td>
</tr>
</tbody>
</table>

### Table 4.4: Age and mass values for WASP-17 from comparison with various isochrone models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Age estimate (Gyr)</th>
<th>Mass estimate ($M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Padova</td>
<td>$1.2^{+0.7}_{-0.7}$</td>
<td>$1.30^{+0.04}_{-0.10}$</td>
</tr>
<tr>
<td>Teramo</td>
<td>$1.8^{+0.7}_{-0.6}$</td>
<td>$1.27^{+0.03}_{-0.07}$</td>
</tr>
<tr>
<td>Victoria-Regina</td>
<td>$1.0^{+0.6}_{-0.6}$</td>
<td>$1.30^{+0.07}_{-0.01}$</td>
</tr>
<tr>
<td>Yonsei-Yale</td>
<td>$1.6^{+0.3}_{-0.8}$</td>
<td>$1.32^{+0.04}_{-0.14}$</td>
</tr>
</tbody>
</table>
4.3. Results

Figure 4.3: For WASP-17 the planet signature moves from the blue-shifted side of the line profile to the red-shifted side. This is a clear indication that the planet is in a retrograde orbit around the star. The significance of the top and bottom panels and an explanation of the markings is given in the caption for Figure 4.1.
Figure 4.4: Modified Hertzsprung-Russell diagram showing the updated position of WASP-17 in the density-effective temperature plane. The isochrones for the ages 0.1, 0.6, 1, 2, 3, 4 and 5 Gyr (left to right, black curves) and the evolutionary mass tracks for masses 1.1, 1.2, 1.3 and 1.4 $M_\odot$ (right to left, red dashed lines) are from Demarque et al. (2004).
Table 4.5: System parameters from the MCMC analysis for WASP-18.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit epoch</td>
<td>$T_0$</td>
<td>4856.0200 ± 0.0001</td>
<td>days</td>
</tr>
<tr>
<td>Orbital period</td>
<td>$P$</td>
<td>0.941452 ± 0.00000041</td>
<td>days</td>
</tr>
<tr>
<td>Planet/star radius ratio</td>
<td>$(R_p/R_*)^2$</td>
<td>0.009753 ± 0.0001</td>
<td></td>
</tr>
<tr>
<td>Transit duration</td>
<td>$T_{14}$</td>
<td>0.0885 ± 0.0003</td>
<td>days</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>$b$</td>
<td>0.513 ± 0.018</td>
<td></td>
</tr>
<tr>
<td>Eccentricity</td>
<td>$e$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Orbital separation</td>
<td>$a$</td>
<td>0.0201 ± 0.0001</td>
<td>AU</td>
</tr>
<tr>
<td>Orbital inclination</td>
<td>$i$</td>
<td>83.8 ± 1.3</td>
<td>degrees</td>
</tr>
<tr>
<td>Projected stellar rotation rate</td>
<td>$v \sin I$</td>
<td>10.83 ± 0.03</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Projected alignment angle</td>
<td>$\lambda$</td>
<td>−1 ± 4</td>
<td>degrees</td>
</tr>
<tr>
<td>Intrinsic v(FWHM)</td>
<td>$v_g$</td>
<td>9.03 ± 0.08</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>RM centre-of-mass velocity</td>
<td>$\gamma$</td>
<td>3.474 ± 0.008</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Stellar density</td>
<td>$\rho_*$</td>
<td>0.64 ± 0.05</td>
<td>$\rho_\odot$</td>
</tr>
<tr>
<td>Stellar effective temperature</td>
<td>$T_{eff}$</td>
<td>6441 ± 100</td>
<td>K</td>
</tr>
<tr>
<td>Stellar mass</td>
<td>$M_*$</td>
<td>1.22 ± 0.03</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Stellar radius</td>
<td>$R_*$</td>
<td>1.24 ± 0.03</td>
<td>$R_\odot$</td>
</tr>
<tr>
<td>Planet mass</td>
<td>$M_p$</td>
<td>10.18 ± 0.16</td>
<td>$M_J$</td>
</tr>
<tr>
<td>Planet radius</td>
<td>$R_p$</td>
<td>1.19 ± 0.04</td>
<td>$R_J$</td>
</tr>
</tbody>
</table>

...of the average out-of-transit CCF has been subtracted, the time-variable anomaly in the CCF shows up clearly as a bright streak moving from the red-shifted to the blue-shifted half of the line profile (Figure 4.5). A comparison of the planet's trail in Figure 4.5 with Figure 1.10 reveals clearly that the planet must be in a reasonably well aligned, prograde orbit. The discovery paper (Hellier et al., 2009) gives the stellar rotation rate to be $v \sin I = 11 \pm 1.5$ km s$^{-1}$ from a spectral-synthesis analysis of the stellar abundances, surface gravity and rotational broadening. Our method produces a result of $v \sin I = 10.83^{+0.03}_{-0.03}$ km s$^{-1}$ which is in agreement with this value but has a much higher confidence level. Results from the MCMC analysis of all system parameters are shown in Table 4.5. Comparing with the isochrone models listed in Section 4.3.1 we get a mean age of 0.4 Gyr for the system. This age estimate is slightly lower than the one presented in the discovery paper (Hellier et al., 2009) which states a value between 0.5 and 1.5 Gyr. Comparing with evolutionary tracks we get a stellar mass estimate of $M_* = 1.30 M_\odot$ which is larger than the value derived from the MCMC analysis of $M_* = 1.22 M_\odot$. Figure 4.6 shows the position of the host star compared with the isochrone and evolutionary track models from Pietrinferni et al. (2004).
In the case of WASP-18 the faster rotation rate produces a clearly resolved bright planet signature moving in a prograde direction. The plot shows the signature starting and finishing near the maximum $v \sin I$ value. This suggests the planet is in a well-aligned orbit with a low impact parameter. The significance of the top and bottom panels and an explanation of the markings is given in the caption for Figure 4.1.
4.3. Results

Table 4.6: Age and mass values for WASP-18 from comparison with various isochrone models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Age estimate (Gyr)</th>
<th>Mass estimate ($M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Padova</td>
<td>$&lt; 0.8$</td>
<td>$1.30^{+0.38}_{-0.03}$</td>
</tr>
<tr>
<td>Teramo</td>
<td>$0.8^{+1.0}_{-0.7}$</td>
<td>$1.17^{+0.13}_{-0.05}$</td>
</tr>
<tr>
<td>Victoria-Regina</td>
<td>$0.2^{+0.6}_{-0.1}$</td>
<td>$1.30^{+0.02}_{-0.01}$</td>
</tr>
<tr>
<td>Yonsei-Yale</td>
<td>$0.1^{+1.1}_{-0.4}$</td>
<td>$1.32^{+0.03}_{-0.05}$</td>
</tr>
</tbody>
</table>

Figure 4.6: Modified Hertzprung-Russell diagram showing the updated position of WASP-18 in the density-effective temperature plane. The isochrones for the ages 0.1, 0.5, 1, 2, 3, 4, and 5 Gyr (left to right, black curves) and the evolutionary mass tracks for masses 1.1, 1.2, 1.3 and 1.4 $M_\odot$ (right to left, red dashed lines) are from Demarque et al. (2004).
WASP-23 is another very slowly rotating star, similar to WASP-16. It hosts a Jupiter-mass planet in a 2.94 day orbit. It is of K1V spectral type and has an effective temperature of $T_{\text{eff}} = 5100$ K. In the discovery paper (Triaud et al., 2011) the standard RM analysis is shown to produce ambiguous results for the system alignment. Two separate values for the stellar rotation rate are presented, one obtained by examining the broadening of the spectral lines ($v \sin I = 2.2^{+0.3}_{-0.3}$ km s$^{-1}$) and the other by measuring the stellar activity levels ($v \sin I = 1.35^{+0.20}_{-0.20}$ km s$^{-1}$). It is then shown that varying the value of $v \sin I$ can significantly alter the resulting spin-orbit misalignment measurement. Figures 4.8 and 4.9 show the correlation between the stellar spin rate and the misalignment angle from Triaud et al. (2011) which leads to the ambiguity in their results. We analyse the same RM data as Triaud et al. (2011), however since we have an independent constraint on the value of $v \sin I$ from the shape of the out-of-transit line-profile, our results remove the ambiguity (see Figure 4.7) and show that the system is in a well-aligned orbit with $\lambda = -4 \pm 18^\circ$. Our result of $v \sin I = 0.97^{+0.27}_{-0.25}$ km s$^{-1}$ is closer to the lower of the two values presented in the discovery paper of $v \sin I = 2.2^{+0.3}_{-0.3}$ km s$^{-1}$ and $v \sin I = 1.35^{+0.20}_{-0.20}$ km s$^{-1}$. Despite the slow rotation of the star we can still observe the signature of the planet crossing the line-profile once the average out-of-transit model has been subtracted (Figure 4.10). It appears to show a reasonably well aligned, prograde planet. Even though WASP-23 is a slower rotator than WASP-16 it shows a brighter streak in the trailed spectra. This is most likely due to the difference in star-planet radius ratio between the two systems. WASP-23b covers a larger fraction of its host star’s photosphere during transit. Results from the MCMC analysis of all system parameters are shown in Table 4.7. From our comparison of the results with isochrone models we can only put a lower limit on the age of 9 Gyr. The upper limits are found to lie above the 14 Gyr isochrone, making them non-physical. Figure 4.11 shows the position of WASP-23 relative to the isochrones from Demarque et al. (2004), where the top five isochrones are older than 14 Gyr. Comparison with the evolutionary tracks gives a mass estimate of $M_* = 0.78 M_\odot$. 

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4.3. Results

Table 4.7: System parameters from the MCMC analysis for WASP-23.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit epoch</td>
<td>$T_0$</td>
<td>4966.7923 ± 0.0004</td>
<td>days</td>
</tr>
<tr>
<td>Orbital period</td>
<td>$P$</td>
<td>2.945489 ± 0.000051</td>
<td>days</td>
</tr>
<tr>
<td>Planet/star radius ratio</td>
<td>$(R_p/R_*)^2$</td>
<td>0.01751 ± 0.0005</td>
<td></td>
</tr>
<tr>
<td>Transit duration</td>
<td>$T_{14}$</td>
<td>0.1033 ± 0.0014</td>
<td>days</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>$b$</td>
<td>0.463 ± 0.066</td>
<td></td>
</tr>
<tr>
<td>Eccentricity</td>
<td>$e$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Orbital separation</td>
<td>$a$</td>
<td>0.0509 ± 0.0005</td>
<td>AU</td>
</tr>
<tr>
<td>Orbital inclination</td>
<td>$i$</td>
<td>86.0 ± 0.7</td>
<td>degrees</td>
</tr>
<tr>
<td>Projected stellar rotation rate</td>
<td>$v \sin I$</td>
<td>0.97 ± 0.27</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Projected alignment angle</td>
<td>$\lambda$</td>
<td>-3.95 ± 18</td>
<td>degrees</td>
</tr>
<tr>
<td>Intrinsic v(FWHM)</td>
<td>$v_g$</td>
<td>6.1 ± 0.1</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>RM centre-of-mass velocity</td>
<td>$\gamma$</td>
<td>5.68 ± 0.01</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Stellar density</td>
<td>$\rho_*$</td>
<td>1.34 ± 0.21</td>
<td>$\rho_\odot$</td>
</tr>
<tr>
<td>Stellar effective temperature</td>
<td>$T_{\text{eff}}$</td>
<td>5128 ± 100</td>
<td>K</td>
</tr>
<tr>
<td>Stellar mass</td>
<td>$M_*$</td>
<td>0.88 ± 0.03</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Stellar radius</td>
<td>$R_*$</td>
<td>0.87 ± 0.03</td>
<td>$R_\odot$</td>
</tr>
<tr>
<td>Planet mass</td>
<td>$M_p$</td>
<td>0.95 ± 0.02</td>
<td>$M_J$</td>
</tr>
<tr>
<td>Planet radius</td>
<td>$R_p$</td>
<td>1.12 ± 0.07</td>
<td>$R_J$</td>
</tr>
</tbody>
</table>

4.3.5 WASP-31b

WASP-31b is another low density planet orbiting a late-F-type star with $T_{\text{eff}} = 6300$ K with an orbital period of 3.41 days (Anderson et al., 2011). Our analysis finds that it is in a well aligned, prograde orbit with $\lambda = -1^{+8}_{-5}$°. As with WASP-18b, the trailed spectra (Figure 4.12) clearly show the prograde nature of the planet’s orbit. We analysed the same HARPS dataset as Brown et al. (2012a) who found a value of $\lambda = 2.8 \pm 3.1$° using the analytic formula presented by Hirano et al. (2011). Our result also agrees with those of Albrecht et al. (2012b), who also based their models on the formula from Hirano et al. (2011) and found values of $\lambda = -6 \pm 3$° and $\lambda = 2 \pm 3$° depending on which ephemeris they used. This is an interesting result as, along with WASP-18b, it presents a weak exception to the trend of systems with $T_{\text{eff}} > 6250$ K being preferentially misaligned. The 1-sigma error in effective temperature for WASP-31 covers the 6250 K cut-off point. We find the stellar rotation rate to have a value of $v \sin I = 7.05^{+0.06}_{-0.06}$ km s$^{-1}$. Results from the MCMC analysis of all system parameters are shown in Table 4.8. We derive an age estimate for WASP-31 of 1 Gyr from comparison with isochrones. We find a separate estimate for the stellar mass of $M_* = 1.26 M_\odot$, slightly more massive than the value obtained via the MCMC analysis of $M_* = 1.21 M_\odot$. Results for the age
Figure 4.7: Correlation plots of the MCMC output from our analysis of WASP-23.
4.4 Discussion

As mentioned previously in Section 2.3 we find that our method corrects for the problem encountered when simply fitting a Gaussian profile to measure the centroid shift of the CCF during transit. One artefact of this problem, outlined in Section 2.2, is that \( v \sin I \) values measured this way are systematically increased. The values in Table 4.10 show the discrepancy between \( v \sin I \) values calculated using the tomographic method, and the results from previous spectroscopic measurements for all 8 systems which have been treated tomographically to date. For all cases except WASP-16, the \( v \sin I \) value measured via the tomographic method is lower than that derived during the original RM analysis of the system. The results from tomography are much more in keeping with those obtained via spectral synthesis, where we find the results to be reasonably similar for each system, with the tomographic values being on average 13\% smaller but mostly in agreement within the 1\( \sigma \) error ranges.

Figure 4.14 shows the position of the five planets from this study in the \( T_{\text{eff}} - \lambda \) plane, together with all of the systems with measured misalignment angles. The intriguing region on this plot is the area in the bottom right, corresponding to well-aligned systems with high
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Figure 4.10: Top: The anomaly is clearly visible in the upper plot despite the slow rotation rate of WASP-23. It appears to move from the red to the blue side of the line profile as the transit occurs. This simple piece of information helps break the ambiguity over the system’s alignment, showing that it is indeed in a prograde orbit. The significance of the top and bottom panels and an explanation of the markings is given in the caption for Figure 4.1.
Figure 4.11: Modified Hertzsprung-Russell diagram showing the updated position of WASP-23 in the density-effective temperature plane. The isochrones for the ages 6-20 Gyr (left to right, black curves) and the evolutionary mass tracks are from (Demarque et al., 2004).
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Table 4.8: System parameters from the MCMC analysis for WASP-31.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit epoch</td>
<td>$T_0$</td>
<td>5219.9364 $\pm$ 0.0004</td>
<td>days</td>
</tr>
<tr>
<td>Orbital period</td>
<td>$P$</td>
<td>3.405902$^{+0.0000047}_{-0.0000041}$</td>
<td>days</td>
</tr>
<tr>
<td>Planet/star radius ratio</td>
<td>$(R_p/R_*)^2$</td>
<td>0.0149 $\pm$ 0.0003</td>
<td></td>
</tr>
<tr>
<td>Transit duration</td>
<td>$T_{14}$</td>
<td>0.1064$^{+0.001}_{-0.001}$</td>
<td>days</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>$b$</td>
<td>0.761$^{+0.015}_{-0.017}$</td>
<td></td>
</tr>
<tr>
<td>Eccentricity</td>
<td>$e$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Orbital separation</td>
<td>$a$</td>
<td>0.0472 $\pm$ 0.0004</td>
<td>AU</td>
</tr>
<tr>
<td>Orbital inclination</td>
<td>$I$</td>
<td>84.4 $\pm$ 0.4</td>
<td>degrees</td>
</tr>
<tr>
<td>Projected stellar rotation rate</td>
<td>$v\sin I$</td>
<td>7.05$^{+0.06}_{-0.06}$</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Projected alignment angle</td>
<td>$\lambda$</td>
<td>$-1^{+8}_{-5}$</td>
<td>degrees</td>
</tr>
<tr>
<td>Intrinsic v(FWHM)</td>
<td>$v_g$</td>
<td>8.54 $\pm$ 0.09</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>RM centre-of-mass velocity</td>
<td>$\gamma$</td>
<td>$-0.12 \pm 0.01$</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>Stellar density</td>
<td>$\rho_*$</td>
<td>$0.62^{+0.06}_{-0.06}$</td>
<td>$\rho_\odot$</td>
</tr>
<tr>
<td>Stellar effective temperature</td>
<td>$T_{eff}$</td>
<td>6357$^{+90}_{-90}$</td>
<td>K</td>
</tr>
<tr>
<td>Stellar mass</td>
<td>$M_*$</td>
<td>1.21 $\pm$ 0.03</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Stellar radius</td>
<td>$R_*$</td>
<td>1.25$^{+0.05}_{-0.04}$</td>
<td>$R_\odot$</td>
</tr>
<tr>
<td>Planet mass</td>
<td>$M_p$</td>
<td>0.52 $\pm$ 0.05</td>
<td>$M_J$</td>
</tr>
<tr>
<td>Planet radius</td>
<td>$R_p$</td>
<td>1.49 $\pm$ 0.06</td>
<td>$R_J$</td>
</tr>
</tbody>
</table>

Table 4.9: Age and mass values for WASP-31 from comparison with various isochrone models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Age estimate (Gyr)</th>
<th>Mass estimate ($M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Padova</td>
<td>$0.6^{+0.8}_{-0.6}$</td>
<td>$1.26^{+0.04}_{-0.26}$</td>
</tr>
<tr>
<td>Teramo</td>
<td>$1.5^{+1.0}_{-0.9}$</td>
<td>$1.20^{+0.02}_{-0.15}$</td>
</tr>
<tr>
<td>Victoria-Regina</td>
<td>$0.6^{+1.4}_{-0.5}$</td>
<td>$1.30^{+0.01}_{-0.05}$</td>
</tr>
<tr>
<td>Yonsei-Yale</td>
<td>$1.1^{+0.7}_{-1.0}$</td>
<td>$1.27^{+0.03}_{-0.07}$</td>
</tr>
</tbody>
</table>
4.4. Discussion

Figure 4.12: Top: The trailed spectra for WASP-31b, showing a clear anomaly moving in the prograde direction. The significance of the top and bottom panels and an explanation of the markings is given in the caption for Figure 4.1.
Figure 4.13: Modified Hertzsprung-Russell diagram showing the updated position of WASP-31 in the density-effective temperature plane. The isochrones for the ages 0.1, 0.8, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 Gyr and the evolutionary mass tracks are from Demarque et al. (2004).
effective temperatures. It was observed by Winn et al. (2010) that planets around stars with $T_{\text{eff}} > 6250$ K are preferentially in misaligned orbits. This value corresponds to the temperature above which stars no longer exhibit a convective outer shell. Therefore Winn et al. (2010) suggest that hot Jupiters start off with a random distribution of alignments resulting from the migration process and systems with lower temperatures than 6250 K find it easier to realign themselves due to larger amounts of tidal dissipation in their outer convective shells. The only one of the system examined in this study which is found to significantly penetrate the excluded region of the plot is WASP-18. With a projected spin-orbit misalignment of $\lambda = -1 \pm 4^\circ$ and $T_{\text{eff}} = 6441^{+100}_{-100}$ it is very well-aligned and hotter than the cut-off proposed in Winn et al. (2010). WASP-31 also proves a weak exception to the rule, being well-aligned with $T_{\text{eff}} = 6357^{+90}_{-90}$.

This idea was expanded on by Albrecht et al. (2012a) who calculated ‘tidal timescales’ for 14 systems, based on their orbital separation, planet-star mass ratio and stellar effective temperature, and showed that those with longer timescales had planets in well-aligned orbits. Taking into consideration the other factors involved in tidal realignment may explain the low obliquities of WASP-18 and WASP-31. For example, WASP-18 has a high steller effective temperature, however the planet is of high-mass and orbits very closer to the parent star. These latter two factors could serve to reduce the systems tidal timescale.

In Figure 4.15 we have plotted the intrinsic linewidth $v_g$ as a function of stellar effective temperature for the eight stars measured using the tomographic method to date. The intrinsic broadening arises through turbulence in the stellar atmosphere, which has been shown to be a function of effective temperature as presented in Doyle et al. (2013). The trend we observe gives us an empirical calibration of the degree of turbulence as a function of $T_{\text{eff}}$.

4.5 Conclusions

We set out not only to measure the spin-orbit obliquities of these five WASP systems, but to show that the tomographic Rossiter-McLaughlin analysis method can be used on transiting systems with faint, slowly-rotating host stars. Until now this type of analysis had only been performed on bright, rapidly-rotating stars which make it easier to fit the model. The results of this chapter show that the tomographic analysis is indeed a viable option for measuring the parameters of slowly-rotating systems. It can even produce well-constrained results for
systems such as WASP-16 and WASP-23, where the stellar $v\sin I$ is significantly smaller than the intrinsic profile width.

We have confirmed the previously reported results for WASP-18b suggesting that it is in a well-aligned orbit with $\lambda = -1.0 \pm 4.0^\circ$. The accuracy of our measurement of $v\sin I$ is a major improvement on existing measurements. We confirm the highly misaligned retrograde orbit of WASP-17b with $\lambda = -168 \pm 18^\circ$ and again we obtain a more precise measurement of the projected stellar rotation rate $v\sin I$. Our results show that WASP-31b is in a well-aligned orbit with $\lambda = -1^{+8}_{-5}^\circ$. We find a result for WASP-23b which eliminates the ambiguity presented in the discovery paper. Our value of $\lambda = -4 \pm 18^\circ$ implies that WASP-23b is in a well aligned orbit around its host star. Being able to tell whether a planet is in a prograde or retrograde orbit simply by looking at the streak produced in the trailed spectra is a very powerful diagnostic. Our results for WASP-16b and WASP-23b suggest that they are well aligned systems though the uncertainty range on $\lambda$ is much higher for these two planets due to the extremely slow rotation rate of their host stars.

In the context of the tendency of hotter systems to be misaligned and planets around stars with $T_{\text{eff}} < 6250$ K to be in well-aligned orbits, we find WASP-16, 17, and 23 follow the trend, with WASP-17 being the only system with a significant degree of spin-orbit misalignment. However, WASP-31 appears to be a weak exception to the rule, being well-aligned with $T_{\text{eff}} = 6300$ K. The WASP-18 system is a stronger exception, appearing to be very well-aligned yet with $T_{\text{eff}} = 6441^{+100}_{-100}$. However, the low obliquity of these two systems may be explained in the context of tidal timescales presented in Albrecht et al. (2012a). At the moment there are only a relatively small fraction of transiting planets with alignment measurements. With more Rossiter-McLaughlin observations we will start to fill the parameter space and begin to get a proper idea of the full picture.
Table 4.10: Comparison of $v_{\sin I}$ values obtained via different methods (Systems measured in this chapter are marked with *).

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral synthesis $v_{\sin I}$ (km/s)</th>
<th>Non-tomographic $v_{\sin I}$ (km/s)</th>
<th>Tomographic $v_{\sin I}$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD189733</td>
<td>3.32$^{+0.02}_{-0.07}$</td>
<td>3.32$^{0.02}_{-0.07}$</td>
<td>3.10$^{0.03}_{-0.03}$</td>
</tr>
<tr>
<td>WASP-3</td>
<td>15.7$^{+1.4}_{-1.3}$</td>
<td>15.7$^{1.4}_{-1.3}$</td>
<td>13.90$^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>WASP-16*</td>
<td>3.0$^{+1.0}_{-1.0}$</td>
<td>2.3$^{0.4}_{-0.4}$</td>
<td>2.5$^{+0.5}_{-0.5}$</td>
</tr>
<tr>
<td>WASP-17*</td>
<td>9.8$^{+0.5}_{-0.5}$</td>
<td>19.1$^{+0.3}_{-0.4}$</td>
<td>8.4$^{+0.1}_{-0.1}$</td>
</tr>
<tr>
<td>WASP-18*</td>
<td>11.4$^{+0.4}_{-0.4}$</td>
<td>-</td>
<td>10.80$^{+0.04}_{-0.04}$</td>
</tr>
<tr>
<td>WASP-23*</td>
<td>1.2$^{+0.3}_{-0.3}$</td>
<td>1.21$^{0.17}_{-0.23}$</td>
<td>1.0$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>WASP-31*</td>
<td>7.6$^{+0.4}_{-0.4}$</td>
<td>8.1$^{0.5}_{-0.5}$</td>
<td>7.1$^{+0.1}_{-0.1}$</td>
</tr>
<tr>
<td>WASP-33</td>
<td>90.0$^{+10.0}_{-10.0}$</td>
<td>-</td>
<td>86.1$^{+0.1}_{-0.1}$</td>
</tr>
</tbody>
</table>
Figure 4.14: Plot showing the magnitude of the projected spin-orbit misalignment angle $\lambda$ against stellar effective temperature $T_{\text{eff}}$. The horizontal dotted line at $\lambda = 30^\circ$ defines the critical limit for systems to be considered significantly misaligned. The vertical dotted line at $T_{\text{eff}} = 6250$ K corresponds to the effective temperature above which stars no longer have a convective outer shell. The horizontal dotted line at a $T_{\text{eff}}$ of 6250 K is used to identify systems that are misaligned. However, our values for WASP-18 show it to be an exception to this trend. The plot shows the trend of systems with effective temperatures greater than 6250 K to be misaligned. Systems above the line are considered to be significantly misaligned.

- WASP-16 = blue circle
- WASP-17 = blue square
- WASP-18 = blue triangle
- WASP-23 = blue diamond
- WASP-31 = blue star
- The plot shows the trend of systems with effective temperatures greater than 6250 K to be misaligned. However, our values for WASP-18 show it to be an exception to this trend. The horizontal dotted line at $T_{\text{eff}} = 6250$ K is used to identify systems that are misaligned. Systems above the line are considered to be significantly misaligned.
Figure 4.15: The intrinsic spectral linewidth, $v_g$, plotted as a function of stellar effective temperature, $T_{\text{eff}}$. The linear trend gives an empirical calibration of the degree of turbulence as a function of $T_{\text{eff}}$. 
Chapter 4. Rossiter-McLaughlin analyses of five transiting systems
Detecting planets orbiting early-type stars

In this chapter we show how the tomographic Rossiter-McLaughlin analysis method, described in Section 2.3, can be applied to systems in which planet candidates are orbiting hot, rapidly-rotating, early-type stars. These systems cannot be followed-up via traditional radial velocity measurements due to their heavily rotationally-broadened spectral lines, so the tomographic method provides a unique way of examining the distribution of transiting planets at the hotter end of the main sequence.
## 5.1 Introduction

The spectra of young, hot stars tend to have broadened lines due to rapid-rotation (for example, see Figure 5.2 which shows two of the averaged line-profiles for the hot, rapidly-rotating star J025712). They also have a lower abundance of spectral lines than cooler, older stars. This makes it very difficult to attain accurate radial velocity measurements of the system. Only upper limits can be placed on the mass of any transiting companion as the uncertainties on the RV measurements are so high. The tomographic method does not rely on accurate radial velocity measurements. It also performs better on rapidly-rotating stars where the anomalous signature is stronger and the lines are broad enough for the spectrograph to resolve it more easily. This makes it uniquely suited to confirming the existence of planetary companions to early-type stars. The method was used by [Collier Cameron et al.](2010c) to confirm the existence of the first planet known to transit an A-type star. Measuring the distribution of spin-orbit misalignment angles in early-type systems may be key to understanding the processes by which hot-Jupiter planets migrate. As mentioned in Chapter 1, it has been shown by [Winn et al.](2010) that there is a relationship between the degree of spin-orbit misalignment and the stellar effective temperature, with orbits tending to be misaligned in systems with $T_{\text{eff}} > 6250$ K. However, so far there are only a handful of spin-orbit misalignment measurements for systems above this boundary.

In an attempt to add vital data to this sparsely populated parameter space, we observed the spectroscopic transits of four early-type systems flagged as planet hosting candidates by the SuperWASP survey and analysed the resulting data using the tomographic method described in Chapter 2.

## 5.2 Target selection

There are tens transiting planet candidates in the SuperWASP data archive which show periodic dips in brightness consistent with a planet-sized companion but that have been dropped from the radial velocity follow-up campaigns as their host stars are early-type rapid rotators. We searched the archive to find objects such as this, orbiting stars of mid-F or earlier spectral type, with small, well-defined periodic dips in brightness. Some of the targets we found already had radial velocity measurements which, despite not being accurate enough to confirm the mass of the companion, were able to rule out the existence of a stellar-mass
5.3 Observations

The OPTICON-TAC awarded 5 nights on the 2-m Bernard Lyot Telescope at Pic du Midi Observatory for observations from proposal 2010B/008, and 3 nights for proposal 2012A/026. In total, 4 candidates from a proposed list of 15 were observed with the Narval spectrograph. The observations were carried out in SPEC6 (star+sky) mode, in which the spectrograph has a resolution of $R = 65000$. Exposure times were calculated using the online tool for Narval to produce a target signal-to-noise ratio of 50. A log of the observations is shown in table 5.1 along with selected properties of the host stars.

The data were reduced using the Libre-ESpRIT package (DoNati et al., 1997) to produce average line-profiles from each of the spectra.

5.4 Results

Full tomographic MCMC analysis has not yet been performed on the data from these observations, however the spectroscopic transits have each undergone preliminary analysis which shows some interesting results. In the preliminary analysis of each object we simply computed the average line profile of the observations and then removed this average from each individual observation to reveal any large, time-varying components in the spectrum.

5.4.1 J025712

J025712 is a star of spectral type F0 with effective temperature $T_{\text{eff}} = 6935 \pm 147$ K. It has been shown in WASP data to undergo dips in brightness of approximately 0.7% on a 2.22 day period. Spectral observations from the FIES spectrograph attached to the 2.5 m Nordic Optical Telescope on La Palma, and the Sophie spectrograph on the 1.93-m telescope at Haute-Provence Observatory show it to be a rapid-rotator with $v\sin{i} > 100$ km s$^{-1}$. For this reason, radial velocity follow-up was abandoned by the SuperWASP survey in 2009. Our preliminary analysis appears to show a stellar-mass companion transiting the host. In Figure 5.1 we see the broad streak of light produced by the Doppler shadow moving through the spectra as the large companion transits the host star.
Table 5.1: Properties of the target stars and a log of the observations.

<table>
<thead>
<tr>
<th>Target</th>
<th>Spectral type</th>
<th>$T_{eff}$ (K)</th>
<th>$v$</th>
<th>Season</th>
<th>Date of observation</th>
<th>Number of exposures</th>
<th>$t_{exp}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J025712</td>
<td>F0</td>
<td>6935 ± 147</td>
<td>10.4</td>
<td>18th Oct 2010</td>
<td>29</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>J091630</td>
<td>A5</td>
<td>7873 ± 164</td>
<td>9.7</td>
<td>13th Mar 2012</td>
<td>25</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>J091630</td>
<td>A5</td>
<td>7873 ± 164</td>
<td>9.7</td>
<td>15th Mar 2012</td>
<td>25</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>J205027</td>
<td>F6</td>
<td>6339 ± 141</td>
<td>9.9</td>
<td>04th Jun 2012</td>
<td>22</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>J212530</td>
<td>F5</td>
<td>6407 ± 140</td>
<td>11.1</td>
<td>12th Aug 2012</td>
<td>10</td>
<td>660</td>
<td></td>
</tr>
</tbody>
</table>
5.4. Results

Figure 5.1: Top: Trailed spectra of the 29 observations made of J025712. Barycentric radial velocity is plotted along the x-axis and the y-axis shows the orbital phase at which each observation was taken (where zero phase corresponds to predicted mid-transit time). Flux is plotted as a greyscale, with black indicating lower flux and white higher flux. The darker region shows the core of the line-profile. Bottom: Here the average of all the spectra has been subtracted from each observation, showing the broad, bright signature of the transiting stellar-mass companion.
By measuring the radial velocity shift in the line-profiles between the start and the end of the observations we are able to produce an estimate for the mass of the transiting companion. Our measurements of the radial velocity of the line centroid for the first and last observations reveal a total shift in velocity of $15.0 \pm 1.4 \text{ ms}^{-1}$. The observations lasted for a total of 19,140 seconds. So the acceleration of the host star caused by the gravitational force of the companion is given by

$$a = \frac{\text{total shift in radial velocity}}{\text{total time of observations}} = a = 0.80 \pm 0.08 \text{ms}^{-2}. \quad (5.1)$$

Next by equating Newton’s 2nd law and his law of gravitation we get

$$M_* a = G \frac{M_c r^2}{r^2}, \quad (5.2)$$

where $M_*$ is the mass of the host star, $M_c$ is the mass of the companion body, $r$ is the orbital separation, and $G$ is the gravitational constant. Dividing both sides by $M_*$ and rearranging we find the mass of the companion is given by

$$M_c = \frac{a r^2}{G}. \quad (5.3)$$

From the MCMC analysis of the WASP lightcurve data we find the orbital separation to be $r = 0.0374 \pm 0.0005 \text{ AU}$. Therefore, we find the mass of the companion body to be $M_c = 190 \pm 30M_J$. This mass suggests the companion is most likely an M-dwarf star. Figure 5.2 shows the shift in radial velocity of the line centroid from first to last observation.

### 5.4.2 J091603

J091603 exhibits regular transit-like events with a depth of 0.5% every 2.04 days. The star is of A5 spectral type, similar to WASP-33, and has an effective temperature of $T_{eff} = 7873 \pm 164 \text{ K}$. It has had 2 previous spectral observations taken with the Coralie spectrograph, showing it to be a very rapid-rotator with no significant radial velocity variation. Our analysis shows what appear to be non-radial pulsations (Figures 5.3 & 5.4) similar to those reported by [Collier Cameron et al. (2010c)] on WASP-33. However, in this case we see no sign of the residual signature which would be caused by a transiting companion. A visual inspection of
5.4. Results

Figure 5.2: The average line-profiles of the initial and final observations of J025712. The estimated centroid of the line-profile for each observation is marked by a vertical line. The total shift in radial velocity over the course of the observations appears to be around 15 km s\(^{-1}\), suggesting the companion is an M-dwarf with a mass of roughly 190\(M_J\), the photometry from the WASP telescopes shows no sign of pulsations, so it is unlikely that they are resposible for the transit-like events. The similarity to WASP-33 suggests it is most likely a \(\gamma\) Dor or \(\delta\) Scuti-type non-radial pulsator \cite{Herrero2011}.

5.4.3 J205027

J205027 is an F6V spectral type star with \(T_{\text{eff}} = 6339 \pm 141\) K, and was first flagged as a planet-hosting candidate in the 2004 SuperWASP data, showing transits on a period of 1.23 days. It was subsequently dismissed as a probable eclipsing binary system. However the latest combined lightcurve data shows it to have a low impact parameter and a transit depth of less than 2%, implying that there is still a possibility it has a companion of sub-stellar mass. Three spectra were taken with Sophie which revealed no large-scale radial velocity variation. As with J212530, our initial analysis shows nothing significant in the spectroscopic data from Narval (see Figure 5.5). A full tomographic MCMC analysis will be required to reaveal whether the signature of a transiting companion lies within the spectra.
Figure 5.3: Top: Trailed spectra of the 25 observations of J025712. Bottom: Here the average of all the spectra has been subtracted from each observation, revealing the broad tiger-stripe pattern created by non-radial stellar pulsations.
Figure 5.4: Top: As in Figure 5.3, all 25 spectra stacked. Bottom: A streak caused by non-radial pulsations on the stellar surface can be seen once the average of the spectra has been removed.
Figure 5.5: Top: Trailed spectra map of the 22 observations of J205027. Bottom: With the average line profile subtracted, no obvious residual signature is revealed via this preliminary analysis.
5.4. Results

5.4.4 J212530

J212530 is a star of spectral type F5 and $T_{\text{eff}} = 6407 \pm 140$ K. It was first detected as a candidate in the SuperWASP data in 2008 and shows regular transit-like dips in brightness every 3.8 days. Spectra taken with Sophie show it to be a rapid rotator, with $v \sin I > 35$ km s$^{-1}$. 6 spectra in total were taken using Sophie in 2010 and they show no large-scale radial velocity movement. Our analysis shows no obvious sign of a transit signature (Figure 5.6), however there may be a planet signature hidden under the noise level. A full MCMC analysis will give a clearer picture. There is also the possibility that the observations were taken at the wrong time and the transit may have been missed (see Section 5.4.5).

5.4.5 Ephemeris drift

There is always the possibility that the observations of these systems were scheduled for the wrong time due to ephemeris drift, and the transit was missed. There is an uncertainty associated with the period measurement for any given SuperWASP planet candidate. This means that the longer the amount of time which has passed since the last transit observation, the more the predicted time of transit could have slipped from the true time of transit. In order to estimate the possible amount of ephemeris drift at the time of observation for each target we first calculated the number of transits which have occurred since the ephemeris was set:

$$N_{\text{transit}} = \frac{t_{\text{obs}} - t_0}{P}$$  \hspace{1cm} (5.4)

where $t_{\text{obs}}$ is the Julian Date of the observation, $t_0$ is the epoch from the ephemeris used to predict the transit, and $P$ is the orbital period of the planet candidate. The uncertainty on the period is $\sigma_P$, so the uncertainty on the predicted time of transit, $\sigma_T$, is then given by

$$\sigma_T = \sqrt{(N_{\text{transit}} \times \sigma_P)^2 + (\sigma_{\text{epoch}})^2}$$  \hspace{1cm} (5.5)

where the uncertainty on the epoch, $\sigma_{\text{epoch}}$, has been added in quadrature. Our results show that there should not have been a major drift in predicted transit time for any of the targets, with the maximum shift being just 26 minutes for J212530. The drifts and values used to calculate them for each object can be seen in table 5.2. Since the spectroscopic transit observations were each much longer than the calculated uncertainty in transit time it is unlikely
Figure 5.6: Top: Trailed spectra of the 10 observations of J212530. Bottom: After removing the average spectrum there is no immediate signature of a transiting companion.
that ephemeris drift has caused the transit to be missed completely by the observations.

5.5 Preliminary tomographic MCMC analysis

Initial attempts at a full tomographic MCMC analysis of the data for these systems has proven fruitless. The code fails to find suitable values for the parameters during the burn-in phase, and instead wanders around the parameter space. Varying values for the initial jump parameters have been tried with no success. This would suggest that there is no solution to be found due to there being no actual planetary transit in the data.

5.6 Other selected targets

Two of the targets we proposed to examine with Narval in the 2010B season (namely J000126 and J003750), which we were not able to observe due to poor weather conditions, have subsequently been shown via separate observations to host companions of sub-stellar mass. J000126 has been designated KELT-1b, the first sub-stellar object to be confirmed by the Kilodegree Extremely Little Telescope (KELT) wide-field survey (Silverd et al., 2012) using their northern telescope located at the Winer Observatory, Arizona. They find a mass of $27.23 \pm 0.50 M_J$ for the companion, making it either a low-mass brown dwarf or supermassive planet. They also find the orbit of the companion to be well-aligned with the rotation of the host star with $\lambda = 2 \pm 16^\circ$. Good quality lightcurves from the NITES, PIRATE (Holmes et al., 2011) and James Gregory telescopes all yielded low values for the radius of the companion orbiting J003750 of $R_p = 1.11 \pm 0.08 M_{Jup}$ and radial velocity measurements from the Sophie spectrograph ruling out a stellar-mass companion, so it is now considered by the SuperWASP survey to be a planet and has been given the identifier WASP-93b.

5.7 Conclusions

We have shown that even a preliminary analysis of the transit spectra provides useful information on the nature of early-type planet-host candidates. We have ruled out one candidate (J025712) as an eclipsing binary star system with an early-F-type primary and an M-dwarf companion of mass $M = 190 \pm 30 M_J$. We have revealed J091630 to be a non-radial pulsator similar to WASP-33. Analysis of the ephemeris drift for each target has shown that the time of transit should not have moved significantly enough for it to be missed by the observations.
Table 5.2: The uncertainties on the predicted transit time for each target, calculated from the uncertainties on the period and epoch used to predict the transit. Epoch is stated in truncated Julian Days (JD-2450000).

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Period (days)</th>
<th>$\sigma_P$ (minutes)</th>
<th>Epoch (TJD)</th>
<th>$\sigma_{\text{epoch}}$ (minutes)</th>
<th>$\sigma_T$ (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J025712</td>
<td>2.036325</td>
<td>0.034</td>
<td>5291.71179</td>
<td>2.53</td>
<td>11.26</td>
</tr>
<tr>
<td>J091630</td>
<td>2.222488</td>
<td>0.016</td>
<td>3970.62224</td>
<td>2.64</td>
<td>10.97</td>
</tr>
<tr>
<td>J205027</td>
<td>1.229676</td>
<td>0.008</td>
<td>4558.80337</td>
<td>2.42</td>
<td>10.29</td>
</tr>
<tr>
<td>J212530</td>
<td>3.809699</td>
<td>0.086</td>
<td>5055.24603</td>
<td>8.06</td>
<td>26.16</td>
</tr>
</tbody>
</table>
Initial attempts at a detailed tomographic MCMC analysis of these hot systems unfortunately seems to suggest that there are no transit events present in the data.

We conclude that, despite the null results presented in this chapter, tomographic RM analysis is a strong and useful tool which can be implemented effectively in the follow-up campaigns for transiting planet candidates with hot, early-type, rapidly-rotating host stars. In light of recent studies suggesting varying distributions of spin-orbit alignments with stellar effective temperature and other properties of the system, it is important that the full range of planetary systems are examined. The tomographic method can contribute greatly to populating the parameter space at the hot end of the stellar main sequence, which will in turn provide valuable insights into planet formation and evolution processes.
Chapter 5. Detecting planets orbiting early-type stars
Conclusions and Outlook

In this final chapter I will summarise the findings contained within this thesis, discuss their significance in the broader context, and finally I will provide some insights into possible future work that can build on what I have carried out thus far.
Chapter 6. Conclusions and Outlook

6.1 Main findings

My doctoral work has consisted of two main aims. Firstly, to test the tomographic Rossiter-McLaughlin analysis method on a range of known planetary systems to see how well it copes with factors such as low stellar rotation rate, and fainter host stars. Secondly I have used it to search for the existence of new transiting planets in orbits around rapidly-rotating early-type stars, of which only two (WASP-33b & WASP-93b) are known to exist.

I can separate my analysis of the known SuperWASP planets into two categories; planets orbiting moderately fast-rotating stars with $v \sin I \approx 10$ km s$^{-1}$, and planets in orbits around much more slowly rotating host stars for which the RM effect is not as pronounced.

6.1.1 Moderately fast-rotating stars

Of the six known planets I have analysed in this thesis, four of them are orbiting moderately fast-rotating host stars with $7 < v \sin I < 16$ km s$^{-1}$, namely WASP-3b, WASP-17b, WASP-18b and WASP-31b. For each of these targets I show the tomographic method is easily able to detect the effect of the Doppler shadow created by the planet as it crosses the disc of its host star. For WASP-3b, WASP-18b and WASP-31b, I have been able to confirm previous results that there is very little misalignment between the projected stellar spin axis and the orbital axis of the planet. I have been able to confirm the highly misaligned retrograde orbit of WASP-17b, which I find to have $\lambda \approx 170^\circ$. In addition I produce a more accurate measure of the stellar rotation rate for each target.

6.1.2 Slowly rotating stars

WASP-16b and WASP-23b are in orbits around much slower rotating host stars, with $v \sin I \approx 2.5$ km s$^{-1}$ and $v \sin I \approx 1$ km s$^{-1}$ respectively. These low rotation velocities provide a challenge for measurements of the RM effect. Despite this I am able to detect the radial velocity anomaly caused by the transiting planet and produce values for the system parameters related to the RM effect. Results for the degree of spin-orbit misalignment are not as accurate as for the faster-rotating system, however my result showing the orbit of WASP-16b to be reasonably well-aligned with stellar rotation is in agreement with previous studies of the system.

In my analysis of the WASP-23 system I highlight one of the major advantages of the tomographic method. An RM analysis of the system had already been performed by Triaud 98.
et al. (2011), however they were unable to determine the true value of $\lambda$ for the system due to an ambiguity in their results for $v\sin I$. They showed that using differing values of $v\sin I$ leads to very different values of $\lambda$ being produced. Using the tomographic method I was able to remove the ambiguity in $v\sin I$, as the technique provides an independent measure of the stellar rotation rate from the shape of the out-of-transit line-profile. This meant I was able to present an initial confirmation of the obliquity of the planet’s orbit. I found it to be a well-aligned system with $\lambda = -4 \pm 18^\circ$.

6.1.3 Early-type stars

Finally, I aimed to use the tomographic method to search for planets orbiting rapidly-rotating, early-type stars. This outlines another major advantage of the method. As it does not require accurate measurements of the radial velocity of the target star, it is able to probe the spectra of early-type stars exhibiting transit-like events, the line-profiles of which are most commonly rotationally broadened to such an extent that they are dismissed at the radial velocity follow-up stage.

During the course of my degree I was the principle investigator of two successful telescope proposals to observe such candidates. Of the fifteen targets I proposed, four had their spectroscopic transits observed by the Narval spectrograph on the Telescope Bernard Lyot at the Pic du Midi Observatory. I was not able to perform full tomographic MCMC analysis of the observations before submission of this thesis; however, I was able to perform a preliminary tomographic inspection of each target.

The preliminary analysis has allowed me to reject the candidate J025712 as an astrophysical false-positive. It shows a large streak running through the trailed spectra during transit and a simple measurement of the radial velocity shift during the observations yields a companion mass of $M = 190 \pm 30 M_J$. I therefore propose that the transits are a result of an eclipsing binary system, with an M-dwarf companion to an F-type primary.

Two spectroscopic transits were observed of the candidate J091630 and my analysis has so far revealed that the star is undergoing non-radial pulsations similar to those observed in WASP-33.

My initial analyses of J091639, J205027 and J212530 do not show the signature of any transiting companion. I calculated the uncertainty in transit time due to ephemeris drift and
found it to be very small compared to the length of the observations. Therefore I suggest that
the transit signatures may not be strong enough to be revealed by a preliminary analysis and
subsequent full tomographic MCMC analysis is required to investigate the true nature of these
systems.

At point of final submission of this thesis I had attempted full tomographic MCMC analysis
of these datasets. Unfortunately the results seem to suggest that no planetary transits occurred
during the observations.

6.1.4 Orbital obliquities and the migration process

As previously discussed in Section 1.4, Section 3.4 and Section 4.4, Albrecht et al. (2012a)
has shown that perhaps hot Jupiters start-off with a wide range of random orbital obliquities,
and the ones which we now observe to be in well-aligned orbits are in systems with short tidal
timescales where the planet and star can realign faster via tidal dissipation. They suggest that
systems with cooler stars and larger planet-star mass ratios will have shorter timescales for
tidal realignment. Younger systems will also therefore be more likely to have high observed
obliquities, as they have not had enough time to align themselves. They were building on
the work of [Winn et al.] (2010) who observed that hot Jupiters around hot stars were prefer-
rentially in misaligned orbits perhaps due to their lack of convective envelope in which tidal
dissipation can take place more efficiently.

It is shown in Section 3.4 that the WASP-3 system does not fit perfectly into this picture, as
it is a relatively hot, young system (Age $\sim$ 2 Gyr & $T_{\text{eff}} = 6332 \pm 105$) with a low planet-mass
ratio ($\sim 0.001$), yet it is well-aligned. In Section 4.4 I presented the WASP-18 and WASP-
31 systems as being weak exceptions to the effective temperature-obliquity relation of [Winn
et al.] (2010). The low obliquity of WASP-18 may be explained in the context of the tidal
timescale idea (Albrecht et al. 2012a) as, despite being hot and young, it has a large planet-
star mass ratio of $\sim 0.008$. However, the low obliquity WASP-31 cannot be explained in the
same manner, as it has a similar age and stellar effective temperature to WASP-18, but with a
much smaller planet-star mass ratio. The other 3 systems analysed in Chapter 4 all agree well
6.2 Outlook

So far tomographic analysis has only been performed on eleven known transiting planetary systems, six of which are presented in this thesis. One of these planets, WASP-33b, is the first transiting planet to be confirmed orbiting an A-type star. Recent studies by Winn et al. (2010), Triaud (2011) and Albrecht et al. (2012a) have presented evidence for relationships between spin-orbit misalignment and various properties of the system, in particular the stellar effective temperature. It is my belief that the tomographic RM analysis method presented in this thesis is a vital tool for examining the distribution of spin-orbit misalignment angles for transiting planetary systems, especially at the hotter end of the main sequence, where other methods cannot look due to the broader spectral lines of the more rapidly-rotating host stars.

To this end, the SuperWASP team at the University of St Andrews is continuing the program of observing planet candidates orbiting early-type stars. A third proposal to observe five more of these candidates with Narval, on which I am a co-investigator and helped select the targets, has been awarded 2.5 clear nights by the OPTICON-TAC. I am hopeful that the observations will produce positive results which will increase our knowledge of planets orbiting early-type stars, providing us with vital new information that will help us to better understand the formation and evolution of all planets.
As the SuperWASP telescopes have a very wide field-of-view, follow-up photometry of individual planet candidates using a more powerful telescope is often required in order to confirm planetary nature of the transit event. Follow-up observations using a larger telescope can rule out false-positive detections such as grazing eclipsing binary star systems and background blends. They also help confirm the radius of actual planet-sized transiting objects.

In this appendix I will describe the photometric follow-up campaign that is run at the University of St Andrews Observatory, and of which I have been heavily involved in during my time as a doctoral student.
Appendix A. SuperWASP follow-up observations using the James Gregory Telescope

The observatory at the University of St Andrews is home to the James Gregory Telescope (JGT) which, with a 38" primary mirror, is the largest optical telescope operating in the United Kingdom. A programme of follow-up photometry of SuperWASP candidates is run by the group at the University of St Andrews headed by Professor Andrew Collier Cameron. A major part of my work during my degree has been concerned with these observations. I was part of a team of four or five observers who each spend a week on-call every month or so following a rota. In the last four years I have spent over one hundred nights observing with the JGT. For the last three years I have been responsible for managing the observing programme. My duties included carrying-out observations, organising the observing rota, selecting priority candidates for observation, reducing and analysing the data, updating the resulting parameters of the observed candidates in the SuperWASP archive, commissioning new instruments and software, and training new observers how to use the telescope and all the other duties just mentioned. Most of these tasks were also performed by Professor Andrew Collier Cameron and David Brown (who is also a SuperWASP PhD student at the University of St Andrews).

The JGT photometry is performed using a 1024 x 1024 pixel E2V CCD chip cooled to $-50\degree$ C. Observations are carried out in the Cousins R-band as it is the broadest of the six filter options, therefore letting through the maximum possible amount of light from our target. We recently installed an SBIG SG4 autoguider on the finderscope of the JGT. This allows us to keep the target on the same pixel throughout our observations, eliminating pixel-to-pixel variations, as the target drifts across the chip, which can have the same magnitude as the dip in stellar flux cause by a transiting planet. A quick data reduction and analysis pipeline was created by Sarah Brown (an undergraduate student) with help from Prof. Collier Cameron during a summer placement in the School of Physics & Astronomy. It allows us to reduce the data and plot the variation in brightness of the star in real-time during an observing session. The images are reduced using flat-field frames (normally produced at the start of each observing season) and are de-biased using the overscan strip. The observer then selects the target and multiple reference stars, signalling that aperture photometry is to be performed on each star. The resulting lightcurve is plotted along with the raw flux, sky background variations and brightness variation of the comparison stars. Example of the JGT reduction pipeline output from observations performed by myself can be seen in Figure A.1 and Figure A.2.

During my time in St Andrews the JGT has been used to observe hundreds of SuperWASP candidates. It has confirmed the planet-sized radius of tens of objects (including qatar-1b,
Figure A.1: Plots output from the JGT data reduction pipeline for the observations of the planet Qatar-1b. The data shown here helped confirm the planet-sized radius of the transiting object (Alsubai et al., 2011).

Figure A.2: A blended eclipsing binary system. Here the JGT observations have revealed that the true reason for the periodic dips in brightness is a faint nearby eclipsing binary system. This is shown by the large dip in the K-C comparison, whereas the target (V-C) shows little variation.
Appendix A. *SuperWASP follow-up observations using the James Gregory Telescope*

The first planet announced by the Qatar Exoplanet Survey (Alsubai et al., 2011), for which the JGT observations taken by myself (see Figure [A.1]) proved instrumental in confirming its planetary status, and has ruled-out many more as background blends or grazing eclipsing binary stars (which produce a tell-tale V-shaped lightcurve). Several observations have shown no brightness variation in either target or comparison stars. These candidates may be the victims of ephemeris drift, which is caused by large uncertainties on the period and epoch values, or too much time passing between observations (see Section 5.4.5).
Online resources

Images in chapter headings

Each of the images on the chapter title pages are relevant to the work carried out during my postgraduate degree:

Chapter 1 - The Horsehead Nebula and Flame Nebula near the bright star Alnitak in Orion's Belt. This is digitised scan I had done of the original image which is on a photographic plate exposed at the University of St Andrews Observatory in 1984.

Chapter 2 - The Nordic Optical Telescope which I used during my first radial velocity observing run in January 2009.

Chapter 3 - The 1.93-m telescope at the OHP where I spent two observing runs in 2010 and 2012.

Chapter 4 - The 3.6-m ESO telescope at La Silla in Chile. It hosts HARPS spectrograph which was used to observe the spectroscopic transits analysed in this chapter.

Chapter 5 - The observatory on Pic du Midi where the Bernard Lyot Telescope is located. It houses the Narval spectrograph which was used to obtain the data for the targets in this chapter.

Chapter 6 - An image of the Great Orion Nebula (M42) taken by myself and my colleague Lee Kelvin using the 10'' telescope in the Napier Building at the University of St Andrews observatory.

Appendix A - A long exposure image of the James Gregory Telescope (and two smaller telescopes) at the University of St Andrews observatory, taken by Joe Llama (with my assistance).
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