The Frequency of Binary Companions Around KELT Planet Host Stars

DISSERTATION

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By

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Abstract

I conducted a search for binary companion stars around 10 stars hosting hot Jupiter exoplanets from the KELT survey and a large comparison sample of stars shown by KELT to not host transiting hot Jupiters. The goal of this study was to determine whether hot Jupiter hosts are more likely to have stellar companions than the general population of stars. The primary stars are bright ($7.5 < V < 11$) and of similar distance from Earth ($100 < d < 300$ pc). In this dissertation, I present the results of my observations using the Differential Speckle Survey Instrument (DSSI) on the 3.5-meter WIYN telescope and LMIRCam on the Large Binocular Telescope Interferometer (LBTI), on the 2x8.4-meter Large Binocular Telescope. Across both instruments, I observed 10 of the 16 KELT planet hosts which are visible from the Northern Hemisphere and 71 comparison stars, discovering seven new potential companions and re-observing four previously known possible binary systems, as well as one confirmed binary system. I estimate the distances and masses of each binary system, as well as place lower limits on their orbital periods. I also provide an estimate of the chance alignment probability for our observed candidate binaries. I find that the KELT planet hosts have a stellar companion fraction of $50 \pm 8.1\%$. 
compared to $36.8 \pm 6.3\%$ for the comparison sample. This is a $1.6\sigma$ excess, indicating that hot Jupiter hosts are slightly more likely to have stellar binary companions.
Dedication

To Mom.
Acknowledgments

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This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory, and made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

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List of Acronyms and Abbreviations

2MASS ..................... Two-Micron All-Sky Survey
ADI ........................ Angular Differential Imaging
CMD .......................... Color-Magnitude diagram
Dec ........................ Declination
DR1 ........................ Data Release 1
DSS .......................... Digitized Sky Survey
DSSI ......................... Differential Speckle Survey Instrument
FWHM ........................ Full Width at Half Maximum
KELT ........................ Kilodegree Extremely Little Telescope
LBT .......................... Large Binocular Telescope
LBTI ........................ Large Binocular Telescope Interferometer
mas .......................... milliarcseconds
Myr ........................ Million (Mega-) Years
NOMIC ...................... Nulling Optimized Mid-Infrared Camera
Pan-STARRS ................ Panoramic Survey Telescope and
                          Rapid Response System
PSF .......................... Point Spread Function
RA .......................... Right Ascension
RMS ........................ Root Mean Square
SIMBAD ..................... Set of Identifications, Measurements and Bibliography
                          for Astronomical Data
TYC ........................ Tycho-2 Catalog
WDS ........................ Washington Double Star Catalog
Chapter 1: Introduction

1.1. The Formation Mechanism of Hot Jupiters

Although the existence of planets outside the Solar System had long been taken for granted, the first exoplanet discovered around a Sun-like star in 1995 came as a shock to the astronomical community. It was expected that giant planets would be the first ones found using the Doppler radial velocity method, as they are more massive and have a larger gravitational influence on their host star, but it was entirely unexpected for a giant planet to be found in a 4-day, 0.05 AU semimajor axis orbit, as was the case with 51 Pegasi b (Mayor & Queloz 1995). 51 Pegasi b in fact became the prototype for a new class of planet, the “hot Jupiters.” In the years that followed, many more hot Jupiters were found via the radial velocity and transit methods. Although ultimately determined to be relatively rare (roughly 1% of Sun-like stars have a hot Jupiter; Wright et al. 2012) as surveys uncovered more and different types of exoplanets, hot Jupiters remain a subject of interest in the exoplanet community.

In particular, the formation mechanism of hot Jupiters is still a subject debate. It is currently thought that they cannot form in situ at very small semimajor axes, and thus must have migrated from the site of their formation to their present orbits (e.g., Lin et al. 1996). In this picture, their initial formation would occur through core accretion beyond the snow line (Pollack et al. 1996), like that of other giant planets, including those in our Solar System. Most of the debate about hot Jupiter formation focuses on the possible migration mechanisms, for which three main possibilities have emerged: interaction between the giant planet and the protoplanetary disk (Lin et al. 1996; Ward 1997), dynamical interactions with other giant planets in the system (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Chatterjee et al. 2008), or perturbations from stellar companions through, for example, the Kozai-Lidov
mechanism (Kozai 1962; Lidov 1962). In the Kozai-Lidov mechanism, the outer body in a hierarchical triple system is able to excite eccentricity and inclination oscillations in the inner binary (in this case, the primary star and giant planet), potentially driving it to eccentricities up to $e \sim 1$ (Holman et al. 1997; Ford et al. 2000; Fabrycky & Tremaine 2007; Naoz et al. 2011). For hot Jupiters, the primary host star would then act to tidally circularize the planet’s orbit at a much smaller semimajor axis. Because of the possibility for inclination oscillations as well, the Kozai-Lidov mechanism also offers an attractive explanation for the relatively large population of hot Jupiters which are orbitally misaligned with their parent star (Fabrycky & Tremaine 2007).

If the Kozai-Lidov mechanism is important for the formation of hot Jupiters, it admits a straightforward observational test: image the hot Jupiter host stars and search for the stellar binary companions. Indeed, the Friends of Hot Jupiters survey (Knutson et al. 2014; Ngo et al. 2015, 2016; Piskorz et al. 2015) used the Keck telescope to obtain high-resolution, high-contrast adaptive optics (AO) images and radial velocity spectroscopy of a large sample of hot Jupiter hosts, looking for stellar and planetary companions to hot Jupiters. They found that the binary stellar companion fraction with semimajor axes between 50-2000 AU for their sample was 2.9 times higher than the field companion fraction for FGK stars found by Raghavan et al. (2010), and that the probability for a hot Jupiter having a massive companion of some kind was very high (72% ± 16%).

1.2. A Search for Binary Companions

For this dissertation, I conducted a similar search for stellar companions to hot Jupiter hosts detected by the Kilodegree Extremely Little Telescope (KELT). The KELT survey is a wide-field photometric survey designed to detect extrasolar planets around bright stars using the transit method (Pepper et al. 2007, 2012). It consists of two telescopes, one at Winer Observatory in Arizona and one at the South African Astronomical Observatory. At the time of this writing, KELT has discovered 20 transiting planets, of which 15 have been published (Beatty et al. 2012; Siverd et al. 2012; Pepper et al. 2013, 2016; Collins et al. 2014; Bieryla et al. 2015; Fulton et al. 2016).

I used two different imaging techniques to conduct the survey: Speckle Interferometry and Adaptive Optics (AO) imaging. For ground-based observations, both techniques offer a large increase in resolution and sensitivity over traditional seeing-limited imaging by attempting to remove the effects of atmospheric turbulence, although they do so in very different ways.

### 1.2.1. Speckle Interferometry

Speckle interferometry (Labeyrie 1970) takes advantage of the convolution theorem by noting that any optical image is the convolution of the object with the point spread function (PSF) of the imaging optics and whatever else is between the object and the detector. In the case of ground-based astronomical imaging, this includes the atmosphere. In seeing-limited imaging, the exposure time is long compared to the timescale on which the turbulence in the atmosphere changes (a few tens of milliseconds), causing the jittering image of the star/object to smear out on the detector. In speckle interferometry, very short exposures are used to effectively measure the “instantaneous” PSF of the atmosphere+telescope system on the turbulence timescale. The power spectra of these images may then be compared to that of an image of a reference point source, typically a nearby star which is known to be single (Horch et al. 2004; Howell et al. 2011). Section 2.1.2 describes this process in more detail. In general, speckle interferometry produces relatively constant contrast of 3-4 magnitudes to very small angular separations.

For the speckle interferometry portion of this survey, I used the Differential Speckle Survey Instrument (DSSI; Horch et al. 2009) on the WIYN 3.5-meter telescope at Kitt Peak National Observatory. A schematic of the instrument from Horch et al. (2009) is shown in Figure 1.1. Light enters the instrument and is collimated before being split into two bands with a dichroic beam splitter and sent to the two separate CCD detectors and filters. The tip-tilt mirrors are only used to position the star correctly on the detectors, not to perform fast tip-tilt image motion.
compensation as they would be in an AO system. Two interchangeable filters are used to set the imaging bands. All of the filters used with DSSI are narrowband filters (width $\sim 500$ Å), as the PSF of the atmosphere+telescope depends strongly on wavelength, and using broader bandpasses would smear out the speckle images, degrading spatial resolution and contrast.

1.2.2. Adaptive Optics Imaging

AO systems, in contrast, attempt to measure and correct for atmospheric turbulence directly, enabling even very large ground-based telescopes to perform at the diffraction limit. They do so through the use of deformable mirrors which act to approximately cancel out the wavefront aberrations imposed by the atmosphere, and, to a lesser extent, the quasistatic aberrations due to the telescope optics themselves. Typically, AO systems split off some of the light from the main science beam and divert it to a wavefront sensor. The wavefront sensor measures the shape of the incoming, aberrated wavefront up to several thousand times per second, and uses this shape information to configure the shape of a deformable mirror so as to cancel out the wavefront distortions. The system is then typically run in a closed loop, with each previous wavefront correction being used to help compute the next set of changes to the deformable mirror’s shape. Figure 1.2 shows a schematic of a typical AO system. Like speckle cameras, adaptive optics systems must also use a bright reference source to measure atmospheric aberrations. Because my survey targets were all bright stars, I was able to use my science targets as reference stars for the AO system. This “self-correction” is advantageous as AO wavefront correction using a single source degrades with radius from the reference star. Since we are searching for faint companions, having the maximum correction on the science target increases the contrast and sensitivity of the observations. In general, AO observations are capable of generating very high contrasts of up to 7-8 magnitudes at angular separations of $\sim 0\farcs5$, but this degrades rapidly at smaller angular separations or with poor seeing.

I conducted the AO imaging portion of my survey with the LMIRCam instrument (Skrutskie et al. 2010) on the Large Binocular Telescope Interferometer (LBTI; Hinz et al. 2008, 2016). The core LBTI infrastructure consists of a beam
combiner, the interferometer, and two detectors, LMIRCam and NOMIC. See Figure 1.3 for a schematic of the instrument. Visible light from the two telescopes is diverted to the wavefront sensors for the AO system, while infrared light is allowed to enter the instrument. The beam combiner can be set to either combine the light for interferometric studies or leave it as two separate images from each telescope, which is helpful for discriminating between speckles and faint objects. My observations used this latter (uncombined) mode. Once the light reaches the Nulling and Imaging Camera, the near-infrared light can be split off to LMIRCam, which is optimized for 3-5 µm usage, while the mid-infrared light is sent to NOMIC, which is optimized for 8-13 µm light. Either detector can be used for imaging, spectroscopy, or interferometry. I chose LMIRCam as the shorter wavelength offers increased resolution, and I was searching for faint companion stars, not attempting to directly image colder planets.

1.3. Scope of the Dissertation

The outline of this dissertation is as follows: In Chapter 2, I present the results of DSSI imaging of nine of the 14 Northern Hemisphere KELT exoplanet host stars and a comparison sample of 51 stars shown by KELT to not host a transiting hot Jupiter. In Chapter 3, I present the results of LBTI/LMIRCam imaging of 10 of the 14 Northern Hemipshere KELT exoplanet host stars, H- & K-band photometry and astrometry of the three binaries (re)discovered in the DSSI data, as well as LBTI/LMIRCam K-band imaging of 23 stars shown by KELT to not host a transiting hot Jupiter. In Chapter 4 I give a brief discussion of the results and a conclusion.
Fig. 1.1.— Schematic view of DSSI, taken from Horch et al. (2009). Light enters the instrument at top, reflects off the tip-tilt mirrors, and is then split and sent to the two science cameras. DSSI is thus able to image in two bands at once, halving observing time for multi-band surveys.
Fig. 1.2.— Schematic of a typical adaptive optics system. Incoming starlight is distorted by atmospheric turbulence and gathered by the telescope. It is then sent to a deformable mirror, where it is corrected and then split. Most of the light goes on to the science camera, but some is sent to the wavefront sensor. The wavefront sensor measures the wavefront, and a computer calculates the correction needed to cancel the remaining aberrations. This is done up several thousand times per second to match the frequency at which the atmosphere changes. Image credit Claire Max, Director, UC Observatories.
Fig. 1.3.— Schematic of LBTI, taken from Hinz et al. (2016). Visible light from the two telescopes is sent to the wavefront sensors, while infrared light is combined and sent to the interferometer and science imagers. Of the two science imagers, LMIRCam is optimized for 3-5 \( \mu \text{m} \), while NOMIC is optimized for 8-13 \( \mu \text{m} \).
Chapter 2: DSSI Speckle Interferometry

2.1. Observations and Methods

2.1.1. Sample Selection

We observed 60 stars in support of a survey to determine the binary companion fraction of hot Jupiter hosts: Nine hosts of hot Jupiters detected by KELT, and 51 field stars rejected as hot Jupiter hosts by KELT, as a comparison sample. As hot Jupiters are relatively rare (~1% of Solar-type stars have a hot Jupiter; Wright et al. 2012), the 51 field stars are close to a true statistical control sample. We selected them based on several properties: their proximity in the sky to each KELT target, their magnitude range ($7.5 < V < 12$), distance from Earth ($100 < d < 300$ pc), and spectral type. We chose these properties to ensure that the demographics of the comparison stars were as similar as possible to the hot Jupiter hosts. We thus rejected all giants and eclipsing binaries when creating the comparison sample to provide the cleanest possible comparison between the two populations, isolating the presence of a hot Jupiter as the primary variable.

2.1.2. Observations

We observed all 60 targets over ten nights of queue observations (two nights total observing time) using DSSI on the WIYN 3.5-meter telescope with the 692 nm and 883 nm filters (see Horch et al. 2009 for the detailed filter properties). DSSI is a speckle imaging camera which takes images in two bands simultaneously. Images are taken as sets of 1000 40-ms speckle frames and then later combined using the method detailed in Horch et al. (2004) and Howell et al. (2011). Briefly, the average spatial frequency power spectrum is computed for each observation. The speckle transfer function is then deconvolved by dividing this average power spectrum by
the spectrum of a reference point source, and then a weighted least-squares fit of the fringe pattern is performed. The position angle, separation, and relative magnitude measurements come from this fit. Additionally, each of the final images presented in this paper consists of multiple frame sets stacked into one reconstructed image using bispectral analysis.

The uncertainties on the position angle and separation measurements follow the estimates of Horch et al. (2011), which found that for DSSI, the uncertainty on the derived separation is \( \sim 1.5 \) mas regardless of filter, while the uncertainty on the position angle is \( \sim 0.12 \) degrees at 1" separation, and is inversely proportional to the separation. The uncertainties on the relative magnitudes are estimated using the parameterized curves derived in Horch et al. (2004).

### 2.2. Results

Table 2.1 shows the results of our observations for all 60 stars. In total, we found two (TYC 2420-0124-1 and TYC 2996-0671-1) new candidate binary companions to stars in our comparison sample; two more (TYC 3157-1143-1 and 2393-1280-1) were previously listed in the Washington and Tycho Double Star Catalogs (though apparently unconfirmed as true binaries), while a fifth (TYC 2785-0116-1) turned out to already have a Grade 3 orbit in the 6th Orbital Catalog maintained at the U.S. Naval Observatory. We detected only one of the known companions to the KELT hot Jupiter hosts (KELT-4B); the rest were either too faint or outside of DSSI’s field of view. We measured the angular separation and position angle for each binary, as well as their relative brightnesses in each filter. Table 2.2 summarises this information, while Figures 2.1 to Figure 2.4 show the reconstructed images and 5\( \sigma \) contrast curves for each candidate binary system. The relative magnitudes for the two widest separation binaries (TYC 2785-0116-1 and KELT-4) are not shown, as the companions are near the edge of the detector, and the photometry is therefore unreliable (see Horch et al. 2017 for more details). We omit the previously known binary TYC 2785-0116-1 from our analysis, although we present our observations of it. Since our study’s objective was to compare the KELT planet hosts to similar stars, and the planet hosts are all significantly hotter or more evolved than the two
K dwarfs which make up the system, it should have been rejected during target selection.

The contrast curves are generated following the method detailed in Horch et al. (2011). In each reconstructed image, the magnitude difference between every local maximum and the central peak is calculated, and these relative magnitudes are then taken as a function of separation and placed in bins of width 0.1′′. The 5σ detection limit is then the mean peak value of the bin minus five times the standard deviation of these peak values.

2.2.1. Chance Alignment Probability

For TYC 3157-1143-1 and TYC 2393-1280-1, we have archival observations from the Washington and Tycho Double Star Catalogs showing them as doubles. This allows us to examine the motion of the stars in each system relative to each other to determine whether or not they are bound. If the candidate companions are distant background objects instead of bound to the primary, then we would expect the stars to have moved toward or away from each other by $\Delta \alpha \sim \mu \Delta t$, where $\mu$ is the proper motion of the primary and $\Delta t$ is the time since the first observation.

The observations for TYC 2392-1280-1 indicate that, ignoring uncertainties on the data, the two components have changed position by approximately 53 mas relative to each other since 1904, much less than the primary’s proper motion of $610 \pm 222$ mas over that time based on data from SIMBAD. In the case of TYC 3157-1143-1, there are two archival observations from 1991 and 2008. The epoch from 2008 agrees with our astrometry to within the errors, which are also smaller than the expected proper motion over that time of $21.7 \pm 10.5$ mas. The epoch from 1991 shows a large difference in position angle and separation (153.1° and 0.33′′, respectively), but given that this discovery observation was made by Tycho and the separation here is relatively small for that satellite, it is possible, perhaps even likely, that these data suffer from larger uncertainties. Therefore, we find that both systems are very likely bound.
As we do not presently have multi-epoch observations of TYC 2420-0124-1 and TYC 2996-0671-1, we are only able to approximately estimate the probability that the two stars detected in each image are aligned by chance. We also wanted to provide a check on our determination above that TYC 3157-1143-1 and TYC 2392-1280-1 are bound. To estimate the chance alignment probability, we first looked at the relative colors for each of the candidate binaries as compared to the magnitude difference. If a candidate companion is only marginally fainter than the primary, yet is still much redder than it is, this would indicate that the candidate companion is actually more likely to be a background giant than a companion star. The primaries for each of our three candidate binary systems have $B - V$ colors consistent with being A or early F stars, using the main-sequence reference tables from Pecaut & Mamajek (2013). We would thus expect an M dwarf companion, for example, to be at least 5 magnitudes fainter than its primary in $R$ band.

As we have insufficient information on the properties of the primary stars to perform a constraining isochrone fit, we are left with examining our relative photometry to provide weak constraints on the properties of the companion stars. Within the range of $B - V$ colors for our primary stars, and the likely colors of our companions, the DSSI 692 nm filter gives approximately the same results as Johnson/Cousins $R$, while the other filters also provide fairly similar measurements as long as $B - V < 1$ (Horch et al. 2009). Thus, our 692 and 883 nm measurements provide an equivalent to a relative $R - I$ measurement for each potential binary system. We calculated the expected $R - I$ for the companion star based on an estimate of this property for the primary from the reference tables of Pecaut & Mamajek (2013). We then converted this to a spectral type and expected absolute magnitude, then compared to the primary. Within our limits, each candidate binary is consistent with being bound.

Next, we determined the fractional area of sky in the vicinity of each observed star covered by circles with the same radius as their measured separations surrounding all sources at least as bright as the candidate fainter binary companion, similarly to Oberst et al. (2017). We use the Pan-STARRS 3π survey (Chambers et al. 2016) as the database for our sources, looking in a circular 1 deg$^2$ area around
each candidate. For our magnitude cutoff, we assume that the DSSI 692 and 883 nm filters approximate the Sloan $r$ and $i$ bands used in the Pan-STARRS survey, adding an additional safety factor of one magnitude (i.e., for a measured $\Delta m_{692}$ of 2 magnitudes, we look for all sources that are brighter than 3 magnitudes fainter than the primary). We reject all sources which do not have either $r$ or $i$ photometry in the database in order to avoid infrared-only sources. We also reject sources which do not have an RA/Dec solution, but do not impose any further conditions. The results of our analysis are given in Table 2.3. We find that all three candidates are likely bound by this measure at at least the 4$\sigma$ confidence level.

### 2.2.2. Orbital Parameter Estimates

Even though our knowledge of the properties of the primary stars for our candidate binary systems is insufficient to provide strong constraints, we can still compute a rough estimate of the possible orbital parameters for the candidate binaries. Table 2.4 contains the apparent $V$ magnitudes for each system from SIMBAD as well as our estimates for the absolute magnitude, distance, projected separation, component masses, and minimum orbital periods for each candidate binary.

Our stars do not have either Hipparcos or Gaia parallaxes, except for TYC 2996-0671-1. They are slightly too far away from Earth or slightly too dim to be in Hipparcos, and are all likely seen as blends/binaries in Gaia, so they are not in Gaia DR1. In order to get distance and mass estimates for the stars, we note that although our stars are not in the Hipparcos catalog, they are almost bright and close enough to Earth to be in it. This means that we can use the Hipparcos CMD to get a rough estimate of our stars’ absolute $V$ magnitudes given their $B - V$ colors. We then use this $M_V$ estimate and combine it with archival $V$-band photometry from SIMBAD to get an estimate of the distance, assuming negligible extinction. From this and our measured separations, we get an estimate of the projected separation $a$. For TYC 2996-0671-1, which does have a Gaia parallax of $3.63 \pm 0.91 \pm 0.3$ mas (Gaia Collaboration et al. 2016a, 2016b), we determine $M_V$ via the standard way using archival $V$-band photometry from SIMBAD.
To estimate the orbital period, we also need masses for each component. We use the Dartmouth isochrones (Dotter et al. 2008) to estimate the mass of the primary component. We use an age of 800 Myr for our stars to avoid interpolation problems with the younger datasets. Using an older age runs into the main-sequence turnoff for TYC 2393-1280-1. The age otherwise does not have a large enough effect on the stellar luminosities to change our results. We assume solar metallicity for all of our stars. In order to estimate the mass of the candidate binary companions, we first estimate the absolute $R$ magnitudes of each component. To do this, we combine the $V - R$ colors from Pecaut & Mamajek (2013) with the absolute $V$ magnitudes we estimated above to get an estimate of $M_R$ for the primary. Because our differential 692 nm measurement from DSSI is essentially $\Delta m_R$ for stars in our range of $B - V$ (Horch et al. 2009), we can then take that measurement and our estimate of $M_R$ for the primaries and get an estimate of $M_R$ for the candidate companions. We then translate this back into a mass, and combine these mass estimates with our estimate of the projected separation to get an estimate for the minimum orbital period assuming a circular orbit. As above, Table 2.4 contains our estimates of the stellar properties derived in this section.
Fig. 2.1.— Reconstructed 692 filter images of the four candidate binaries, shown using a logarithmic intensity scale. The upper left panel shows TYC 3157-1143-1, the upper right panel shows TYC 2393-1280-1, the lower left panel shows TYC 2420-0124-1, while the lower right panel shows TYC 2996-0671-1. North is at top, while East is to the left. The fainter double images seen in each image are artifacts of the image reconstruction process.
Fig. 2.2.— Reconstructed 883 filter images of the four candidate binaries. Otherwise identical to the images in Figure 2.1.
Fig. 2.3.— Estimated 5σ contrast curves for the 692 filter images. The solid line is the 5σ contrast curve, obtained by fitting a spline fit to the mean of the minima and maxima in 0′′1 bins, with the limit being this mean spline minus 5 times the RMS, taken starting at 0′′2 separation. Each square represents a local maximum used in computing the overall contrast limit, while the dots represent a local minimum. The quoted limiting magnitude is given at 0′′2 separation.
Fig. 2.4.— Estimated 5σ contrast curves for the 883 filter images. These were generated in the same way as the curves in Figure 2.3.
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Table 2.2. Candidate Binary System Parameters

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Table 2.3. Chance Alignment Probability Results
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<th>(a) (AU)</th>
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Table 2.4. Orbital Parameter Analysis Results
Chapter 3: LBTI/LMIRCam Adaptive Optics Imaging

3.1. Observations and Methods

3.1.1. Sample Selection

I observed a total of 31 targets to complete the survey to estimate the binary companion fraction of hot Jupiter hosts: 10 KELT hot Jupiter hosts, two of the binaries from the DSSI survey with hot primaries, and 19 new comparison stars. The comparison stars were selected in an identical manner to the DSSI sample, as described in Chapter 2.

3.1.2. Observations

I observed 31 targets over 19 nights of queue-scheduled observations (six nights total observing time) using LMIRCam (Skrutskie et al. 2010). LMIRCam is an infrared imaging camera mounted on the Large Binocular Telescope Interferometer (LBTI; Hinz et al. 2008), which is itself part of the instrument suite for the twin 8.4-meter Large Binocular Telescope. LBTI is an adaptive optics (AO) fed instrument, so we were able to achieve very high resolution and contrast around each of our target stars. I used LMIRCam for $H$- and $K$-band imaging of the previously known binaries, and $K$-band imaging alone where no binary companion had been previously detected by me or the KELT survey. LMIRCam supports up to 20x20″ field of view, but often only a particular subarray is read out to reduce overheads. My exposures typically used either a 10x20″ field or the full array. I observed each target for a total clock time of one hour, resulting in an aggregate exposure time of about 30 minutes. Each observation used a standard up/down or left/right nodding pattern.
to allow for sky subtraction. A typical nod moved the target by 5-10″. The duration of individual exposures varied; most exposures were under one second to avoid saturation, although they lengthened to as long as 30 seconds in poor conditions or when I was explicitly acquiring saturated data. Purposely saturating some exposures increases the efficiency of observations due to mitigating read out overhead and allows the detection of fainter companions outside the saturated core than stacks of purely unsaturated data. In the event that a companion is found, follow-up unsaturated data is still required to perform photometry.

3.1.3. Methods

To reduce the data, I first generated a bad pixel mask from a long-exposure dark frame and flat field. “Bad” pixels were defined to be those that were at least 1σ above the mean pixel value in the dark frame or 0.5σ below the median pixel value in the flat field. For the bad pixels in the flat field, I excluded a large portion of the detector as the flat field was heavily vignetted towards the edges of the frame, and not all of the detector was illuminated. To mask out the bad pixels in the data, I set the value of each bad pixel to the average of their eight nearest neighbors.

Once the bad pixels had been masked off, I subtracted the median sky background from each image. I created the median sky frame in two passes. The first pass computes the median of all the images of a given star and subtracts the result from each raw image. This removes most of the detector structure, but also removes some starlight. I then determined the positions of each star in each subtracted frame, and masked a 100-pixel radius region around each star to prevent it from contaminating the sky background and partially self-subtracting starlight. I then recalculated the sky frame with the mask, using the result as the final sky frame. This final sky frame was then subtracted from all images.

I then derotated and stacked the images to produce a final image. For the dual-aperture data, I did this separately for each side in most cases (I was able to ignore the separate nature of the fields when the total field rotation was very small).
Once the final images had been constructed, I generated contrast curves and performed relative aperture photometry on those stars which had potential companions. I took the mean of the data in 50-mas-wide annuli around the brightest star in each image, then added five times the estimated noise, resulting in a 5σ contrast curve. I estimated the noise as a combination of Poisson noise from the star, readout noise from the detector, and the RMS dispersion of the underlying subtracted sky background, taken in a window elsewhere in the final constructed image far away from any stars. As I had only or mostly saturated data for some of the stars, the calculated contrast curves for these will underestimate the achieved contrast. These have been noted in the tables and figures.

3.2. Results

Table 3.1 summarises the results of our observations for all 31 stars. In total, I found seven new candidate binaries. Two more binaries were already listed in the WDS catalog. I also successfully recovered all of the known companions to the KELT objects we observed, as well as the two DSSI binaries I re-observed with LBT. I measured the angular separation and position angle for each binary, as well as their relative brightnesses in each filter. Table 3.2 summarises the astrometric and photometric properties of the binaries, while Figures 3.1 to Figure 3.16 show the final co-added images and 5σ contrast curves for each candidate binary system.

I used aperture photometry to obtain the relative magnitudes for each system, as PSF-fitting photometry is difficult due to the non-Gaussian nature of diffraction-limited PSFs. In an AO-corrected image, the PSF varies with time and over the field of view with the level of correction obtained. In general, the correction worsens with increased radial separation from the guide star (in this case, the primary star for each system), causing the PSF to widen. To determine the full width at half maximum (FWHM) of each star image, I used the radial profiling functionality provided by Aperture Photometry Tool (v2.6.9; Laher et al. 2012), which fits a combination of a Gaussian and fourth-order polynomial model to the PSF to determine its shape. For most images, this produced reasonable estimates for the FWHM of each star. I then set the aperture radius to the FWHM of the star.
image. Although the typical practice in aperture photometry in uncrowded fields is to use aperture radii of 3-5 times the FWHM, in my images the stellar PSFs often extended out to very large radii and contributed to the background level for the companion stars, especially on nights of poor seeing. I therefore decided that using a smaller aperture would give more consistent results.

The other issue with the photometry is estimation of the background. In principle, the sky subtraction step should remove all of the background from the image, but this is not perfect in practice. Additionally, the derotation and co-adding process introduces fixed-pattern noise into the final image. In the final shifted+added image, I looked for a position on the image with similar background levels to what was under each star, and then subtracted that background level from the initial aperture photometry measurement. For the widely separated binaries, I placed the window far away from both stars and then used it for each star. In the case of close binaries, where the secondary overlapped with the primary star’s PSF, I used the sky-only window for the primary star and a window on the opposite side of the primary’s PSF for the secondary.

The uncertainties on the photometry presented in Table 3.2 only reflect the random error from the photon statistics - that is, the shot noise from the stars, the RMS variation of the subtracted background, and the read noise in each image. They do not take into account the uncertainties inherent in the FWHM estimation or placement of the background estimation window, which I was unable to quantify robustly. As such, there are modest unaccounted-for systematic uncertainties which increase the uncertainty on the photometry. Despite this, the photometry appears fairly reliable. The one apparent outlier, the companion to TYC 2534-0255-1, has an unusually blue $H - K$ color. However, earlier observations by Wallerstein & Spinrad (1960) show that it is, in fact, an O star. Assuming it is bound (which, as discussed below, is very likely), it would be a subdwarf.
3.2.1. Chance Alignment Probabilities

As with our DSSI survey (Chapter 2), several of the binaries I observed had previous observations from the Washington and/or Tycho Double Star Catalogs, or from previous AO imaging taken as part of the KELT survey. These systems are KELT-1, 2, 3, 4, and 16, as well as TYC 2109-0205-1, TYC 2534-0255-1, and TYC 3157-1143-1 (which we also observed with DSSI; see Chapter 2 for those results). For these systems, I looked at their proper motions over time to see if they might be unbound, just as with the DSSI observations. All of them except for TYC 2109-0205-1 were highly consistent with being bound. In the case of TYC 2109-0205-1, I believe the initial data from the Tycho Double Star Catalog were a spurious detection, as the two components are listed as having nearly equal brightnesses. No such second bright star is seen anywhere in the field of my observation, and examination of archival 2MASS and DSS images of the region indicated that there are no bright high proper-motion stars that might be the second star listed in the Tycho catalog. The faint source that is seen the field near TYC 2109-0205-1 is also likely unbound, as discussed below.

For some of the candidate companions, we obtained both $H$ and $K$-band relative photometry, allowing me to use the relative spectral type to determine whether each pair is likely bound or not. I derived an $H - K$ color for each secondary star based on archival $H$ and $K$-band photometry of the primaries from SIMBAD and the relative $H$ and $K$ magnitudes I found using aperture photometry. I then compared these derived colors to the reference tables of Pecaut & Mamajek (2013) to get an approximate spectral type. The results of this analysis are presented in Table 3.3. Given the size of the uncertainties on the $H - K$ colors compared to the relatively small differences between spectral types in $H - K$, the spectral types of the candidate companions are broadly consistent with the them being bound.

For the rest of the candidate binaries, I do not have multi-epoch observations or multi-band photometry. Therefore, I used the same method presented in Chapter 2 to estimate the probability that the two stars are aligned. As in that Chapter, I also performed this analysis on the other stars as a check. As I had relative $K$-band photometry for every observed star, I used archival 2MASS data (Skrutskie et al.
2006) instead of Pan-STARRS. I only rejected sources which do not have an RA/Dec solution in 2MASS. The results of this analysis are presented in Table 3.4. I find that all but two of the candidate binaries are bound at at least the 3σ level by this measure. The chance alignment probability for TYC 3157-1380-1 and TYC 2109-0205-1 is at least 5%, so they cannot be said to be bound through this method, and I do not count them in the final companion statistics.

3.2.2. Orbital Parameter Estimates

To estimate orbital parameters for the candidate binaries, I used the same method as applied to those in the DSSI dataset (see Section 2.2.2). For stars where I was able to calculate an $H - K$ color, I interpolated on the Pecaut & Mamajek (2013) reference tables to get an approximate spectral type and mass. For those stars lacking a Gaia or Hipparcos parallax, I also took an approximate $M_K$ from the Pecaut & Mamajek (2013) table to use as a distance estimator. For those systems without $H$-band photometry, but which are still likely bound according to the analysis in the previous section, I simply assumed that the system was bound and estimated the mass based on the relative $K$-band magnitude of the two stars. Otherwise, the procedure is the same as that presented in Chapter 2. Table 3.5 contains my estimates for the stellar properties described in this section.

3.2.3. Companion Fraction

For all of the KELT planet hosts that have AO observations, eight of the 16 have companions, giving a companion fraction of $50 \pm 8.1\%$. For our LBTI observations of the 20-star comparison sample, the companion fraction is $36.8 \pm 6.3\%$ (seven out of 19). Assuming that my survey would have detected any stellar companion present, the KELT planet hosts have a $1.6\sigma$ companion excess compared to field A and F stars. These results also indicate that A and F stars have a binary fraction consistent with the value found by Raghavan et al. (2010) for FGK stars in the Solar neighborhood ($33 \pm 2\%$). This is also consistent with the results from the DSSI study (Chapter 2), where I found a companion fraction of $8.0\%^{+3.0\%}_{-2.4\%}$ for the comparison
sample, compared to the Horch et al. (2014) expected rate of $7.8 \pm 0.4\%$ using DSSI on WIYN. This indicates that hot Jupiters have at least a slight preference for binary systems at the roughly $2\sigma$ level.

The Friends of Hot Jupiters project (Ngo et al. 2016) found a similar, though stronger result that hot Jupiter hosts are 2.9 times more likely to host a stellar companion with a separation between 50-2000 AU than the general population of stars; $47 \pm 7\%$ of their hot Jupiter systems had stellar companions in this range. This result is consistent with the multiplicity of the KELT planet hosts reported here. Combined with my result, this indicates that a dynamical formation mechanism for most hot Jupiters is likely, especially given that they found that the probability that a hot Jupiter had a massive companion of some kind, whether giant planet, brown dwarf, or binary star, was $72 \pm 16\%$ (Ngo et al. 2015). However, given the large projected separations estimated in Table 3.6, it is unlikely that the Kozai-Lidov mechanism played a dominant role in the formation of the KELT hot Jupiters (see Ngo et al. 2016).

The major limitations of my estimate are the relatively small sample size for the AO observations and the low contrast at very small separations, which made it difficult to detect faint companions with separations of only a few tens of AU. I had originally intended to use angular differential imaging (ADI) to suppress the stellar PSF, but was unable to implement it for most of my observations as ADI places tight constraints on scheduling. ADI requires at least $\sim 30^\circ$ of field rotation to adequately suppress the stellar PSF, but that amount of field rotation only happens when the target is within about one hour of the meridian, and the amount of rotation decreases with zenith distance. Performing the full survey on such tight scheduling constraints is impractical. Observing more hot Jupiter hosts and more comparison stars would improve the uncertainties on my multiplicity estimates, but given that a similar study with a much larger sample size found a similar result, markedly increasing the size of this study would be unlikely to change the outcome.
Fig. 3.1.— $H$-band images of all binaries observed with LMIRCam, shown with a logarithmic intensity scale. Starting from the top left, read left to right, the systems are KELT-2, TYC 2420-0124-1, KELT-3, and TYC 2508-0285-1. The faint squares visible in some images are artifacts from the sky subtraction process. Outside the squares, the wide tails of the stellar PSF partially self-subtract due to the sky background being estimated by median combination of the science frames. Various other image artifacts can also be seen on the images, and are either remnants of the data reduction process/detector structure (bad pixels, etc.), or PSF artifacts caused by the telescope optics.
Fig. 3.2.— $H$-band images of all binaries observed with LMIRCam (2 of 2). Starting from the top left, read left to right: KELT-4, TYC 2534-0255-1, TYC 3157-1143-1, KELT-16.
Fig. 3.3.— $K$-band images of all binaries observed with LMIRCam (1 of 3). Starting from the top left, read left to right: KELT-2, TYC 2420-0124-1, KELT-3, TYC 2420-0394-1, TYC 2508-0285-1, KELT-1. For additional notes on the images, see the caption to Figure 3.1.
Fig. 3.4.— $K$-band images of all binaries observed with LMIRCam (2 of 3). Starting from the top left, read left to right: KELT-4, TYC 1994-1098-1, TYC 2996-0462-1, TYC 2109-0205-1, TYC 2532-0546-1, TYC 2534-0255-1.
Fig. 3.5.— $K$-band images of all binaries observed with LMIRCam (3 of 3). Starting from the top left, read left to right: TYC 3157-1143-1, KELT-16, TYC 3157-1380-1, TYC 1993-1660-1.
Fig. 3.6.— $H$-band 5$\sigma$ contrast curves for all the stars observed with LMIRCam (1 of 2). The contrast curves were generated by taking an azimuthal average of the data in 50 mas-wide rings around the primary star, and then adding five times the noise in that ring, consisting of the shot noise from the star, readout noise from the detector, and the RMS variation of the remaining background. Bumps and other structures are due to structure in the PSF, close binary companions, or image artifacts. Curves labeled “saturated” are underestimates of the true contrast achieved, as they were taken entirely with saturated data, which compresses the dynamic range between the saturated core and unsaturated wings of the PSF.
Fig. 3.7.— $H$-band 5σ contrast curves for all the stars observed with LMIRCam (2 of 2). The large dip in the curve for KELT-16 is due to processing artifacts at the boundary of the mask placed over KELT-16 during the sky subtraction step. It ultimately did not affect the photometry for the primary or companion.
Fig. 3.8.— $K$-band $5\sigma$ contrast curves for all the stars observed with LMIRCam (1 of 9). Otherwise identical to the $H$-band curves.
Fig. 3.9.— $K$-band $5\sigma$ contrast curves for all the stars observed with LMIRCam (2 of 9).
Fig. 3.10.— $K$-band $5\sigma$ contrast curves for all the stars observed with LMIRCam (3 of 9).
Fig. 3.11.— $K$-band 5σ contrast curves for all the stars observed with LMIRCam (4 of 9).
Fig. 3.12.— $K$-band 5σ contrast curves for all the stars observed with LMIRCam (5 of 9).
Fig. 3.13.— $K$-band 5σ contrast curves for all the stars observed with LMIRCam (6 of 9).
Fig. 3.14.— $K$-band 5σ contrast curves for all the stars observed with LMIRCam (7 of 9).
Fig. 3.15.— $K$-band $5\sigma$ contrast curves for all the stars observed with LMIRCam (8 of 9).

Fig. 3.16.— $K$-band $5\sigma$ contrast curves for all the stars observed with LMIRCam (9 of 9).
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<td>N</td>
<td>N</td>
<td>-</td>
<td>6.5</td>
</tr>
<tr>
<td>TYC 2532-0546-1</td>
<td>13:03:50.7</td>
<td>+30:45:22.9</td>
<td>Y</td>
<td>N</td>
<td>-</td>
<td>7.5</td>
</tr>
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<td>TYC 2534-0255-1</td>
<td>13:00:25.7</td>
<td>+35:45:20.4</td>
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<td>Y</td>
<td>4.5</td>
<td>6\textsuperscript{b}</td>
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<td>TYC 2996-0184-1</td>
<td>09:54:32.0</td>
<td>+40:32:17.3</td>
<td>N</td>
<td>N</td>
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<td>7</td>
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Table 3.1. LBTI/LMIRCam Observations of All Stars
Table 3.1—Continued

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>Dec</th>
<th>Source?</th>
<th>Known?</th>
<th>∆m_H</th>
<th>∆m_K</th>
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<tbody>
<tr>
<td>TYC 2996-0679-1</td>
<td>09:55:02.9</td>
<td>+40:12:40.8</td>
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<td>TYC 3157-1143-1</td>
<td>20:32:44.0</td>
<td>+40:08:24.8</td>
<td>Y</td>
<td>Y</td>
<td>6.5</td>
<td>7</td>
</tr>
<tr>
<td>KELT-8</td>
<td>18:53:13.3</td>
<td>+24:07:38.6</td>
<td>N</td>
<td>N</td>
<td>6</td>
<td>6.5</td>
</tr>
<tr>
<td>KELT-16</td>
<td>20:57:04.4</td>
<td>+31:39:39.6</td>
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<td>Y</td>
<td>6</td>
<td>6.5</td>
</tr>
<tr>
<td>TYC 3157-1225-1</td>
<td>20:31:24.5</td>
<td>+40:04:03.4</td>
<td>N</td>
<td>N</td>
<td>-</td>
<td>4.5</td>
</tr>
<tr>
<td>TYC 3157-1380-1</td>
<td>20:31:11.5</td>
<td>+39:58:58.7</td>
<td>Y</td>
<td>N</td>
<td>-</td>
<td>4.5</td>
</tr>
<tr>
<td>TYC 1453-0891-1</td>
<td>13:09:04.9</td>
<td>+19:35:52.4</td>
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<td>N</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>TYC 1993-1660-1</td>
<td>13:06:16.1</td>
<td>+25:47:47.5</td>
<td>Y</td>
<td>N</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>TYC 1993-1998-1</td>
<td>13:06:52.1</td>
<td>+24:46:06.8</td>
<td>N</td>
<td>N</td>
<td>-</td>
<td>6.5^a</td>
</tr>
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</table>

Notes: Under “Source Found?” and “Previously Known Companion?”, Y = yes, N = no. Under ∆m_{692} and ∆m_{883}, the number quoted is the maximum achieved contrast at 0″5, even in cases where a candidate companion was detected.

^aSome data for this star was saturated.

^bAll data for this star was saturated.
<table>
<thead>
<tr>
<th>Name</th>
<th>$\Delta m_H$</th>
<th>$\Delta m_K$</th>
<th>$\Delta (H - K)$</th>
<th>$\rho''$</th>
<th>$\theta^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KELT-2</td>
<td>2.4607 ± 0.0006</td>
<td>2.3033 ± 0.0008</td>
<td>0.1574 ± 0.0010</td>
<td>2.39</td>
<td>335.25</td>
</tr>
<tr>
<td>TYC 2420-0124-1</td>
<td>2.0006 ± 0.0009</td>
<td>1.8455 ± 0.0012</td>
<td>0.1551 ± 0.0015</td>
<td>0.63</td>
<td>268.04</td>
</tr>
<tr>
<td>KELT-3</td>
<td>2.6461 ± 0.0017</td>
<td>2.6355 ± 0.0028</td>
<td>0.0105 ± 0.0033</td>
<td>3.74</td>
<td>43.65</td>
</tr>
<tr>
<td>TYC 2420-0394-1</td>
<td>-</td>
<td>0.0382 ± 0.0010</td>
<td>-</td>
<td>0.13</td>
<td>13.76</td>
</tr>
<tr>
<td>TYC 2508-0285-1</td>
<td>2.5072 ± 0.0013</td>
<td>2.3648 ± 0.0015</td>
<td>0.1424 ± 0.0020</td>
<td>6.08</td>
<td>111.52</td>
</tr>
<tr>
<td>KELT-1</td>
<td>-</td>
<td>5.700 ± 0.016</td>
<td>-</td>
<td>0.59</td>
<td>160.32</td>
</tr>
<tr>
<td>KELT-4</td>
<td>1.1968 ± 0.0016</td>
<td>1.1615 ± 0.0020</td>
<td>0.0354 ± 0.0026</td>
<td>1.62</td>
<td>30.78</td>
</tr>
<tr>
<td>TYC 1994-1098-1</td>
<td>-</td>
<td>3.3634 ± 0.0019</td>
<td>-</td>
<td>0.35</td>
<td>112.52</td>
</tr>
<tr>
<td>TYC 2996-0462-1</td>
<td>-</td>
<td>2.7578 ± 0.0038</td>
<td>-</td>
<td>0.71</td>
<td>345.28</td>
</tr>
<tr>
<td>TYC 2109-0205-1</td>
<td>-</td>
<td>6.8572 ± 0.0128</td>
<td>-</td>
<td>9.22</td>
<td>156.61</td>
</tr>
<tr>
<td>TYC 2532-0546-1</td>
<td>-</td>
<td>5.0401 ± 0.0030</td>
<td>-</td>
<td>3.07</td>
<td>67.57</td>
</tr>
<tr>
<td>TYC 2534-0255-1</td>
<td>2.5341 ± 0.0013</td>
<td>2.6471 ± 0.0012</td>
<td>−0.1130 ± 0.0018</td>
<td>0.48</td>
<td>349.55</td>
</tr>
<tr>
<td>TYC 3157-1143-1</td>
<td>1.8989 ± 0.0007</td>
<td>1.8267 ± 0.0007</td>
<td>0.0722 ± 0.0010</td>
<td>0.58</td>
<td>132.37</td>
</tr>
<tr>
<td>KELT-16</td>
<td>4.2979 ± 0.0036</td>
<td>4.1615 ± 0.0032</td>
<td>0.1364 ± 0.0048</td>
<td>0.72</td>
<td>95.01</td>
</tr>
<tr>
<td>TYC 3157-1380-1</td>
<td>-</td>
<td>4.5198 ± 0.0040</td>
<td>-</td>
<td>3.40</td>
<td>337.88</td>
</tr>
<tr>
<td>TYC 1993-1660-1</td>
<td>-</td>
<td>4.2352 ± 0.0094</td>
<td>-</td>
<td>4.90</td>
<td>252.80</td>
</tr>
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</table>

Table 3.2. LBT Observations Results
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>KELT-2</td>
<td>0.071 ± 0.040</td>
<td>0.228 ± 0.040</td>
<td>G2 (F7)</td>
<td>M1.5</td>
</tr>
<tr>
<td>TYC 2420-0124-1</td>
<td>0.057 ± 0.025</td>
<td>0.212 ± 0.025</td>
<td>F6</td>
<td>M0</td>
</tr>
<tr>
<td>KELT-3</td>
<td>0.066 ± 0.027</td>
<td>0.077 ± 0.027</td>
<td>G0 (F6)</td>
<td>G6</td>
</tr>
<tr>
<td>TYC 2420-0394-1</td>
<td>0.040 ± 0.031</td>
<td>-</td>
<td>A7</td>
<td></td>
</tr>
<tr>
<td>TYC 2508-0285-1</td>
<td>0.050 ± 0.033</td>
<td>0.192 ± 0.033</td>
<td>F2</td>
<td>K8</td>
</tr>
<tr>
<td>KELT-1</td>
<td>0.097 ± 0.036</td>
<td>-</td>
<td>K1 (F5)</td>
<td></td>
</tr>
<tr>
<td>KELT-4</td>
<td>0.101 ± 0.030</td>
<td>0.1364 ± 0.030</td>
<td>K3 (F7)</td>
<td>K5</td>
</tr>
<tr>
<td>TYC 1994-1098-1</td>
<td>0.073 ± 0.027</td>
<td>-</td>
<td>G2</td>
<td></td>
</tr>
<tr>
<td>TYC 2996-0462-1</td>
<td>0.058 ± 0.026</td>
<td>-</td>
<td>F6</td>
<td></td>
</tr>
<tr>
<td>TYC 2109-0205-1</td>
<td>0.048 ± 0.036</td>
<td>-</td>
<td>F2 (F2)</td>
<td></td>
</tr>
<tr>
<td>TYC 2532-0546-1</td>
<td>0.055 ± 0.040</td>
<td>-</td>
<td>F6 (F2)</td>
<td></td>
</tr>
<tr>
<td>TYC 2534-0255-1</td>
<td>0.033 ± 0.028</td>
<td>−0.080 ± 0.028</td>
<td>A2 (F2)</td>
<td>O7 (O9)</td>
</tr>
<tr>
<td>TYC 3157-1143-1</td>
<td>0.077 ± 0.024</td>
<td>0.149 ± 0.024</td>
<td>G6 (F0)</td>
<td>K6</td>
</tr>
<tr>
<td>KELT-16</td>
<td>0.050 ± 0.027</td>
<td>0.186 ± 0.027</td>
<td>F2 (F7)</td>
<td>K8</td>
</tr>
<tr>
<td>TYC 3157-1380-1</td>
<td>0.033 ± 0.024</td>
<td>-</td>
<td>A2 (A2)</td>
<td></td>
</tr>
<tr>
<td>TYC 1993-1660-1</td>
<td>0.042 ± 0.035</td>
<td>-</td>
<td>A8</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Spectral types in parentheses are from SIMBAD when available, or, in the case of the KELT objects, from the original planet discovery papers. These spectral types are based on a multitude of inputs, including spectra, and are more reliable than $H − K$ photometry alone.

Table 3.3. LBT Relative Photometry and Estimated Spectral Types
<table>
<thead>
<tr>
<th>Name</th>
<th>Searched Mag. Limit</th>
<th>No. Stars</th>
<th>Sep. (&quot;)</th>
<th>NCAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>KELT-2</td>
<td>10.5</td>
<td>249</td>
<td>2.39</td>
<td>99.9655% (3.6σ)</td>
</tr>
<tr>
<td>TYC 2420-0124-1</td>
<td>12</td>
<td>745</td>
<td>0.63</td>
<td>99.9931% (4.0σ)</td>
</tr>
<tr>
<td>KELT-3</td>
<td>12</td>
<td>76</td>
<td>3.74</td>
<td>99.9742% (3.7σ)</td>
</tr>
<tr>
<td>TYC 2420-0394-1</td>
<td>10</td>
<td>189</td>
<td>0.13</td>
<td>99.9999% (4.9σ)</td>
</tr>
<tr>
<td>TYC 2508-0285-1</td>
<td>12</td>
<td>84</td>
<td>6.08</td>
<td>99.9247% (3.4σ)</td>
</tr>
<tr>
<td>KELT-1</td>
<td>16</td>
<td>4,820</td>
<td>0.59</td>
<td>99.9593% (3.5σ)</td>
</tr>
<tr>
<td>KELT-4</td>
<td>12</td>
<td>109</td>
<td>1.62</td>
<td>99.9931% (4.0σ)</td>
</tr>
<tr>
<td>TYC 1994-1098-1</td>
<td>13.5</td>
<td>232</td>
<td>0.35</td>
<td>99.9993% (4.5σ)</td>
</tr>
<tr>
<td>TYC 2996-0462-1</td>
<td>13.5</td>
<td>282</td>
<td>0.71</td>
<td>99.9966% (4.1σ)</td>
</tr>
<tr>
<td>TYC 2109-0205-1</td>
<td>18</td>
<td>26,251</td>
<td>9.22</td>
<td>45.9056% (0.6σ)</td>
</tr>
<tr>
<td>TYC 2532-0546-1</td>
<td>13.5</td>
<td>243</td>
<td>3.07</td>
<td>99.9445% (3.5σ)</td>
</tr>
<tr>
<td>TYC 2534-0255-1</td>
<td>12.5</td>
<td>110</td>
<td>0.48</td>
<td>99.9994% (4.5σ)</td>
</tr>
<tr>
<td>TYC 3157-1143-1</td>
<td>11</td>
<td>1,253</td>
<td>0.58</td>
<td>99.9898% (3.9σ)</td>
</tr>
<tr>
<td>KELT-16</td>
<td>16</td>
<td>23,560</td>
<td>0.72</td>
<td>99.7039% (3.0σ)</td>
</tr>
<tr>
<td>TYC 3157-1380-1</td>
<td>14.5</td>
<td>19,740</td>
<td>3.40</td>
<td>94.4684% (1.9σ)</td>
</tr>
<tr>
<td>TYC 1993-1660-1</td>
<td>14.5</td>
<td>453</td>
<td>4.90</td>
<td>99.7363% (3.0σ)</td>
</tr>
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Table 3.4. LBT Chance Alignment Probability Results
<table>
<thead>
<tr>
<th>Name</th>
<th>$m_{K,\text{prim}}$</th>
<th>$M_{K,\text{prim}}$</th>
<th>$\pi$ (mas)</th>
<th>$d$ (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KELT-2</td>
<td>7.346 ± 0.031</td>
<td>1.71 ± 0.19</td>
<td>7.47 ± 0.63</td>
<td>134 ± 11</td>
</tr>
<tr>
<td>TYC 2420-0124-1</td>
<td>9.312 ± 0.019</td>
<td>2.52$^{+1.04}_{-1.26}$</td>
<td>-</td>
<td>230$^{+180}_{-86}$</td>
</tr>
<tr>
<td>KELT-3</td>
<td>8.662 ± 0.019</td>
<td>2.05 ± 0.29</td>
<td>4.75 ± 0.63</td>
<td>211 ± 28</td>
</tr>
<tr>
<td>TYC 2420-0394-1</td>
<td>9.846 ± 0.020</td>
<td>1.55$^{+1.77}_{-1.14}$</td>
<td>-</td>
<td>460$^{+310}_{-240}$</td>
</tr>
<tr>
<td>TYC 2508-0285-1</td>
<td>8.631 ± 0.022</td>
<td>2.07$^{+1.52}_{-1.24}$</td>
<td>-</td>
<td>210$^{+160}_{-100}$</td>
</tr>
<tr>
<td>KELT-1</td>
<td>9.437 ± 0.019</td>
<td>2.60 ± 0.61</td>
<td>4.3 ± 1.2</td>
<td>233 ± 65</td>
</tr>
<tr>
<td>KELT-4</td>
<td>8.689 ± 0.020</td>
<td>1.85 ± 0.28</td>
<td>4.29 ± 0.56</td>
<td>233 ± 30</td>
</tr>
<tr>
<td>TYC 1994-1098-1</td>
<td>9.112 ± 0.018</td>
<td>2.85 ± 0.21</td>
<td>5.58 ± 0.55</td>
<td>179 ± 18</td>
</tr>
<tr>
<td>TYC 2996-0462-1</td>
<td>9.702 ± 0.019</td>
<td>3.13 ± 0.35</td>
<td>4.85 ± 0.79</td>
<td>206 ± 34</td>
</tr>
<tr>
<td>TYC 2109-0205-1</td>
<td>9.996 ± 0.019</td>
<td>1.75 ± 0.56</td>
<td>2.24 ± 0.58</td>
<td>450 ± 120</td>
</tr>
<tr>
<td>TYC 2532-0546-1</td>
<td>7.471 ± 0.018</td>
<td>1.21 ± 0.23</td>
<td>5.59 ± 0.58</td>
<td>179 ± 19</td>
</tr>
<tr>
<td>TYC 2534-0255-1</td>
<td>8.830 ± 0.019</td>
<td>1.28$^{+1.45}_{-1.11}$</td>
<td>-</td>
<td>320$^{+310}_{-160}$</td>
</tr>
<tr>
<td>TYC 3157-1143-1</td>
<td>8.510 ± 0.016</td>
<td>3.38$^{+0.69}_{-1.12}$</td>
<td>-</td>
<td>106$^{+71}_{-30}$</td>
</tr>
<tr>
<td>KELT-16</td>
<td>10.642 ± 0.016</td>
<td>2.66 ± 0.21</td>
<td>2.53 ± 0.24</td>
<td>395 ± 37</td>
</tr>
<tr>
<td>TYC 3157-1380-1</td>
<td>8.954 ± 0.018</td>
<td>−0.43 ± 1.08</td>
<td>1.33 ± 0.66</td>
<td>750 ± 370</td>
</tr>
<tr>
<td>TYC 1993-1660-1</td>
<td>9.403 ± 0.020</td>
<td>3.07 ± 0.23</td>
<td>5.42 ± 0.58</td>
<td>185 ± 20</td>
</tr>
</tbody>
</table>

Table 3.5. Orbital Parameter Analysis Results
<table>
<thead>
<tr>
<th>Name</th>
<th>$a$ (AU)</th>
<th>$M_1$ ($M_\odot$)</th>
<th>$M_2$ ($M_\odot$)</th>
<th>$P_{\text{min}}$ (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KELT-2</td>
<td>319 ± 27</td>
<td>$1.64^{+0.14}_{-0.11}$</td>
<td>$0.84^{+0.03}_{-0.07}$</td>
<td>$3600^{+630}_{-550}$</td>
</tr>
<tr>
<td>TYC 2420-0124-1</td>
<td>$150^{+110}_{-54}$</td>
<td>$1.25^{+0.87}_{-0.31}$</td>
<td>$0.73^{+0.32}_{-0.14}$</td>
<td>$1300^{+2100}_{-780}$</td>
</tr>
<tr>
<td>KELT-3</td>
<td>790 ± 100</td>
<td>$1.45^{+0.14}_{-0.13}$</td>
<td>$0.70^{+0.02}_{-0.07}$</td>
<td>$15000^{+3900}_{-3200}$</td>
</tr>
<tr>
<td>TYC 2420-0394-1</td>
<td>$60^{+40}_{-31}$</td>
<td>$1.76^{+1.36}_{-0.72}$</td>
<td>$1.76^{+1.36}_{-0.72}$</td>
<td>$250^{+450}_{-190}$</td>
</tr>
<tr>
<td>TYC 2508-0285-1</td>
<td>$1280^{+760}_{-610}$</td>
<td>$1.44^{+1.30}_{-0.51}$</td>
<td>$0.72^{+0.30}_{-0.23}$</td>
<td>$31000^{+59000}_{-22000}$</td>
</tr>
<tr>
<td>KELT-1</td>
<td>138 ± 38</td>
<td>$1.22^{+0.27}_{-0.20}$</td>
<td>$0.15^{+0.06}_{-0.03}$</td>
<td>$1385 \pm 620$</td>
</tr>
<tr>
<td>KELT-4</td>
<td>377 ± 49</td>
<td>$1.55^{+0.19}_{-0.12}$</td>
<td>$1.08^{+0.10}_{-0.09}$</td>
<td>$4500^{+1100}_{-1000}$</td>
</tr>
<tr>
<td>TYC 1994-1098-1</td>
<td>62.0 ± 6.1</td>
<td>$1.13^{+0.08}_{-0.07}$</td>
<td>$0.45 \pm 0.04$</td>
<td>$388^{+76}_{-67}$</td>
</tr>
<tr>
<td>TYC 2996-0462-1</td>
<td>146 ± 24</td>
<td>$1.04^{+0.12}_{-0.08}$</td>
<td>$0.50^{+0.07}_{-0.05}$</td>
<td>$1400^{+450}_{-400}$</td>
</tr>
<tr>
<td>TYC 2109-0205-1</td>
<td>4100 ± 1100</td>
<td>$1.60^{+0.60}_{-0.26}$</td>
<td>$0.14 \pm 0.03$</td>
<td>$200000^{+110000}_{-92000}$</td>
</tr>
<tr>
<td>TYC 2532-0546-1</td>
<td>550 ± 57</td>
<td>$2.18^{+0.29}_{-0.33}$</td>
<td>$0.44 \pm 0.04$</td>
<td>$8000^{+14000}_{-1500}$</td>
</tr>
<tr>
<td>TYC 2534-0255-1</td>
<td>150$^{+100}_{-77}$</td>
<td>$2.08^{+1.23}_{-0.90}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TYC 3157-1143-1</td>
<td>$61^{+42}_{-17}$</td>
<td>$0.98^{+0.38}_{-0.17}$</td>
<td>$0.61^{+0.19}_{-0.11}$</td>
<td>$380^{+540}_{-180}$</td>
</tr>
<tr>
<td>KELT-16</td>
<td>284 ± 27</td>
<td>$1.20 \pm 0.08$</td>
<td>$0.34^{+0.04}_{-0.03}$</td>
<td>$3900^{+730}_{-660}$</td>
</tr>
<tr>
<td>TYC 3157-1380-1</td>
<td>2600 ± 1300</td>
<td>$4.5^{+4.0}_{-1.6}$</td>
<td>$0.81^{+0.27}_{-0.19}$</td>
<td>$58000^{+72000}_{-42000}$</td>
</tr>
<tr>
<td>TYC 1993-1660-1</td>
<td>904 ± 97</td>
<td>$1.06 \pm 0.07$</td>
<td>$0.26 \pm 0.04$</td>
<td>$23700^{+1300}_{-4500}$</td>
</tr>
</tbody>
</table>

Notes: No mass is provided for the companion to TYC 2534-0255-1 as it is an O subdwarf and not on the main sequence.

Table 3.6. Orbital Parameter Analysis Results
Chapter 4: Discussion and Conclusion

In this dissertation, I have presented the results of my study of 10 hot Jupiter hosts from the KELT survey and 70 comparison stars of similar properties which were rejected as hosts of transiting hot Jupiter hosts by KELT. I detected 11 new candidate binary companions as well as four which were previously known to be binaries. I only recovered one of the known KELT companions with DSSI; the rest were either too faint, or their wide angular separations placed them outside of DSSI’s field of view. With LBTI, I was more successful, recovering the five known KELT binaries which I observed with that instrument.

Tables 2.1 and 3.1 summarizes the achieved contrast in each of our observations. The mean contrast we achieved with DSSI at $0''.2$ separation was 3.7 magnitudes in the 692 nm filter and 3.1 magnitudes in the 883 nm filter. Although this did not allow me to rule out fainter M dwarf companions, DSSI did achieve very high resolution, delivering the achieved contrast at $0''.2$ or even smaller separations. Despite this, our detected companion fraction of $8.0\%^{+3.0\%}_{-2.4\%}$ is consistent with the predicted binary detection rate of DSSI at WIYN of $7.8 \pm 0.4\%$ (Horch et al. 2014). This indicates that the companion fraction for our sample of hot stars is likely consistent with the field binary fraction for FGK stars from Raghavan et al. (2010), at least for the separations and magnitude differences to which DSSI is sensitive at WIYN.

With LBTI, I observed 19 new comparison stars, observing candidate binary companions around nine of them. Two of these were rejected as companions due to the high probability of them being a chance alignment, resulting in a final tally of seven likely binaries. The total companion fraction of the LBTI comparison sample is then $36.8 \pm 6.3\%$ compared to $50 \pm 8.1\%$ for the KELT planet hosts. This indicates that hot Jupiter hosts have a slight excess of binary stellar companions compared...
to the field. This is a similar result to the Friends of Hot Jupiter survey (Ngo et al. 2015), and the companion fraction for the KELT planets is actually in excess of their non-completeness-corrected hot Jupiter host stellar companion fraction of $35 \pm 7\%$ (Ngo et al. 2016). Both of these results point towards the conclusion that while binary stars may encourage the formation of hot Jupiters, the Kozai-Lidov mechanism is unlikely to be the dominant formation pathway.

Together, my results from DSSI and LBTI show that the general population of A and F stars in the KELT fields have a similar binary fraction to FGK stars in the Solar neighborhood ($33 \pm 2\%$; Raghavan et al. 2010). This has implications for star formation and cluster dynamics, implying that A and F stars form under similar conditions to Sun-like stars.

In the future, further refinements to the LMIRCam data reduction and analysis process could also be made. Several of the stars observed with LBT show significant field rotation during the observations, making them good candidates for suppressing the stellar PSF through ADI. This would enhance the ability to detect faint, close-in companions to those stars. Completeness correction simulations could also be done to compensate for the fact that my observations would not be expected to detect all stellar companions to the stars in the sample. A larger sample size would also improve the estimate of the companion fraction for both the hot Jupiter hosts and the comparison sample, potentially leading to a stronger result.

Additional questions for future work include the issue of misalignment of the planetary orbital axis with the stellar rotation axis. A significant fraction of hot Jupiters are misaligned with their star (Fabrycky & Tremaine 2007), and binary star interactions such as Kozai-Lidov could change the inclination of a giant planet’s orbit. Rossiter-McLaughlin measurements have not yet been taken for all of the KELT sample; if these were performed, they could answer whether binary star interactions are responsible for the misalignments. Although Friends of Hot Jupiters found a negative result (Ngo et al. 2015), it is possible that hot stars with $T_{\text{Eff}} > 6200$ K represent a different regime for this than their sample.
References


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Wallerstein, G., & Spinrad, H. 1960, PASP, 72, 486