A SEARCH FOR VARIABLE STARS AND TRANSIT TIMING VARIATIONS IN
KNOWN EXOPLANETARY SYSTEMS

A THESIS

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ABSTRACT

THESIS: Searching for Transit Timing Variations in Known Exoplanetary Systems and Variable Stars

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This thesis involves the study of a wide range of variable stars in several different contexts. This includes external variable stars such as exoplanet transits and contact binaries to intrinsic variable stars. More specifically it can be broken into four subcomponents. The first of which deals with the characterization of seven known exoplanets and the development of a method to estimate an exoplanet’s orbital period and semi-major axis from a single partial transit. This helps us gain a better understanding of the properties of worlds outside of our solar system. This section resulted in indication of different radii for two of the seven exoplanets observed. The second subcomponent deals with using known transiting exoplanets to search for additional unseen planetary companions using transiting timing variations (TTV) and transit duration variations (TDV). Both of these techniques allow us to probe for exoplanets that might not be easily found due to its alignment or orbital distance. Potential TTV signals were seen for KELT-16 b at a period of 2.444±0.002 days and WASP-43 b at a period of 1.359±0.001 days. Additionally, there was a potential TDV signal seen for WASP-52 b at a period of 5.382±0.002 days. The third subcomponent details the discovery of five new contact binary star systems and the reanalysis of two previously known contact binary systems. Additionally, this component
also details the potential discovery of a new transiting, bloated Hot Jupiter exoplanet candidate or stellar companion and potential confirmation of a previously ruled false positive variable star. The final subcomponent covered in my thesis is a search for variable stars in the dense core of the Globular Cluster 47-Tucanae. Although many Globular Clusters have had their less dense regions studied, the interior of many of these systems has remained difficult to observe. By gaining a deeper understanding of this system we can gain further insights into the makeup and evolution of Globular Clusters. In this portion of my analysis I observed 125 variable star candidates of which 31 have previously been listed in at least one of three papers. Of these 31, six showed evidence of short period variations in my dataset instead of long period variations. This leaves 14 new long period variable star candidates, 78 new short period variable star candidates, and three strange light curves for which I was not able to determine a period type.
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Finally, I would like to thank all of the faculty of the department for providing an excellent learning environment especially their willingness to help their students and providing an appropriately challenging level of course work that allows their students to flourish. I’ve truly enjoyed my time in the department and at Ball State University.

Daniel J. Brossard
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1. Introduction

1.1. Objectives

There are two main objectives to my thesis: first to attempt to find additional exoplanets in known planet-hosting systems using the Transit Timing Variation (TTV) method, and second to look for exoplanet candidates and variable stars in the Globular Cluster 47-Tucane.

1.2. Exoplanet Background

For thousands of years the only planets we knew of were the Earth and the 5 planets visible in the night sky. With the invention of telescopes gradually more planets were found starting with Uranus in 1781 and then Neptune in 1846. Other bodies were also found in our Solar System such as asteroids in the Asteroid Belt or the comets and dwarf planets in the Kuiper Belt. But in the end, it took nearly 150 years before we found another planet that fits the current IAU planetary definition, only this time outside our own Solar System. In 1992 the first confirmed exoplanet was found around a pulsar, since then the number of planets discovered has exploded, with over 4150 exoplanets listed on the NASA Exoplanet Science Institute at Caltech’s Exoplanet Archive (NASA Exoplanet Archive, 2020) as of May 13th, 2020.

There are several different techniques that are used to discover exoplanets such as the radial velocity (Doppler) method, the transit method, and even more exotic ones such as gravitational lensing. The majority of exoplanets have been found using the transit method.

1.2.1. Transit Method

To date (May 2020) over 4100 exoplanets have been discovered, with over 3100 of those coming from the Transit method alone. One of the best methods to search for exoplanet transits is to use a technique called differential photometry (Henden & Kaitchuk 1990, Castellano 2000).
which measures the relative brightness of a star to the other stars in the CCD image, then repeats this process for an entire set of observations. The individual measurements are then plotted and examined, looking for the tell-tale dip, known as a transit, in the star’s light curve.

Differential photometry has many other uses such as finding eclipsing-binary star systems. In most cases the light-curves of these systems would have two transits as each star takes a turn blocking the light from its companion, or intrinsic variable stars such as RR Lyrae stars, whose brightness varies in a periodic fashion due to pulsations in the star’s atmosphere.

One of the main difficulties in searching for exoplanets with the transit method is how small the decrease in the brightness of the star is compared to the expected noise during the observations. For instance, a Jovian sized planet orbiting a Sun-like star would only cause an approximately one-percentage change in the brightness of the star, which requires a high signal-to-noise-ratio (SNR) in order for the change in brightness to be larger than the expected noise of the observations. To detect smaller planets, such as Earth or Neptune sized, and retain a good time resolution the light gathering power of the telescope must be increased and seeing conditions have to be nearly perfect to produce the best possible SNR. This problem can be somewhat mitigated by looking at stars smaller than the Sun. This is because the same sized planet will cover a larger percentage of the stellar disk of a smaller star, causing a deeper transit. This comes from the fact that the luminosity of a star is dependent on the radius of the star squared. So, if the ratio of the planet’s radius to the star’s radius increases then the amount of light blocked will increase.

Another potential issue that could arise while observing is the inevitable presence of bad pixels or dead columns in the telescope’s CCD chip. If the tracking is not perfect it is possible
that the target star could pass through these bad pixels or dead columns simulating the appearance of an exoplanet or binary star transit as shown in Figure 1-1.

**Figure 1-1:** The leftmost image is an example of a real planet transit, while the rightmost image is an example of a star that passed over a bad column throughout a set of observations.

### 1.2.2. TTVs

Along with the standard transit method there is a related method called Transit timing variations (TTVs) that can also be used to find exoplanets using the variations from the expected time of the midpoint of the planet’s transit between different orbits. If TTVs are present then by looking at transits over a wide enough timeframe a sinusoidal pattern should emerge, as seen in Figure 1-2, potentially indicating additional unseen planets or even potentially exomoons. This happens due to the differences in the orbital periods of each planet. As the inner planet passes the out planet the gravitational pull of the outer planet will slow the inner planet down slightly causing the transit to start later than expected. As it continues to orbit around eventually the alignment will change such that the gravitational pull of the outer planet causes the transit to
happen earlier than expected. An equal and opposite change should be seen in the transits of the outer planet if it aligns in such a way that it too transits.

![Figure 1-2: A series of figures from Mazeh et al 2019 shows the types of patterns that could be seen due to transit timing variations. These observations come from the Kepler space telescope and so they were able to capture consecutive images and did not need to undergo any work trying to get the period in phase.](image)

Using the TTV method has several important advantages over just the Transit method by itself. Just because one planet transits its star does not mean the other exoplanets in a system will as well. There is a narrow range in inclinations in which a transit would be visible from the Earth, this range depends on the size of the star and is inversely dependent on the planet’s semi-major axis (Borucki and Summers 1984). Therefore, even if the innermost planet transits its star as seen by Earth it does not guarantee the other planets will transit as well. One good example of this phenomenon is the star 55 Cancri. Although all the planets in the system were originally found using the radial velocity method, it was later found that the innermost planet, 55 Cancri e actually transits the star as well (Winn et. al., 2011). Out of the remaining four planets though known are aligned in such a way in which they transit their star. There are many more systems
that have a similar issue with the planetary alignment but are too dim to perform radial velocity measurements on making TTV analysis the best method to find these unseen planets.

With the TTV method only one of the planets needs to transit the star to have the potential to infer the existence of additional planets, without the need of radial velocity measurements of the star. Telescopes like the Kepler space telescope generally requires at least three transits before the object is confirmed (NASA press release 11-99AR, 2011) or confirmation using a different technique such as radial the radial velocity method (Perryman, 2018 pg 196). TTVs can be used as a substitute to these requirements allowing for faster confirmation of exoplanet candidates (Perryman, 2018 pg. 198 & 262).

TTVs can give us important information about the planets in a system that the transit method alone cannot, most importantly is an estimate of the masses of the planets involved. If multiple planets are transiting it is possible to watch the variations in the midpoint of each of their transits and model the potential masses that each such planet would need to cause the variations seen in a given system (Holman & Murray 2005). Having a mass and radius estimate can give us a way to estimate the density of the planet which give us our first look at the planet’s possible composition (Seager et al. 2007, Weiss & Marcy 2014; Zeng et al. 2016).

Finally, TTVs have recently been used to provide evidence for the first serious exomoon candidate Kepler-1625-b-i around the Jovian planet Kepler-1625-b (Teachey & Kipping 2018). Although currently not confirmed, and in fact still controversial, the combination of the detection of large amplitude TTVs, combined with evidence of a second dip in some of the light curves just before or just after the primary transit, indicate that there could be a large exomoon orbiting this planet (Teachey & Kipping 2018). As the global data base of transit events continue to grow
for planets in larger orbits it is likely that TTVs will play an important role in the eventual first confirmation of an exomoon.

1.3. Variable Stars

Variable stars can be broadly broken into two distinct classes, intrinsic and extrinsic variables. Intrinsic variable stars have luminosity changes due to some inherent property of the star itself, such as a pulsation in the stellar atmosphere or even characteristics such as star-spots. Certain types of pulsating intrinsic variables can even be used to obtain distance estimates, due there being a relationship between their luminosity and their pulsation period. One type of these intrinsic variable stars, known as Cepheids are one of the main tools used to estimate distances to Globular Clusters and even nearby galaxies.

Extrinsic variables on the other hand could be something like an eclipsing binary system or even an exoplanet transit. Systems such as eclipsing binaries could be used to obtain mass estimates of the stars in question. By measuring the masses of many eclipsing binary star systems compared to their color, an indication of their temperature, we can obtain a method of estimating the masses of companionless stars based on their temperature. Planetary transits can provide a wealth of information about the planet in question.

1.3.1. Variable Star Candidates

In total 7 objects of interest were found in field stars from my TTV observations of KELT-16. Of these 2 previously discovered variable stars are seen in the field observed using the Ball State Observatory 20-inch telescope (BSUO), which has the largest field of view out of the telescopes used in my research. These two stars are known as ASASSN-V J205658.12+314215.9, referred to as V1 in this thesis, and ASASSN-V J205552.88+314615.9 referred to as V2, both discovered during the All-Sky Automated Survey for Supernovae
(Shappee et al. 2014). Both stars are listed in the ASAS-SN Catalog of Variable Stars: VI
(Jayasinghe et al. 2018). Both have period estimates obtained using V-band images from the
ASAS-SN survey, which monitors the whole sky every 3 days and has amassed at least 100
ePOCHS for each field as of 2018. With this setup relatively few images are taken of each field
over the course of each night. Because of the relatively few samples taken the periods of each
should be examined further.

In addition to the 2 previously known variables I also discovered 5 new variable star
candidates in this field, labeled as V3 through V7 in this paper. All five of these stars have GAIA
(Gaia 2018, IRSA) and 2-MASS (The Two Micron All Sky Survey) designations and but do not
appear to have been the focus of any prior studies.

Although all 7 of these targets are visible in the wider BUSO field only 2, one previously
known variable star and one new candidate, are seen in the smaller field of view offered by the
Telescopes of the Southeastern Association for Research in Astronomy (SARA) consortium.
There was one additional target of interest that appeared using one of the SARA telescopes
though, which has the general shape of a transit. Like with the variable star candidates it has
GAIA and 2-MASS designations but again this star does not appear to have been the focus of
any prior studies.

In addition to these 2 known variable stars, and 5 additional candidates near KELT-16,
there was one additional candidate variable star near the star WASP-121. The star is named
TYC 7630-268-1 and appears on the ASAS-SN website under the title AP44024420, but is not
currently listed as a variable star on their website. Instead ASAS-SN has this target listed as a
False Positive. In my data this star appears to show variations during the one night of observing I
completed. But without further observations it cannot be confirmed as a variable star.
1.4. Targets

This section provides an overview of the various targets observed throughout my thesis. This overview includes information on why the target was chosen and what properties could prove difficult. The indicator WASP indicates a planet found during the Wide-Angle Search for Planets survey (Pollacco 2006). K2 indicates a planet found during the K2 mission for the Kepler Space Telescope. WD indicates the star is a white dwarf. HATS indicates a planet found during the HATNet Southern Exoplanet Survey. KPS indicates a planet found as part of the Kourovka Planet Search survey (Burdanov et al. 2018), KELT indicates the planet was found using the The Kilodegree Extremely Little Telescope (Pepper 2007).

1.4.1. WASP-52 b

WASP-52-b was not one of my initial targets, but it became a target, because I had previously obtained a transit of it observing with Cameron Gray and Brielle Tilson for the Astronomy 532 class at Ball State University. Because we had obtained the transit, after looking into the target more I was able to determine that it actually ended being a very good TTV target in its own right. WASP-52 is a 12th magnitude Sun-like star. The planet orbiting it is a Hot Jupiter, which means it is a Jovian sized planet has an orbital period on the order of a few days. In this case WASP-52-b has an orbital period of approximately 1.75 days (Hébrard, G., et. al 2013). Its short period has allowed for a sizable number of prior observations to be available in the ETD, with 131 prior observations currently listed. The planet itself has several other attractive properties for TTV analysis, such as a mass of only 146Me (Earth masses), while also having a large radius at 1.27RJ (Jupiter Radii). Because of its large size and the star’s somewhat smaller radius, only 0.8M☉ (Solar Radii), the planet’s transit is the deepest transit out of all of
my targets at 0.029 magnitudes. Finally, it had an average transit length of only 109 minutes, so the transit was easy to capture in a single night of observing.

1.4.2. K2-22 b

Initially, this planet was chosen for its extremely short orbital period, only 0.381 days, and the fact K2-22 itself is a relatively small star 0.57 Solar radii (Sanchis-Ojeda et al. 2015). The planet itself is quite small, so despite the small host star its transit is near the limit of what would be visible with the available telescopes with good seeing conditions. It was worth attempting to observe because of its small size, ~2.5 Earth radii, meant it likely had a small mass as well. If it has a smaller mass it would be more susceptible to the gravitational pull of any additional planets in the system, leading to a larger amplitude in the TTV signal. The star itself is quite dim with an R-band apparent magnitude of 15.38 (Zacgarias et al. 2012), which is dimmer than most of the stars I attempted to observe. This meant longer exposures would be necessary to achieve a good SNR, but because of the TTV signal is expected to be larger due to the planet’s low mass TTV analysis should be achievable. Additionally, the planet is interesting because it is disintegrating under the radiation of its host star. In prior observations of this world there is evidence for a comet like tail of debris trailing after the planet as it transits (Sanchis-Ojeda et al. 2015).

1.4.3. WD-1145+017 b

Like with K2-22, WD-1145+017 has an extremely short orbital period, at 0.188 days (Vanderburg et al. 2015). Although there were only 9 previous transit observations listed on the Exoplanet Transit Database (ETD), because the planet transits 5 times a day, it is a target in which it is possible to gain enough observations to undergo TTV analysis in a short period of time. Not only does it have a short period but because it orbits a White Dwarf, with a stellar
radius similar to that of the Earth’s own radius (1.4Re), which means that any planet transiting would cause a substantial decrease in the light observed. This is because the luminosity of a star is a function of the radius of the star squared. So, for the same sized planet the overall percentage of the star blocked by the planet’s transit increases causing a greater decrease in the light observed during the transit of the planet. In WD-1145+017 b’s case, it can cause decreases of up to 1.5% of the total flux of the star, similar to a Jovian planet transiting a Sun-like star.

Unfortunately, the star itself is quite dim at a V-band apparent of magnitude of 17th magnitude. Observing this star requires either long exposures or a large telescope and perfect viewing conditions. Another interesting factor about WD-1145+017 b is that it is believed to actually believed to be a series of planetary fragments dissolving under the intense radiation of its host (Vanderburg et al 2015). If these planetary fragments are all in similar orbits it is possible that they could be gravitationally interacting with one another so it may be possible to estimate the mass of the varies fragments if enough data is gathered. The total duration of the object’s transit is on the order of only 60 minutes (Exoplanet Transit Database) though, making balancing the amount of light gathered, and by extension the exposure length, with the time sensitivity needed to search for TTVs difficult to manage.

1.4.4. HATS-25 b

HATS-25 is a 13th magnitude star with a Jovian sized transiting exoplanet. Although it was not a primary target there were still several good qualities that made it viable for my research. The star was within the range for which I had the best results, between 10th and 13th magnitude, and a good transit depth at 0.0148 magnitudes. It did have a good mass for TTVs at only 195Me. Among its weaker attributes was the relatively long orbital period, at 4.29 days (Espinoza et al. 2016), which made matching up available observing dates to the transit dates
difficult. There was also only one other transit of this planet listed in the Exoplanet Transit Database (ETD) so multiple transits would be needed in order to attempt any sort of TTV analysis.

1.4.5. WASP-121 b

WASP-121 b is a Jovian exoplanet around a 10th magnitude star, making it among the brightest stars observed during my research. Because the star is comparatively bright, the exposure length of each image can be drastically reduced while still retaining a good SNR. This in turn allows for more time resolution for TTVs searches. Additionally, WASP-121-b has a relatively deep transit at around 0.0167 Magnitude (Poddany, Brat, & Pejcha 2010), a short period of 1.27 days and reasonable transit length of 173 minutes (Delrez et al. 2016). Its biggest weakness though was only a moderate number of prior observations listed in the ETD, with 9 completed at the time of my observation.

1.4.6. WASP-13 b

Wasp-13 is a 10th V-band magnitude star, making it among the brightest stars I attempted to observe during my research. The planet has a period of 4.35 days (Stassun et al. 2017), an average transit duration of 233 minutes, and a transit depth of 0.0087 Magnitudes (Exoplanet Transit Database, Poddany & Brat 2010). The planet itself is estimated to be closer in mass to Saturn, at 114 Me (Stassun et al. 2017), making it one of the least massive exoplanets I attempted to observe. Additionally, there were 28 previous observations listed in the ETD making TTV analysis viable. Because of the relatively small mass and good number of previous observations WASP-13 b was one of my primary targets despite the longer orbital period.
1.4.7. KPS-1

The host star KPS-1 is a 13th V-band magnitude star with a relatively recently discovered exoplanet, first being found by amateur astronomers in 2018 (Burdanov et al. 2018). Consequently, there has not been time to build up as many previous observations as some other targets, at the time of my observation there were only 2 previous transits listed on the ETD. In the months since my first observation that number has expanded to 32 transits. Unfortunately, many of these are the same transit captured from multiple observatories on the same nights making analysis still difficult. KPS-1 has several good qualities, the star is at a high declination, at +64 degrees, meaning there is a wider observing window for it. Additionally, the planet’s period is fairly short at just 1.706 days, and has a moderate average duration at 100.8 minutes (Burdanov et al. 2018). Also, the planet has a deep transit at 0.0141 Magnitudes (Exoplanet Transit Database, Poddany & Brat 2010).

1.4.8. WASP-83

Wasp-83 is a Sun-like star with an apparent V-band magnitude of 12.9, orbited by a Hot-Saturn type exoplanet with a mass of 95Me, and an orbital period of 4.97 days (Hellier et al. 2015). Its period was among the longer of those chosen as primary targets, and it only had a few prior observations in the ETD. But because of its relatively small mass and large physical size, $1.04R_j$ (Hellier et al. 2015), it was chosen as one of my primary targets.

1.4.9. HATS-18

HATS-18 b has a deep transit at 0.0195 mags, along with a short orbital period of 0.84 days (Chakrabarty & Sengupta 2019) making it a good target for observations. Although there was only 1 transit currently listed on the ETD, because it has a short period it is easier to make additional observations to get attempt undertake TTV analysis. The star itself is somewhat faint,
at magnitude 14 which meant long exposures would be needed to have a strong SNR, while the
total duration of the transit was only 113 minutes (Exoplanet Transit Database, Poddany & Brat
2010).

1.4.10. HATS-7

HATS-7 is a 13th magnitude star, slightly smaller and less massive than the Sun. It is
 orbited by HATS-7-b a planet between the sizes of Neptune and Saturn with a mass of 38Me,
 and a radius 0.56RJ (Bakos et al. 2015). The estimated transit depth of this planet is 0.0054
 magnitudes (Exoplanet Transit Database, Poddany & Brat 2010). Which while only around a
 third as deep as many of the other transits on this list, this is still large enough to be observable,
especially with a magnitude 13 star. The transit itself is estimated to last approximately 140
 minutes due to the planet having a ~3.2-day orbit (Bakos et al. 2015). This means although the
 period is somewhat long, it should be possible to find a good balance between SNR and time
 sensitivity despite how much smaller the planet is than others on my list. Its biggest issue is a
 lack of any previous observations listed in the ETD coupled with its relatively long period, which
 would make it difficult to get enough data for TTV analysis. Still it would be a promising target
to attempt TTV measurements.

1.4.11. HATS-24

HATS-24 is a Sun-like star with a V-band magnitude of 12.83, orbited by a Hot Jupiter
type exoplanet named HATS-24-b. HATS-24-b is more than twice as massive as Jupiter at
718Me, and a radius greater than Jupiter at approximately 1.4Rj (Oliveira et al. 2019). The
planet’s transit causes 0.0183 magnitude drop, which among the largest of the exoplanets I
observed for my research. Additionally, the period of the planet is 1.35 days (Bento et al. 2017),
which provides a transit length of 138 minutes (Exoplanet Transit Database, Poddany & Brat
Each of these factors makes HATS-24 a good balance between the transit length and the orbital period of a planet. The only downside to this planet is the small number of prior observations, with only 3 transits currently listed in the ETD.

1.4.12. WASP-43

WASP-43 is among the brighter stars I observed, with a V-band magnitude of 12.4. Its brightness had more to do with its relatively close location than the total luminosity of the star as it is a small main sequence K star, and therefore somewhat cooler and smaller than our Sun. Because the star itself is so small the planet’s transit is deeper than it would be for a more Sun like star. In this case WASP-43-b actually produces the second deepest transit out of all of the planets I observed, with a depth of 0.0289 magnitudes despite only being an averaged sized Jovian planet at 0.96\(R_J\) (Hellier et al. 2011). In addition to a very deep transit and a bright star, the planet has several other advantages. The period is only 0.81 days (Hellier et al. 2011) and this allows for a short transit duration of only 70 minutes (Exoplanet Transit Database, Poddany & Brat 2010). Because it is such a deep transit and the star is bright enough to allow for very good time sensitivity with a good SNR. WASP-43 b is also very massive at 565\(M_e\) (Hellier et al. 2011), more than twice the mass of Jupiter, reducing the amplitude of TTV signals from additional planets in the system. There are over 145 transit observations currently in the ETD, so despite the large planetary mass WASP-43 is in fact one of my best candidates for TTV analysis due to the abundance of data available for it.

1.4.13. HATS-1

HATS-1 was a backup option for one of my nights observing. It did have several interesting qualities including a relatively bright star at a V-band magnitude of 12 and a large planetary radius of 1.3\(R_J\) (Penev et al. 2013), leading to one of the deeper transits for my
research at 0.0162 magnitudes. It also had a fairly average transit length at only 145 minutes (Exoplanet Transit Database, Poddany & Brat 2010). Though It also has a relatively long period, for the planets I was observing at just over 3.5 days (Penev et al. 2013). There are currently 7 observations listed in the ETD, which although not enough to complete TTV analysis provide a foundation to build upon.

1.4.14. KELT-16

Kelt-16 was one of my best targets. First, it was among the brightest stars I observed with a V-band magnitude of 11.72. The star itself is a F-class star meaning it is both larger and hotter than our Sun. The planet’s orbital period 0.97 days (Oberst et al. 2017) caused a somewhat unique observing experience, as it meant the planet transit was only visible a maximum of 12 consecutive days out of the month. This is because the planet’s orbit is about 40 minutes shorter than a day, and so the transit happens 40 minutes earlier each night. Because the best viewing time for this star is from June through October, when the nights are shortest, many of the possibly observable transits actually fall during the daytime instead. Also, the nights of consecutive transits could cause some months to be wasted if large weather system affect a region for multiple days. Each transit lasts approximately 149 minutes (Exoplanet Transit Database, Poddany & Brat 2010), which is observable even during a shorter summer night. The planet itself is fairly massive at 874\(M_e\) (Oberst et al. 2017), meaning the amplitude of potential TTV signals produced by additional planets will be relatively weak. The planet also has a large physical size though at 1.42\(R_J\) (Oberst et al. 2017), producing a transit depth of 0.0124 magnitudes (Exoplanet Transit Database, Poddany & Brat 2010) despite the larger than average star. Finally, there was a good number of previous observations of the system with 61 listed in the ETD, allowing for TTV analysis to be performed.
1.5. Globular Clusters

Globular Clusters are spherical clusters containing between one-hundred-thousand and one-million solar masses in a tightly bound system only on the order of 100 parsecs across. Having so many stars in such a small volume, provides a resource to examine the evolution of a variety of stellar masses, since all stars in the cluster are expected to have similar ages. Additionally, by looking at densely populated fields such as near the center of the Milky Way or in a Globular Cluster the odds finding objects such as variable stars or even exoplanet transits should increase as there are more targets to observe in the field.

1.5.1. Difficulty of Searches in Globular Clusters

One of the useful properties of Globular Clusters, their density, is also one of the biggest challenges with observing them. Because so many stars are in such a compact area the odds of the individual stellar discs overlapping one another on the CCD image greatly increases. This issue gets significantly worse near the center of the cluster, to the point where it takes incredibly good seeing conditions to resolve anything besides a solid region of light. Although many variable stars may have already been discovered in the outer regions of a given Globular Cluster, it is possible that many more are waiting to be detected near their centers. One fact that may support this idea is that more massive stars are likely to settle into the core regions of Globular Clusters through repeated gravitational interactions with other stars. Since more massive stars tend to have shorter lifespan, and since variable stars such as Cepheids have already moved off the main sequence they are more likely to have drifted closer to the dense center of the Globular Cluster by dynamical mass segregation (Anderson & King 1996).
1.5.2. 47-Tucanae

47-Tucanae is among the brightest Globular Clusters in the night sky, with a V-band apparent magnitude of 4.09 (Dalessandro et al. 2012). 47-Tucanae is located in the southern constellation Tucana, one of the southern-most of the constellations. 47-Tucanae is interesting for several reasons, first there is an indication of two distinct stellar populations in the cluster (Anderson et al. 2009), which goes against the idea of all the stars in a Globular Cluster forming at relatively the same time. Additionally, it has also been a target of a Hubble search for planetary transit candidates (Gilliland et al. 2000), that revealed no transit candidates, this could be an indication that Globular Clusters are hostile environments for planetary systems. Despite the previous study of this Globular Cluster, I believe a more detailed look at the dense core looking for unknown variable stars is necessary with the continued advancement of programs meant for dealing with dense star fields.

2. Data Acquisition

2.1. Observatories

Ball State University is part of the Southeastern Association for Research in Astronomy (SARA) Consortium. Members of SARA have access to three telescopes, the 0.96m SARA-KP telescope in Kitt Peak Arizona, the 0.6m SARA-CT telescope in Cerro Tololo, Chile, and the 1.0m SARA-RM telescope in Roque de los Muchachos in the Canary Islands. In addition, Ball State University also has access to 0.51m and 0.41m telescopes as part of the Ball State University Observatory in Muncie Indiana. Over the course of my research I was able to utilize all three of the SARA telescopes and the 0.51m BSUO telescope.
2.2. TTV Target Selection

Particular care was taken in choosing targets for each night. First two lists of the planets that are predicted to transit on a given night were prepared. The first one was made using the resources of the NASA Exoplanet Science Institute at Caltech’s Exoplanet Archive Transit Service. This service uses known ephemeris for each of the planets in the archive, to predict whether the exoplanet’s transit will be visible at the observing location. While the second list came from the Exoplanet Transit Database (ETD) of the Czech Astronomical Society (Poddany, Brat, & Pejcha 2010), which has a similar prediction service, and in fact predicts all transits for a given planet for the next year.

Both of these services give a variety of information about each of the potential targets, some of the types of information overlapped between the two, while each source also had information that was unique to that source. Some examples of the types of information that can be found are an expected beginning, midpoint, and end time of the transit, the transit depth and length, and the apparent magnitude of the host star. Additionally, factors such as orbital period, number of previously recorded transits, and exoplanetary characteristics can be found between these two websites. Each of these factors must be carefully considered to decide whether this exoplanet is a good target for my research.

If a star is too dim longer exposures would be required to gather enough light to get accurate photometry, at the risk of lowering the time resolution. If the time resolution is too low it would be difficult to accurately determine the start, midpoint, and end of the transit and so it would be difficult to detect TTVs with any sort of accuracy. Additionally, If the planet’s transit is too long it could be difficult to fit the entire transit into a single night of observing. Due to the

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1 [https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TransitView/nph-visibletbls?dataset=transits](https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TransitView/nph-visibletbls?dataset=transits)

limitation on what nights are available for observing, whether it be due to clouds or the dates
telescopes are available, the orbital period of the planet is another factor that must be considered.
If a long orbital period is chosen the odds of a given exoplanet matching up with multiple
available observing nights decreases dramatically.

With the Exoplanet Transit Database specially, a list of the prior transit observations for
this star have been made and submitted to the database for a given exoplanet. To accurately map
out TTVs it is important to have measurements over a fairly long time-base, so a search can be
conducted for repeating patterns in the O-C plot. Without prior observations being available,
only the shortest of orbital periods could be considered at as options to get enough transits to
complete my analysis. Having more observations can also help better deal with outliers in the
data set, whether they are caused by sources of noise, star spots, or atmospheric effects that could
hide the true beginning or end of a transit.

2.3. Observations

In total I attempted 25 nights of observations, of which I was able to successfully obtain
observations as either the primary or secondary observer 18 nights, with 2 of the nights involving
the operation of multiple telescopes. A complete listing of my attempted nights is described in
Table-2-1. Finding charts to each of the planets except HATS-7 b are provided in Figure-2-1. I
was also given 6 additional nights of data collected by Dr. Guillermo Gonzalez and eventually
given to me to process; this data set is described in Table-2-2.
<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Location</th>
<th>Attempted Target(s) (parentheses mean usable transit)</th>
<th>Duration (Calibration included)</th>
<th>Number of Images</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/8/2018</td>
<td>SARA-CT</td>
<td>(Wasp-52)</td>
<td>3 hr 10 min</td>
<td>206</td>
<td>Observations done with Brielle Tillison and Cameron Gray as part of the Astronomy 586 class along with Dr. Guillermo Gonzalez</td>
</tr>
<tr>
<td>11/11/2018</td>
<td>SARA-CT</td>
<td>47-Tucanae</td>
<td>5 hr 36 min</td>
<td>336</td>
<td>Dr. Guillermo Gonzalez was the primary observer for most of the images this night</td>
</tr>
<tr>
<td>2/5/2019</td>
<td>SARA-CT</td>
<td>47-Tucanae</td>
<td>1 hr 20 min</td>
<td>88</td>
<td>Dr. Guillermo Gonzalez was the primary observer for most of the images this night</td>
</tr>
<tr>
<td>3/1/2019</td>
<td>SARA-RM</td>
<td>K2-22, WD-1145+017</td>
<td>8 hr 35 min</td>
<td>107</td>
<td>Clouds</td>
</tr>
<tr>
<td>3/10/2019</td>
<td>SARA-KP</td>
<td>K2-22</td>
<td>0 hr 0 min</td>
<td>0</td>
<td>Clouds</td>
</tr>
<tr>
<td>3/11/2019</td>
<td>SARA-KP</td>
<td>K2-29, K2-22</td>
<td>2 hr 7 min</td>
<td>63</td>
<td>Dr. Robert Berrington was the primary observer for most of the images of WASP-121</td>
</tr>
<tr>
<td>3/17/2019</td>
<td>SARA-KP</td>
<td>(WASP-121), HATS-25</td>
<td>11 hr 59 min</td>
<td>793</td>
<td>Only started using the telescope a couple hours before dawn due to rain, poor seeing conditions throughout</td>
</tr>
<tr>
<td>3/17/2019</td>
<td>SARA-KP</td>
<td>K2-27</td>
<td>4 hr 29 min</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>4/1/2019</td>
<td>SARA-KP</td>
<td>WASP-13, (KPS-1)</td>
<td>12 hr 7 min</td>
<td>270</td>
<td>A Humidity spike cut the night short</td>
</tr>
<tr>
<td>4/5/2019</td>
<td>SARA-RM</td>
<td>KPS-1, WASP-83</td>
<td>3 hr 31 min</td>
<td>102</td>
<td>Telescope computer crash shortly before dawn</td>
</tr>
<tr>
<td>4/6/2019</td>
<td>SARA-CT</td>
<td>HATS-7, HATS-18, (HATS-24)</td>
<td>11 hr 5 min</td>
<td>237</td>
<td>Dr. Robert Berrington took most of the images for WASP-43</td>
</tr>
<tr>
<td>4/14/2019</td>
<td>SARA-CT</td>
<td>(WASP-43), HATS-1, (HATS-24)</td>
<td>11 hr 20 min</td>
<td>572</td>
<td></td>
</tr>
<tr>
<td>5/13/2019</td>
<td>BSUO</td>
<td>KPS-1</td>
<td>0 hr 0 min</td>
<td>0</td>
<td>Rain</td>
</tr>
<tr>
<td>5/25/2019</td>
<td>BSUO</td>
<td>KPS-1</td>
<td>3 hr 1 min</td>
<td>105</td>
<td>Test run due to a mix up of the transit date</td>
</tr>
<tr>
<td>5/29/2019</td>
<td>BSUO</td>
<td>WASP-103</td>
<td>0 hr 0 min</td>
<td>0</td>
<td>Rain</td>
</tr>
<tr>
<td>5/30/2019</td>
<td>BSUO</td>
<td>WASP-103</td>
<td>0 hr 0 min</td>
<td>0</td>
<td>Rain</td>
</tr>
<tr>
<td>Date (UT)</td>
<td>Location</td>
<td>Attempted Target(s) (parentheses mean the seeing was useable)</td>
<td>Number of Images</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>----------</td>
<td>---------------------------------------------------------------</td>
<td>------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6/24/2017</td>
<td>SARA-CT</td>
<td>47-Tucanae</td>
<td>205</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/4/2017</td>
<td>SARA-CT</td>
<td>(47-Tucanae)</td>
<td>216</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/18/2017</td>
<td>SARA-CT</td>
<td>(47-Tucanae)</td>
<td>497</td>
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<td></td>
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<tr>
<td>10/28/2017</td>
<td>SARA-CT</td>
<td>(47-Tucanae)</td>
<td>408</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11/21/2017</td>
<td>SARA-CT</td>
<td>(47-Tucanae)</td>
<td>279</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/6/2017</td>
<td>SARA-CT</td>
<td>(47-Tucanae)</td>
<td>279</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-1: List of observations

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Location</th>
<th>Attempted Target(s)</th>
<th>Number of Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/3/2019</td>
<td>SARA-CT</td>
<td>(HATS-24), NGC-5986</td>
<td>12 hr 51 min</td>
</tr>
<tr>
<td>6/4/2019</td>
<td>BSUO</td>
<td>KELT-16</td>
<td>~3 hr</td>
</tr>
<tr>
<td>6/5/2019</td>
<td>BSUO</td>
<td>KPS-1</td>
<td>0 hr 0 min</td>
</tr>
<tr>
<td>6/7/2019</td>
<td>SARA-RM</td>
<td>KPS-1, (KELT-16), M13</td>
<td>9 hr 8 min</td>
</tr>
<tr>
<td>6/22/2019</td>
<td>BSUO</td>
<td>KPS-1</td>
<td>0 hr 0 min</td>
</tr>
<tr>
<td>7/4/2019</td>
<td>BSUO</td>
<td>(KELT-16), M56</td>
<td>7 hr 53 min</td>
</tr>
<tr>
<td>7/5/2019</td>
<td>BSUO</td>
<td>(KELT-16), M56</td>
<td>8 hr 11 min</td>
</tr>
<tr>
<td>7/5/2019</td>
<td>SARA-CT</td>
<td>47-Tucanae</td>
<td>5 hr 11 min</td>
</tr>
<tr>
<td>7/6/2019</td>
<td>BSUO</td>
<td>Kelt-16</td>
<td>3 hr 26 min</td>
</tr>
<tr>
<td>8/4/2019</td>
<td>BSUO</td>
<td>(KELT-16), M56</td>
<td>9 hr 0 min</td>
</tr>
<tr>
<td>8/5/2019</td>
<td>BSUO</td>
<td>(KELT-16)</td>
<td>9 hr 4 min</td>
</tr>
</tbody>
</table>

Table 2-2: Datasets given by Dr. Guillermo Gonzalez.
Figure 2-1: Provides a finding chart to each of the exoplanet stars I attempted to observe for my TTV analysis. They were made using the images I took during my observations. There is one missing, HATS-7 which I was not able to locate on the CCD image during my observing attempt. Each star is labeled in its respective panel.
2.4. Observation Breakdown

2.4.1. WASP-52-b

Observations of WASP-52 were completed on the night of 11/8/2018 using the SARA-CT telescope. The observations were completed as part of the requirements of the Astronomy 586 class along with Brielle Tillson, Cameron Gray, and Dr. Guillermo Gonzalez. Because WASP-52 is a relatively bright star, and the planet makes a deep transit, our group was able to keep each exposure down to just 60 seconds. This allowed for both good signal to noise while still having good time resolution. Overall, this was one of the best transits I had for my analysis. WASP-52 b was also one of three planets I was able to do more in-depth TTV analysis. It was also the least massive of the three planets analyzed. Because of this any additional planets in the system should cause larger amplitudes in the TTVs than they would a larger planet such as Jupiter.

2.4.2. K2-22-b

Although I was able to record a transit of this planet on the night of 3/1/2019, using SARA-RM, the observations required 180 second exposures in nearly ideal seeing conditions to have a sufficient SNR to resolve the transit. This coupled with the extremely short transit, on the order of 40 minutes, made getting an accurate estimate of the start and end of the transit difficult. After making additional attempts on 3/10/2019 and 3/11/2019 to get a better time resolution, which were ultimately cut short due to clouds, I decided to focus elsewhere for the rest of my TTV observations despite the many highly attractive properties of this planet, such as the short period and the expected small mass of the planet.

2.4.3. WD-1145+017 b
Although I attempted to observe this planet’s transit on the night of 3/1/2019, multiple issues became apparent. With SARA-RM I was able to get a passible SNR using 210 second R-band exposures, but the SNR was still significantly worse than seen with K2-22. This coupled with the short transit duration, of approximately 60 minutes would have ended up making TTV analysis difficult except for large amplitudes in the transit timing. Unfortunately, there were also additional complications in the form of the star passing over a bad column on the SARA-RM CCD chip early in the transit. Because the star was so dim and small, I couldn’t use a Fixpix correction in this case because the band of dead columns was actually nearly as wide as the star itself on the CCD chip, and so the observations were unfortunately unusable.

2.4.4. WASP-121-b

For WASP-121-b, Dr. Robert Berrington was the primary observer. We were able to go as short as 20 second exposures and still have a good SNR. This allowed a total of 603 R-band images to be taken over the course of 3/17/2019 using SARA-CT. Although it was not my primary target the transit itself is one of the better ones obtained for my thesis despite having limited comparison star options in this field. In total I was able to use 9 comparison stars for this transit, which is among the least used in the analysis of any of my planets. Although a good transit was obtained, there are few additional transits available for this target, with only 3 other transits currently listed on the ETD. Due to its position in the sky, at an RA of 7h 10m 24s, and the date of our observation the star was already past the best observing window for the year so I was unable to get additional transits of this planet.

2.4.5. HATS-25-b

HATS-25 b was a backup target for observing on 3/17/2019 using SARA-CT. I missed the start of my primary transit target this night, WASP-13, attempting to capture sufficient
observations after the end of the egress of WASP-121 b’s transit earlier in the night. There was also a tracking issue near the start of HATS-25 b’s transit that prevented me from capturing the initial ingress of this transit.

### 2.4.6. WASP-13-b

WASP-13 b was my primary target for the night of 4/1/2019 using SARA-KP, even though its period was somewhat longer than I had hoped to aim for, its low mass meant any TTVs in the system should be more noticeable. Unfortunately, I was unable to get a usable light curve. During the start of my observations there was either a light band of clouds over this region of the sky or the seeing was undergoing a rapid, drastic change over the course of my observations. I started with 150 second exposures, but about 15 minutes later the brightness had increased to the point where the star had saturated the pixels of the CCD chip by the next exposure. I then reduced the exposure length to 60 seconds and was able to get 51 more images before the star saturated the CCD chip again. Instead of changing the exposure length a third time I decided to move onto one of my backup planet’s whose transit was starting shortly; KPS-1 b.

### 2.4.7. KPS-1-b

I attempted to observe transits of KPS-1 b a total of 6 nights, with 3 of them (5/13/2019, 6/5/2019, 6/22/2019 using the BSUO telescope) failing due to rain and/or clouds, One starting too early for me to get onto after finishing my flats (4/5/2019 with SARA-RM), and one night (5/25/2019) failing due to an issue mistaking a UT date for a civil date, which became a test run on the BSUO telescope instead. I was able to get a successful transit of the planet on 4/1/2019 using SARA-KP though. Additionally, I got one other partial night of observations on the star looking for transits of any additional unknown planets in the system on (6/7/2019 using SARA-
RM). Although more transits have been added for this target, the fact that many were duplicated by multiple observers meant there were not enough to complete TTV analysis. There were however enough datapoints to attempt to refine the ephemeris used.

2.4.8. WASP-83-b

WASP-83 was my primary backup target on the night of 4/4/2019-4/5/2019 using SARA-RM. Unfortunately, a rapid humidity spike forced me to close the dome and ended my observations that night. Additionally, due to its longer period this was the only night in which its transit coincided with the available telescope time.

2.4.9. HATS-18-b

HATS-18 was originally one of my primary targets for the night of 4/5/2019-4/6/2019, using SARA-CT. I eventually decided to move onto one of my backup options for the night after failing to reach my target SNR value without too long of exposures, which would greatly reduce my timing accuracy.

2.4.10. HATS-7-b

During observations on 4/5/2019-4/6/2019 with SARA-CT, I concluded that HATS-18 would be too faint to have a good balance between time resolution and signal to noise, so I attempted to quickly shift to HATS-7-b. Unfortunately, I was not able to match up the stars in the field before the transit’s scheduled start time and ultimately moved to my third option that night.

2.4.11. WASP-43-b

WASP-43 was one of my primary targets, and was one of two primary targets for 4/13/2019-4/14/2019 with SARA-CT, along with HATS-24. For this planet Dr. Robert Berrington was the primary observer, we were able to go as short as 20 second exposures and
still have a good signal to noise, allowing a total of 291 images to be taken. Overall, this was among the best single transits obtained for my thesis, and with the set of previous observations available this planet was the second of the three in which I was able to perform more intensive TTV analysis.

### 2.4.12. HATS-1-b

I attempted to observe HATS-1 as an additional target between WASP-43 and HATS-24 on the night of 4/13/2019-4/14/2019, with SARA-CT. Unfortunately, a tracking error occurred near beginning of this transit causing the star’s position to change during the observations. This coupled with relatively few comparison stars in the field ultimately lead me to start observing HATS-24 earlier than I anticipated instead of continuing my observations of HATS-1.

### 2.4.13. HATS-24-b

HATS-24 was my third option on 4/5/2019-4/6/2019 with SARA-CT, and actually ended up being the most successful of the stars I observed that are visible in the southern hemisphere in terms of transits captured. HATS-24 also transited two other nights during my observations, on both 4/13/2019-4/14/2019, and 6/2/2019-6/3/2019, doubling the number of recorded transits for the planet. Unfortunately, even with these 6 observations it is not enough to complete TTV analysis, I would likely need either more consecutive transits observed or up to 15 to 20 unique transits before TTV analysis would appear plausible. The observations available could be enough to create an improved ephemeris and potentially search for some basic pattern to the transit timing but likely not clear period.

### 2.4.14. KELT-16-b

KELT-16 was my most successful target with 5 full transits obtained of the planet over the nights of 6/7/2019 with SARA-RM; 7/4/2019-7/6/2019 and 8/4/2019-8/5/2019 with BSUO. The
observations on the nights of 6/7/2019, and 8/5/2019 are among the best transits I was able to obtain for any planet over the course of my observations. There were bands of clouds that passed through during part of the night of 7/4/2019 but the transit was still usable. The clouds were thicker on the night of 7/6/2019 though, to the point where the transit was unusable for TTV analysis. Counting the nights that were unusable due to rain or clouds KELT-16 was the target for observations a total of 7 nights. Because I was able to get so many transits, and because there were already 37 nights with usable transits on the ETD, I was able to use this planet as the third and most successful target of my TTV analysis.

2.5. 47-Tucanae Observations

Although the majority of the 47-Tucanae observations were made by Dr. Gonzalez I was able to help in observing two of the nights, 11/10/2018 and 2/4/2019, and complete one night of observations on the target myself on 7/4/2019, all using SARA-CT. Unfortunately, 11/10/2018 and 2/4/2019 along with 6/24/2017 were the three worst nights in terms of seeing conditions. With full width half max (FWHM) values of over 6 seconds of arc. Additionally, there had been a camera upgrade on SARA-CT prior to my observations on 7/4/2019 from the FLI camera to the Andor camera, so my solo night of observations could not be analyzed with the other nights due to different sized CCD chips.

2.6. Variable Star Data

Along with my observations of KELT-16 I gathered data on two previously known variable stars and five new candidate variable stars. All observations of these stars were completed in the R-band. In addition to my analysis of this R-band data, for the two previously known stars I also had access to the ASAS-SN V-band data on these stars. In total V1 had 173 V-band measurements while V2 had 158 V-band measurements. Because of the relatively few samples
taken I believe the periods of each should be examined further. A finding chart of the two
previously known variable stars is available in Figure 2-2 and available information about each
in Table 2-3. Also available is the location of the magnitude reference star used in my work,
TYC 2688-139-1 now referred to as R1 in this thesis in Figure 2-2, and information concerning
this star is available in Table 2-4.

Table 2-3: Known variable star information from the ASAS-SN catalog and the Gaia mission via
the Nasa/IPAC Infrared Science Archive. (ASAS-SN, Jayasinghe T et al. 2018, IRSA)

<table>
<thead>
<tr>
<th>ASAS-SN designation</th>
<th>ASASSN-V J205658.12+314215.9</th>
<th>ASASSN-V J205552.88+314615.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our Designation</td>
<td>V1</td>
<td>V2</td>
</tr>
<tr>
<td>RA (h:m:s)</td>
<td>20:56:58.1</td>
<td>20:55:52.8</td>
</tr>
<tr>
<td>DEC (º:’:”)</td>
<td>+31:42:14.4</td>
<td>+31:46:15.6</td>
</tr>
<tr>
<td>ASAS-SN V-mag</td>
<td>14.62</td>
<td>14.29</td>
</tr>
<tr>
<td>ASAS-SN Period</td>
<td>0.7543</td>
<td>0.6002</td>
</tr>
<tr>
<td>ASAS-SN Type</td>
<td>EW</td>
<td>EW</td>
</tr>
</tbody>
</table>

Figure 2-2: Provides a finding chart to the two known variables in the field, they are labeled V1
(ASASSN-V J205658.12+314215.9), and V2 (ASASSN-V J205552.88+314615.9). The magnitude
reference star TYC 2688-139-1 is marked as R1 on the image.
3. Methodology

3.1. Image Processing

For this thesis several different programs were used. First, the initial image processing was completed using the CCDRED package (Valdes 1987) of the Image Reduction and Analysis Facility (IRAF) (Tody 1986). This included subtracting the master bias, master dark, and completing the flat field correction. While SAOImage DS9 (Smithsonian Astrophysical Observatory, 2000) was used to look for bad pixels and columns on the CCD chips in the cases where fixpix files were necessary.

Beyond the initial reductions, AstroImageJ (AIJ) (Collins et al. 2017) and the Variability Search Toolkit (VaST) (Sokolovsky & Lebedev 2017) were used to search for sources of variability in the less dense star fields observed during the TTV portion of my research. In the cases where variable stars were found in these fields, I used the Peranso Light Curve Analysis Tool (Vanmunster, 2006) to determine periods for these stars.

Finally, the Difference Image Analysis Package (DIAPL) (Pych 2016), and the Image Subtraction Package (ISIS) (Alard 2000) were used for my examination of 47-Tucanae as they are better able to examine the dense star fields seen in Globular Clusters.

3.1.1. Initial Reductions

When doing any sort of scientific research, it is important to account for sources of noise or systematic errors that are introduced either by the methods used or by the equipment itself. In

<table>
<thead>
<tr>
<th>Comparison Star</th>
<th>RA (h.m.s)</th>
<th>DEC (°,')</th>
<th>R_mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYC 2688-139-1</td>
<td>20:57:03.06</td>
<td>+31:42:43.3</td>
<td>12.03 ±0.03</td>
</tr>
</tbody>
</table>

*Table 2-4: Reference star information from Zacharias et al. 2009*
the case of observations there are two main types of noise that are introduced due to the
equipment: additive and multiplicative. Included in the additive error is a systematic offset that
must be accounted for as well. There are many options available for correcting these types of
errors but IRAF is still considered the best option for reductions.

3.1.1.1. Bias and Overscan Subtraction

Biases are the zero-point offset of each pixel of the CCD chip. Generally, the bias has a
small number of counts built up due to the equipment used. With bias subtraction there are two
main methods, creating a bias image or creating an overscan strip of pixels during the read out of
each image. Though there are two methods, they are not exclusive and can also be used together
during the reduction process.

A bias is made by taking a zero second exposure with the camera’s shutter closed. This
gives an estimate of the baseline value given to each pixel in addition to the overall pattern. A
master bias can then be created, by taking the median value of a set of biases. This provides a
better estimate of how high each pixel’s offset is and allows for this added value to be subtracted
off more accurately. It also protects the results from other sources of noise such as cosmic ray
hits. An example of a master bias is available in Figure 3-1.

In the case of my research the master bias was created using IRAF’s zerocombine tool.
There are a couple of additional pieces of information needed to create an accurate master bias,
such as the gain and read noise of each CCD. The gain and read noises are shown in Table 3-1
for each of the observatories used in my research.
Table 3-1: Description of the gain and read noise for each camera

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Instrument</th>
<th>Gain (e-/counts)</th>
<th>Read Noise (ADU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SARA-KP</td>
<td>ARC Camera</td>
<td>2.30</td>
<td>6.0</td>
</tr>
<tr>
<td>SARA-RM</td>
<td>Andor Ikon-L</td>
<td>1.00</td>
<td>6.3</td>
</tr>
<tr>
<td>SARA-CT</td>
<td>FLI Camera</td>
<td>2.00</td>
<td>9.7</td>
</tr>
<tr>
<td>BSUO</td>
<td>FLI Camera</td>
<td>1.43</td>
<td>10.83</td>
</tr>
</tbody>
</table>

It is possible to make an overscan because the CCD chip is read out through the computer one column at a time. The overscan simply has the computer read out a series of additional columns of fictitious pixels at the end of the image. The median value of these additional ‘pixels’ are then subtracted off from the image. The drawback of the overscan method is that it cannot adjust for the overall pattern of the full set of pixels in the CCD. Therefore, a master bias file should still be created to correct for the residual pattern on the CCD chip. An example of the overscan correction is shown in Figure 3-2 in Section 3.2.3 as it is most noticeable on flat images.

During my observations both methods of bias subtraction were utilized. In some cases, just biases were created, but when possible an overscan was also used giving a better understanding of how the pixels were changing throughout the night. In cases where the overscan correction was utilized the overscan was subtracted off of the bias images as well to avoid subtracting the bias value twice and to still capture the overall bias pattern on the CCD chip. Typically, during my observations at least 2 sets of 25 biases were taken per night.
3.1.1.2. Dark Correction

In addition to the bias correction, the other main additive noise comes from the dark current. The dark current is caused by random excitation detection in a CCD chip. Even though CCD chips are cooled to between -30°C to as low as -50°C, depending on the camera used, there will be some random excitation detections caused by the residual heat in the CCD chip. By taking long exposures, at a minimum a few times longer than the longest science image exposure taken during a night, the pattern caused by the residual heat of the CCD chip can be captured and corrected.

One issue that can arise with master darks is due to the long exposure lengths required, the odds of many cosmic ray hits happening during the exposure increases dramatically. Luckily
this problem can be solved by taking multiple dark images and using the median value for each pixel creating a master dark image. This master dark image should now be free of cosmic ray hits and accurately mapping the dark current of the CCD chip for the night of the observations.

During the course of my observations a minimum of 3 darks were taken with exposure length of at least 10 minutes, though normally I would aim for 5 or more darks on a given night, depending on time constraints. The Master Dark was also scaled relative to the exposure length of each of my observations so that the dark current wasn’t over corrected for.

3.1.1.3. Fixpix

A Fixpix file is a .txt file that contains a list of coordinates of pixels tagged as unordinary in some way. The pixels either react to a signal stronger than normal, recording an artificially high value, called a hot-pixel, or are less responsive creating an artificially low value called a dead-pixel. There can also be entire columns that are considered dead columns as they return very low counts even when bright stars pass through them. In a relatively dense field such as a Globular Cluster having bad pixels could change the counts from one image to the next making much of the data unusable.

By examining the master dark, which should be free of cosmic ray hits, it should be relatively easy to see the hot pixels and dead pixels in our CCD chip simplifying the process of making the Fixpix file, a comparison between the two can be seen in Figure 3-2.
Figure 3-2: Shows a comparison between the master dark without a fixpix file correction (left) and a processed master dark (right). Before the fixpix correction (Left) the largest hot pixels are significantly higher than the average background level. After the fixpix file is run there will still be hot pixels generally but highest hot pixel values will be much closer to the overall background level. It should also be noted that with DS9 the range of brightness and the relative darkness of each pixel is determined by the brightest pixel on the CCD chip. This causes the image on the right to look noisier than the left simply because the overall range is smaller so any deviation is relatively larger. This noise comes in the form of the background pixels appearing relatively brighter than they do in the left image.

3.1.1.4. Flat Field Correction

Unlike the previous examples, the flat field correction corrects for multiplicative issues with the CCD chip. These could include anything from less responsive pixels to dust on the CCD detector itself.

A flat is created by taking exposures of a region of the sky shortly after twilight or shortly before dawn, when the sky is evenly illuminated and the counts are low enough to not saturate the CCD pixels. Between each image the telescope should also be moved slightly to avoid capturing the same stars on the same pixels in multiple images which would make the flats unusable. Flats must be made using every filter that will be used for observing. Additionally, it is necessary to carefully adjust the exposure time to keep the mean number of counts on the image
near a “middle” number of counts, in my case I aimed for around 35,000 counts. When the master flat is created for a given filter band the pixels at each location are normalized to the average value across the master flat. This pixel in each actual science image is then divided by the corresponding normalized value for this pixel from the master flat. Two examples of the Master Flats can be seen in Figure 3-3, one still with the overscan strip and one without.

![Figure 3-3](image)

*Figure 3-3: A: The left image shows an example of a master flat taken with SARA-CT. Dust rings and other dirt can be seen on the flat image, these are objects that must be corrected for in the flat correction. B: The rightmost image shows another example of an unprocessed flat with the overscan stripe shown. The bright spots shown are stars that are starting to become visible around the time this flat image was taken.*

### 3.2. Variable Star/Exoplanet Analysis Process

Beyond the initial reductions it is necessary to come up with a method to actually detect the variability of the system whether it be from an external or internal variable star. The methodology used in this part of the analysis is described in this section.

#### 3.2.1. Variable Star Detection with VaST and AIJ

After the initial image processing was completed, I performed differential photometry with two different programs, AstroimageJ (AIJ), and the Variability Search Toolkit (VaST). Both programs specialize in differential photometry but go about the process different ways.
AstroimageJ is a program that specializes in performing time-series differential photometry on specific targets (Collins et al. 2017). One of the main ways that AIJ differs from VaST is that the user selects the primary targets and the comparison stars instead of every star in the field being compared to one another. This allows for shorter run times needed to create the light curves as there are less measurements needed. In my experience AIJ could create a series of light curves in a couple of minutes while operating with VaST could take over 20 minutes to complete its run.

AIJ is actually the program with which I noticed the first of the variable stars in my fields. I had selected one of the variable stars as a comparison star for KELT 16’s transit. It was then that I noticed that the same star varied on each of my nights, prompting me to run VAST to look for additional variables in the field.

There was one usable R-band reference star, so AIJ provided a means to obtain standardized magnitude estimates for each of the stars of interest in the field. It does this by comparing the relative flux of the other selected stars to the relative flux of the star with a known apparent magnitude. An example AIJ light curve can be seen in Figure 3-4.
Figure 3-4: An example of what can be expected performing differential photometry using AIJ. A: The left image shows the lightcurve of a variable star, V1, along with 5 comparison stars on the night of 7/5/2019 (UT). Each of the stars’ relative fluxes has been manually staggered along the relative flux axis for easier viewing. B: The right image shows the positions of each of the stars on the CCD image for that night.

VaST is a program which specializes in finding multiple objects undergoing brightness variations over a set of observations. VaST operates by creating a list of all detected stars and then doing aperture photometry using the SExtractor program. VaST measures several variability indices for each source and compares it to the indices of all the other sources of similar brightness in order to flag potential variable candidates. Candidate variable stars have a much higher variability index value than stars of similar instrumental magnitude. VaST then generates a plot comparing multiple variability indices of each set of data (Sokolovsky & Lebedev 2017). This plotting feature also allows the user to examine the individual light curves for any of the stars on the image. Additional information includes the location of the target in the CCD image. An example of several of the important screens that VaST generates can be seen in Figure 3-5.
3.2.2. Peranso Period Detection for Variable Stars

Period estimates for each of the variable stars observed were found using the light curve and period analysis software, Peranso 2.0. Peranso contains several period analysis methods broadly broken into two categories; Fourier methods which attempt to fit the data to trigonometric functions, or statistical methods which compare individual points to one another. My data was examined using a variety of the contained methods to find the best-fit period for each variable star.

FALC (Fourier Analysis of Light Curves) (Harris et. al., 1989) is a Fourier method used for both asteroid and variable star light curve analysis. It operates by breaking the light curve
into segments and fitting them using Fourier analysis to fit a set of observations to a period (or phase) of the object’s variations (Paunzen, & Vanmunster 2016).

ANOVA (Analysis of Variance) (Schwarzenberg-Czerny 1996) is a statistical method that uses orthogonal polynomials to analyze a set of observations. It uses multiple Fourier series to approximate the observation set (Peranso 2006, Paunzen, & Vanmunster 2016).

PDM (Phase Dispersion Minimization) (Stellingwerf 1978) works by folding the dataset into a series of trial frequencies. The entirety of the phase of the light curve, from 0 to 1, is then divided into a user designated number of bins. A variance is then calculated for each bin and compared to the variance of original data set (Peranso 2006, Paunzen, & Vanmunster 2016).

The CLEANEST method is a Fourier method used mainly for the analysis of variable stars. In Peranso the CLEANEST method has the benefit of allowing the user to remove periods that appear to be artifacts of the data for period analysis. CLEANEST works by applying an optimally discrete Fourier representation of the data, known as a discrete spectrum. This discrete spectrum is made using the amplitudes of each of the possible frequencies which are combined to form a model function. This model function is then subtracted from the actual data set creating a residual spectrum. This residual spectrum can then be analyzed using a Date Compensated Discrete Fourier Transform (DCDFT) (Foster 1995, Peranso 2006, Paunzen, & Vanmunster 2016).

Peranso assigns each period a certain theta value depending on how good of a fit the period is for the data set. The number of periods it examines is based on the resolution value entered by the user, meaning better fits could be missed if a high enough resolution is not given for a period range. So as the range of possible periods tested increases a higher resolution is needed to keep up. Based on the number of observations available for an object Peranso will give
a starting estimate of what the resolution should be. Depending on the method used a higher theta value can mean a better fit or a worse fit as seen in Figure 3-6.

![Figure 3-6: Shows a comparison between the Theta-period screen of the ANOVA method (left) and the PDM method (Right). For ANOVA the best fit is the highest theta value, which is currently marked with the line giving the period. For PDM it is the opposite the best fit actually has the lowest theta value, again it is marked with a marker giving the period of the variables.](image)

3.2.3. Exoplanet Radius Estimate Methodology

This section details the two methods that can be used to obtain estimates of the planet’s radius. Additionally, this section also provides figure showing how each method is used.

3.2.3.1. Method One

There are two main methods of estimating the radius of an exoplanet, the first of which involves using the fraction of the star’s light blocked by the planet, seen in Figure 3-7, to estimate the ratio of the planet’s radius to the star’s radius. The relation can be seen in Equation (1):

\[
\frac{R_p}{R_*} = (\Delta F^{0.5}).
\]

Here \( \Delta F \) is the change in flux caused by the transit, \( R_p \) is the radius of the planet, and \( R_* \) is the radius of the star (Seager & Mallén-Ornelas 2002)
To actually get a measurement of the planet’s radius some estimate of the star’s radius is needed. One of the more conventional methods of obtaining an estimate of a star’s radius is to examine the luminosity of the star. The luminosity of a star can be characterized using the Stephan-Boltzmann equation, seen here in Equation (2):

$$L_\ast = 4\pi\sigma T^4 R^2,$$

Where $\sigma$ is the Stephan-Boltzmann constant, $\sigma = 5.6704 \times 10^{-8} \text{Wm}^{-2}\text{K}^{-4}$.

With this equation it is possible to use color measurements of the star to estimate its temperature. Once an estimate of the star’s temperature and luminosity, which also requires an estimate of the star’s distance, are obtained it is possible to arrive at an estimate of the radius of the star.

Figure 3-7: An example of how to obtain the $\Delta F$ value. By measuring the mean value of the non-transiting stellar flux shown here in red, to the stellar flux when the minimum is reached it is possible to obtain an estimate of the ratio of the planet’s radius to the star’s radius using Equation (1)
3.2.3.2. Method Two

The second method involves looking at the time it takes the light curve to transition from points A to B, and C to D, shown in Figure 3-8. If the velocity of the planet is already known then an estimate the radius of the planet is achievable by knowing how long it takes the light curve to pass through these two transitions. With two of them they can even be averaged to get a better estimate of the radius.

If the velocity is not initially known, or is not well constrained, there are still options available to get the planet’s radius using Method two. It would simply require a calculation of the planet’s orbital velocity. The simplest and most accurate way to do this is to use the time between successive orbits, known as the planet’s period and the mass of the star to calculate the semi-major axis. From this you can obtain an estimate on the orbital velocity. If consecutive transits are not available you can come up with an estimate of the orbital velocity using a single transit. It requires an estimate of the diameter of the star in question. Then by combining knowledge of the star’s diameter and the planet’s orbital inclination with the time it takes the transit to pass through points A-C and/or B-D, we arrive at an estimate of the planet’s orbital velocity. Using this orbital velocity, it is then possible to obtain an estimate of the exoplanet’s radius using Method Two.

The most important calculations with this method are the determination of where points A, B, C, and D actually fall. Several different methods were used to determine these points including 2 different methods of detrending the light curve. One was manually done removing the trends of the portions of the light curve that are believe should be flat. The other used the “Model Fit Your Data” tool on the Exoplanet Transit Database (ETD) which detrends the data as part of its analysis. Generally, the results obtained using the Model Fit tool from the ETD
resulted in more accurate measurements of these turn off points based on the results of the orbital period and semi-major axis analysis section.

Figure 3-8: Shows the different transitions a transit light curve goes through. Point A shows the start of the planet’s transit where the first part of the planet begins passing in front of the star’s disc. Point B is the minima of the transit where the entirety of the planet’s disc is on top of the star’s disk. Point C is the point where the leading edge of the planet has completely passed over the disc of the star. Finally point D shows the point where the entirety of the planet’s disc has left the star’s disc ending the transit and allowing the star to reach its normal brightness.
3.2.4. Exoplanet Orbital Period Estimate Methodology

Along with planetary radius estimates it is possible to come up with a rough estimate of the planet’s orbital period based on the two radii estimation techniques above. By obtaining the radius estimates using both Method One and Method Two you can obtain an estimate of the orbital velocity of the planet by modeling what velocity is necessary for the radius estimate from Method 2 to equal the obtained result from Method 1.

Once we have obtained an estimate of the planet’s orbital velocity, we can obtain an estimate of the planet’s semi-major axis, if we assume a circular orbit while using Equation (4):

\[ r = \frac{GM_\star}{V^2}. \]  

where \( V \) is the planet’s velocity in meters per second, \( G \) is the gravitational constant, 
\[ G = 6.67408 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}, \]  
\( r \) is the semi-major axis in meters, and \( M_\star \) is the mass of the star in Kg. \( M_\star \) is used instead of the combined stellar-planetary mass because the mass of the star is assumed to be much larger than the mass of the planet, making the planet’s mass irrelevant for this calculation.

From Equation (5) combined with a measure of the star’s mass, we can use Equation (5), to estimate the period of the planet in seconds using just a single transit

\[ P = \frac{2\pi r}{V}. \]
3.3. TTV Data Analysis Process

This section deals with how to use data presented in an O-C diagram to perform TTV analysis searching for the gravitational interactions between the observed exoplanet and any unseen secondary bodies in the system. These gravitational interactions can usually be seen in a sinusoidal pattern in the midpoints of the observed planetary transits.

3.3.1. O-C Diagrams

An O-C diagram shows a comparison between the observed and calculated time of minima for a variable star. The observed value is from the actual observations made on a given night. While the calculated value comes from the ephemeris calculation of the minima. For the case of exoplanet transits the minima would be based on the midpoint of the transit.

The method used to calculate the O-C of each of the transits involves using a program provided on the Exoplanet Transit Database (ETD), “Model Fit Your Data” tool. (Pejcha 2008) which uses the Levenberg-Marquardt non-linear least squares fitting algorithm (Price et. al. 1992). This algorithm has the user enter an initial guess at several parameters of the system and then attempts to solve for the function, shown in Equation (5):

\[
m(t_i) = A - 2.5\log(F(z[t_i, t_0, D, b], p, c_1)) + B(t_i - t_{\text{mean}}) + C(t_i - t_{\text{mean}})^2,
\]

where \(F(z,p, c_1)\) is the relative decrease in the star’s flux as the planet’s disc crosses the stellar disc, \(z\) is the relative distance between the planet and the star compared to the radius of the star, \(p\) is the ratio of the planet’s radius to the star’s radius, \(D\) is the total duration of the transit, \(c_1\) is a coefficient, and \(b\) is the impact parameter of the planet. The impact parameter is described in more detail in Equation (6). Additionally, \(A\) and \(B\) are linear trends to the data, while \(C\)
represents the 0-point shift in the magnitudes, $t_{\text{mean}}$ is the mean time of the set of the observations, and $t_i$ is the time of each individual measurement:

$$b = \frac{a \cos(i)}{R_*}$$  \hspace{1cm} (6)

where $i$ is defined as the inclination of the planet’s orbit, $R_*$ is the radius of the star and $a$ is the orbital radius.

An example of what the results of the ETD’s model fitting tool looks like is shown in Figure 3-9.

![Figure 3-9: Shows the estimate of the transit midpoint generated using the ETD “Model Fit Your Data” tool for KELT-16’s transit on the night of 7/5/2019 (UT). In addition to this it also generates an O-C value that can be used in an O-C plot.](image)

### 3.3.2. Peranso for Transit Timing Variations

Just like with determining variable star periods, the data set contained in an O-C plot can also be entered into Peranso to search any periodicity in this data. Any periodicity in the dataset
could be an indication of additional planets in the system. For this analysis I used the 4 methods described in section 3.3.2 for variable stars.

By performing period analysis, the individual measurements are aligned to match the given period. By aligning the measurements of the O-C plot to a given period estimate what I have referred to in this thesis as the Phased O-C plot is created, as the time axis has changed from heliocentric Julian date to a single phase of the period and each of the data points are aligned to this period.

Each candidate period found using these methods underwent a visual examination to ensure that the data presented a noticeable pattern. In addition, I also have run Peranso’s period significance analysis process to examine how likely it was that the period was real and not an artifact of the observations. The period significance analysis tool assigns a false alarm probability to the period in question by running a user determined number of permutations of the same set of data with randomly generated numbers to add statistical interference. This statistical interference was created using a Fisher Randomization Test, which is a form of Monte Carlo Permutation, that generates random numbers as interference and testing whether the signal still appears. (Peranso 2006, Paunzen, & Vanmunster 2016). Two different false alarm probabilities are generated after each test. The first one is a measure of how likely the chosen period is to actually exist. The second value measures how likely it is that there is actually a stronger period within the period range being examined. Additionally, a variety of period ranges, permutation
numbers, and resolutions were tested as an additional check on the quality of the results. Figure 3-10 shows an example of a candidate period vs an example of an artifact.

![Figure 3-10: A: The left image shows an example of an artifact of the observational sampling frequency. It was by far the highest theta peak for this data set at a period of 1.93 days but it is obviously an artifact of the limited number of observations of the system. B: The right image shows a better option for this dataset at a period of 2.44 days. Although noisy there appears to be a sinusoidal pattern to the data at a period of 2.44 days.]

The results were compiled in a spread sheet to give one final examination to decide which periods were the most likely fits for the data. It should be noted that for Peranso’s period significance analysis program, false probabilities under a value of 0.01 are considered secure periods while anything above 0.2 is likely an artifact of the data. Probabilities between these two values likely exist but are less secure (Peranso 2006, Paunzen, & Vanmunster 2016).

This same process can also be applied to Transit Duration Variations. You can make the equivalent of the O-C plot by comparing the expected transit duration to the observed transit duration. This provides another method to search for the gravitational influence of unseen planets in the system.

3.4. Globular Cluster Analysis Process

The final research area examined in this thesis included a search for variable stars in the Globular Cluster 47-Tucanae. This involved the use of two additional programs known as DIAPL and ISIS to examine the dense core of the Globular Cluster.
3.4.1. Basic Theory

The method known as Image Differencing Photometry (Alard 1998), behind how both ISIS and DIAPL operate, is relatively simple. The process begins with designating a reference image. Once a reference image has been decided upon, the next step is to align all of the other images to this reference image and subtract, pixel by pixel, the reference image from each of the other images in the set. The next step is to take a measurement of how much each pixel varies over the data set.

The overall process is somewhat more complicated than this since stars do not occupy a single pixel but instead extended over a region of pixels known as a point-spread function (PSF). This means that the entirety of the star’s PSF must be matched up between images to fully measure the light from a given star, which requires the full width half max (FWHM) of each PSF on the image to be similar throughout a dataset. Since the PSF of each star constantly changes due to our atmosphere scattering the light, it is necessary to come up with a kernel program that would match the shape of each of the stars over the various images. This method involves using a least squares solution to Equation (9) (Alard & Lupton 1998):

\[ \text{Ref}(x, y) \otimes \text{Kernel}(u, v) = I(x, y) \] (9)

Here \( \otimes \) represents the convolution, \( x \) and \( y \) represent the x and y position of the pixel, and \( u \) and \( v \) represent the displacement from those positions (Hettinger 2018, Alard & Lupton 1998). This problem can be simplified by decomposing the kernel to become a linear least squares problem (Alard & Lupton 1998), which is shown in Equation (10):

\[ \text{Kernel}(u, v) = \sum a \times B(u, v), \] (10)

where \( a \) is constant and \( B \) is a basis function, this solution is known as the Constant Kernel Solution (Hettinger 2018, Alard & Lupton 1998). There are cases in which this solution does not
work so a Space Varying Kernal Solution was also added (Alard 2000). This new solution exchanges the constant $a$, in Equation (10) with a variable $a(x,y)$ which gives a new Equation (11):

$$Kernal(u, v) = \sum a(x, y) \times B(u, v)$$

### 3.4.2. Initial Steps

There were several preparatory steps that were taken before the search program was run on each set of observations. First, IRAF’s HEDIT tool is used to edit the header to add the epoch value. For my observations I used epoch 2000. After adding an epoch to the header, the next step is to add the Heliocentric Julian date to the header of the images. This was completed using IRAF’s setJD tool which, after selecting which observatory the observations were taken from, calculated the Julian and Heliocentric Julian dates of each image in the set. The examination using DIAPL and ISIS was initiated once these steps were completed with these additions with IRAF.

### 3.4.3. DIAPL

After adding the Heliocentric Julian date to the image headers, the next step in my analysis was to run the DIAPL package. Although DIAPL itself is designed to do the complete processing of the images similar to ISIS, as noted in Hettinger (2018), DIAPL was easier to use for the initial steps while ISIS was simpler to use for the later ones.

The initial DIAPL steps involved generating a list with the average FWHM of the PSF for each of the images. First, a .txt file with a list of image names is created in the folder being used. Next, the tpimages number listed in one of the configuration files is set to approximately five to ten percent of images in the run. In my case, this number was greater than 10 for each
night. The tpimages number refers to how many images will be included in the list that DIAPL generates after it finishes measuring the average FWHM of each image. After DIAPL examined the entire set of images and generated a list of the images with the best FWHM, a visual examination of these images is necessary to verify that the PSF of the stars appeared mostly circular since imperfect tracking, where the stars’ discs are distorted taking on a more oval or even triangular shape, can affect the results obtained from the image subtraction.

After confirming that there were no non-circular shaped images in the list, the image with the smallest FWHM was selected as an alignment image that was used in the first step with ISIS.

3.4.4. Pre-ISIS step

Before running ISIS there was one final step that needed to be completed, the creation of the HJDdates file. This file is used by the program to keep the track of the order of the images. To create the HJDdates file it was necessary to use a program called DatesHJD.csh which generated the needed list.

3.4.5. ISIS

After determining the best image from the list generated by DIAPL, and ensuring the PSF was mostly round, the image subtraction process was initiated. Before the images can be subtracted it is necessary to align all of the images in the data set to the alignment image. The alignment image should be a copy of the image with the smallest FWHM from the previously generated tpimages list. (Hettinger 2018, Tutorial ISIS version 2.1)

Aligning the images was completed using the Interp.csh program within ISIS. After the entire set of images had been aligned the next step was to create a reference image from a combination of all of the images selected in the tpimages list. The reference image was created using the Ref.csh program in ISIS.
Image subtraction, in which the reference image was subtracted from every other image in the dataset, was completed with the Subtract.csh program which created a subtracted version of each of the images in the dataset. After subtraction, it was important to look at the configuration files again and determine the threshold required for the detection program to use. The lower the threshold the more detections were made as the brightness of the variation approaches the overall background level of the images. Generally, the number of false positives will be at a minimum at an order of magnitude higher than the number of real detections so a high threshold was needed. For my data set, I used a threshold at or above a value of 1 for each of the nights, with the total number of detections ranging from approximately 2000 to more than 10000 depending on the night observed.

After deciding the detection threshold value, the next step was to run the Detect.csh program to look for variations over the course of the data set. Upon completion of the Detect.csh program, I examined the two files created, the var.fits and the abs.fits, shown in Figure 3-11. These two files show the change in the light hitting these pixels over the course of the observations. These files also provide an indication if something has gone wrong in a prior step such as files not aligning perfectly. Any file that does not align perfectly would ruin the entire set of analysis so it was necessary to completely remove any misaligned file and attempt the run again starting after the alignment step.
After Detect.csh finished running, the next step was to run the Find.csh program which recorded the position of each detection on the CCD chip in a file called Phot.data. This file was then run using the Phot.csh file which created a file for that specific PSF over the course of the observations. Finally, these files could then be entered into the plot_lc_PC.py program provided by Dr. Brian Murphy, Butler University via Paul Hettinger (2018) to actually plot the light curve of each of the measured images provided from the Phot.csh.

These light curves were then manually examined to evaluate if each light curve represented a false positive or a real detection. False positives have a few obvious signs such as a smaller overall variation, such as below 1000-2000 counts over the course of the dataset. Additionally, false positives are generally centered around 0 on the plot, and all of the nights show the same variation profile. Real detections on the other hand generally have a much higher variation, greater than 2000-3000, and are asymmetric around the 0 value of the plot. Additionally, a real detection should appear over each night observed as opposed to a single...
detection. A comparison between a real detection and a false detection can be seen in Figure 3-12.

![Figure 3-12: A: Top left is an actual variable star light curve taken on the night of 10/18/2017. B: Top right shows a four-night composite light curve of the same star in A. From these two figures it should be noted that each of the nights had light curves that were generally far from the zero point of the measurements along with large variations. C: Bottom left shows an example false detection. D: Bottom right shows this same false detection over the span of 4 nights.]

3.4.6. Post-ISIS

One additional step taken post-ISIS was plate-solving my reference.fits image using Astrometry.net in order to assign an RA and DEC position to each variable star candidate in my field. Because 47-Tucanae is such a dense field the normal plate-solving process was unsuccessful requiring Dr. Dustin Lang from the Astrometry.net group to use their newer 5000-series index files containing GAIA DR2 data to successfully solve this field.
4. Results

4.1. Exoplanet Radius and Period Estimates

The literature values of several important properties of each of these seven planets can be seen in Table 4-1. In addition, my estimates of most of these same properties can be seen in Table 4-2.
<table>
<thead>
<tr>
<th>Planet</th>
<th>RA</th>
<th>DEC</th>
<th>Rp/R*</th>
<th>Planetary Radius (Rj)</th>
<th>Semi-major Axis (AU)</th>
<th>Period (days)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WASP-52 b</td>
<td>23 13 58.75</td>
<td>+08 45 40.57</td>
<td>0.1008</td>
<td>±0.0018</td>
<td>1.27</td>
<td>±0.03</td>
<td>0.0272</td>
</tr>
<tr>
<td>K2-22 b</td>
<td>11 17 55.87</td>
<td>+02 37 08.60</td>
<td>0.0749</td>
<td>±0.0039</td>
<td>&lt;0.22</td>
<td>±0.04</td>
<td>0.0088</td>
</tr>
<tr>
<td>WASP-121 b</td>
<td>07 10 24.06</td>
<td>-39 05 50.57</td>
<td>0.1245</td>
<td>±0.0005</td>
<td>1.865</td>
<td>±0.044</td>
<td>0.02544</td>
</tr>
<tr>
<td>KPS-1 b</td>
<td>11 00 40.18</td>
<td>+54 57 50.35</td>
<td>0.1143</td>
<td>±0.0037</td>
<td>-0.0034</td>
<td>1.03</td>
<td>±0.13</td>
</tr>
<tr>
<td>HATS-24 b</td>
<td>17 55 33.76</td>
<td>-61 44 50.36</td>
<td>0.1280</td>
<td>±0.0002</td>
<td>1.395</td>
<td>±0.057</td>
<td>0.0238</td>
</tr>
<tr>
<td>WASP-43 b</td>
<td>10 19 38.00</td>
<td>-09 48 22.60</td>
<td>0.1594</td>
<td>±0.0004</td>
<td>0.930</td>
<td>±0.070</td>
<td>0.0142</td>
</tr>
<tr>
<td>KELT-16 b</td>
<td>20 57 04.44</td>
<td>+31 39 39.63</td>
<td>0.1070</td>
<td>±0.0013</td>
<td>-0.0012</td>
<td>1.415</td>
<td>±0.086</td>
</tr>
</tbody>
</table>

Table 4-1: Details the literature values of the known observables for all seven of the planets in which full or mostly full transits were obtained. The RA is measured in Hours, Minutes, and Seconds, the declination measured in Degrees, Arcminutes, and Arcseconds. The Rp/R* is the ratio of the planet’s radius to the star’s radius, the planetary radius is measured in Jupiter Radii, the semi-major axis is measured in AU and the period is measured in days.
<table>
<thead>
<tr>
<th>Planet</th>
<th>Date Observed (UT)</th>
<th>Rp/R* Fraction</th>
<th>Planetary Radius Method 1 (R_j)</th>
<th>Planetary Semi-major Axis (AU)</th>
<th>Planetary Period (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WASP-52 b</td>
<td>11/8/2018</td>
<td>0.167 ±0.010</td>
<td>1.428</td>
<td>+0.061</td>
<td>-0.064</td>
</tr>
<tr>
<td>K2-22 b</td>
<td>3/1/2019</td>
<td>0.063 ±0.019</td>
<td>0.356 ±0.080</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WASP-121 b</td>
<td>3/17/2019</td>
<td>0.139 ±0.035</td>
<td>2.100 ±0.109</td>
<td>+0.0062</td>
<td>-</td>
</tr>
<tr>
<td>KPS-1 b</td>
<td>4/1/2019</td>
<td>0.116 ±0.009</td>
<td>1.042 ±0.057</td>
<td>+0.053</td>
<td>-0.054</td>
</tr>
<tr>
<td>HATS-24 b</td>
<td>4/6/2019</td>
<td>0.138 ±0.003</td>
<td>1.533 ±0.082</td>
<td>+0.082</td>
<td>-0.085</td>
</tr>
<tr>
<td>HATS-24 b</td>
<td>4/14/2019</td>
<td>0.159 ±0.002</td>
<td>1.775 ±0.053</td>
<td>+0.051</td>
<td>-0.053</td>
</tr>
<tr>
<td>HATS-24 b</td>
<td>6/3/2019</td>
<td>0.146 ±0.013</td>
<td>1.624 ±0.125</td>
<td>+0.125</td>
<td>-0.127</td>
</tr>
<tr>
<td>HATS-24 b</td>
<td>Composite</td>
<td>0.148 ±0.005</td>
<td>1.644 ±0.053</td>
<td>+0.053</td>
<td>-0.054</td>
</tr>
<tr>
<td>WASP-43 b</td>
<td>4/14/2019</td>
<td>0.172 ±0.006</td>
<td>1.029 ±0.063</td>
<td>+0.086</td>
<td>-0.063</td>
</tr>
<tr>
<td>KELT-16 b</td>
<td>6/6/2019</td>
<td>0.104 ±0.008</td>
<td>1.413 ±0.095</td>
<td>+0.108</td>
<td>-0.095</td>
</tr>
<tr>
<td>KELT-16 b</td>
<td>7/4/2019</td>
<td>0.110 ±0.015</td>
<td>1.510 ±0.120</td>
<td>+0.132</td>
<td>-0.120</td>
</tr>
<tr>
<td>KELT-16 b</td>
<td>7/5/2019</td>
<td>0.116 ±0.012</td>
<td>1.593 ±0.122</td>
<td>+0.134</td>
<td>-0.122</td>
</tr>
<tr>
<td>KELT-16 b</td>
<td>8/4/2019</td>
<td>0.105 ±0.018</td>
<td>1.448 ±0.120</td>
<td>+0.131</td>
<td>-0.120</td>
</tr>
<tr>
<td>KELT-16 b</td>
<td>8/5/2019</td>
<td>0.117 ±0.004</td>
<td>1.612 ±0.097</td>
<td>+0.113</td>
<td>-0.097</td>
</tr>
<tr>
<td>KELT-16 b</td>
<td>Composite</td>
<td>0.110 ±0.006</td>
<td>1.515 ±0.050</td>
<td>+0.055</td>
<td>-0.050</td>
</tr>
</tbody>
</table>

Table 4-2: Estimates of the main observables of measured from my transits. The Rp/R* is the ratio of the planet’s radius to the star’s radius, the planetary radius is measured in Jupiter Radii, the semi-major axis is measured in AU and the period is measured in days. **Bold** indicates the best value I have for each planet.

In the case of my research, although I calculated the velocities using both methods the velocity obtained comparing just the Method One radius to the Method Two radius proved more accurate in reproducing the known orbital characteristics of the exoplanets, and so only the velocity obtained by comparing Method One to Method Two was used in this calculation.

Generally, my results matched those seen in the literature, albeit with larger uncertainty. The period and semi-major axis estimates especially are not as accurate as those obtained by using more traditional methods, such as measuring the time between successive transits, but they
still show that a rough estimate of the planet’s period and semi-major axis (SMA) can be found using as little as the initial ingress and a few observations on each side of the ingress.

One of the major areas where I saw significant deviation from the literature values is the significantly larger planetary radii observed for HATS-24 b on all three nights of observations. The smallest radius estimate generated from my three nights is still more than 0.1 $R_J$ greater than the accepted literature value by Oliveira et al. (2019), though they are closer to the original estimate given in Bento et al. (2017).

For the planet K2-22 b, although the accepted literature value for the planet’s radius is under 0.22$R_J$ from Sanchis-Ojeda et al. (2015), my results are more in line with the two newer estimates by Crossfield et al. (2016) (0.268±0.051$R_J$) and Dressing et al. (2017) (0.424±0.032$R_J$). Since there is believed to be a debris cloud around the K2-22 b due to its disintegration it is likely that all of the estimates are closer to that of the debris cloud instead of the planet proper. It is also possible that the observed radius could vary over time due to the debris cloud.

It should be noted that no period or SMA estimate was attempted for K2-22 b because the low time resolution I obtained would have resulted in very high uncertainties associated with each measurement.

4.2. TTV and TDV results

This section covers my search for TTV and TDV signals in the three exoplanetary systems in which I was able to obtain a sufficient number of transits and time resolution. The best results for each system are shown in Table 4-3. It should be noted none of the three exoplanets examined currently have any TTV signals listed as being present in the literature.
<table>
<thead>
<tr>
<th></th>
<th>Period (Days)</th>
<th>Error</th>
<th>Method(s)</th>
<th>False Positive Probability</th>
<th>False Positive Probability Error</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>KELT-16</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTV Best</td>
<td>2.444</td>
<td>±0.002</td>
<td>CLEANEST &amp; ANOVA</td>
<td>0.055</td>
<td>±0.016</td>
</tr>
<tr>
<td>TTV Second</td>
<td>1.605</td>
<td>±0.001</td>
<td>CLEANEST &amp; ANOVA</td>
<td>0.060</td>
<td>±0.017</td>
</tr>
<tr>
<td>TDV Best</td>
<td>3.899</td>
<td>±0.006</td>
<td>CLEANEST</td>
<td>0.244</td>
<td>±0.030</td>
</tr>
<tr>
<td>KELT-16 b</td>
<td>0.969</td>
<td>±2.40E-06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WASP-43</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTV Best</td>
<td>1.359</td>
<td>±0.001</td>
<td>ANOVA</td>
<td>0.020</td>
<td>±0.010</td>
</tr>
<tr>
<td>TTV Second</td>
<td>2.027</td>
<td>±0.001</td>
<td>ANOVA</td>
<td>0.075</td>
<td>±0.019</td>
</tr>
<tr>
<td>TDV Best</td>
<td>5.616</td>
<td>±0.004</td>
<td>ANOVA</td>
<td>0.426</td>
<td>±0.050</td>
</tr>
<tr>
<td>WASP-43 b</td>
<td>0.813</td>
<td>±1.00E-06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WASP-52</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTV Best</td>
<td>3.468</td>
<td>±0.001</td>
<td>CLEANEST</td>
<td>0.198</td>
<td>±0.018</td>
</tr>
<tr>
<td>TDV Best</td>
<td>5.382</td>
<td>±0.002</td>
<td>CLEANEST</td>
<td>0.198</td>
<td>±0.018</td>
</tr>
<tr>
<td>WASP-52 b</td>
<td>1.750</td>
<td>±1.20E-06</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4-3: Shows the best TTV and TDV periods for each of the three planets examined, their false positive probability and the error associated with each.

4.2.1. Kelt-16 b

KELT-16 had a total of 40 transits that had sufficient time resolution to be used in TTV analysis. Of these 40, 35 came from the ETD while the other 5 were my own observations. From these 40 transits I was able to generate the O-C plot seen in Figure 4-1.
Through analysis with Peranso’s period significance analysis tool and visual examination of the phased O-C plots to rule out false detections, I was able to detect two potential TTV periods. Both the CLEANEST and ANOVA methods detected a period of 2.444±0.002 days as the strongest theta value, with a false period probability of 0.055±0.016. Additionally, the second strongest theta value, again detected by both CLEANEST and ANOVA, produced a period of 1.605±0.001 days with a false period probability of 0.060±0.017. While both of these false positive probabilities are above the preferred value of 0.01, they are still well within the acceptable range of 0.20 listed in the Peranso User Manual. Additionally, both phased O-C plots show sinusoidal patterns indicating the possible presence of TTVs, as seen in Figure 4-2.
Beyond TTVs, the TDVs of the system were also examined in a similar manner to the TTV patterns above. The Unphased Duration vs Heliocentric Julian Date plot can be seen in Figure 4-3.

![Figure 4-3: The transit duration vs Heliocentric Julian date plot for KELT-16 with duration in minutes. By comparing duration to Heliocentric Julian date, it is possible to perform TDV analysis much like how TTV analysis can be performed by tracking the midpoint of each transit.](image)

Although a variety of periods were tested with each of the methods discussed, none of the TDV periods exhibited a false positive probability below 0.2. The closest to reaching this threshold, and the overall best TDV period examined, was from CLEANEST method with a period of 3.899±0.006 days. The false positive probability of this period was estimated to be 0.244±0.03. The phased duration vs heliocentric Julian date plot is shown in Figure 4-4.

One interesting feature of this potential period is it is nearly 4:1 orbital resonance with the known planet KELT-16 b. Orbital resonances are important in TTV and TDV analysis as they have more powerful gravitational interactions due to regularly repeated close interactions. These close interactions lead to larger TTV and TDV amplitudes making it easier to see the gravitational interactions caused by relatively small planets. Orbital resonances also appear to be common as many compact exoplanetary systems exhibit them.
One famous example is the Trappist 1 planetary system which has 3:2 orbital resonances between planets d and e. Because there are 7 planets gravitationally interacting with one another in this system there are several TTV patterns superimposed on top of one another but the TTV signals on planets d and e are the appear to be the largest out of the 7 planets in the system with amplitudes potentially even greater than 100 minutes seen for each (Wang et al. 2017).

Figure 4-4: Duration vs Julian date plot of the CLEANEST TDV period of 3.899±0.006 days. The red line represents the fit curve of this data set. The fit curve is the mean curve of the phase dataset using a spline interpolation method (Paunzen, & Vanmunster 2016).

4.2.2. WASP-43 b

WASP-43 has a total of 75 transits that had sufficient time resolution to undergo TTV analysis, 74 of which were obtained from the ETD. The O-C plot for WASP-43 can be seen in Figure 4-5.

Peranso period analysis of the O-C data for WASP-43 resulted in 2 periods that had false positive probabilities that fell within the acceptable range, both were generated by the ANOVA method. The better of the two periods is 1.359±0.001 days, with a false positive probability of
0.020±0.010. The second-best signal, on the other hand had a period of 2.027±0.001 days with a false positive probability of 0.075±0.019. Both periods showed among the best sinusoidal patterns out of all three of the planets that underwent TTV analysis. Both phased O-C plots can be seen in Figure 4-6.

Despite extensive examination, no WASP 43 TDV periods were found that were within the acceptable false positive probability range. The best detected signal was a period of 5.616±0.004 from ANOVA with a false positive probability more than twice the acceptable range at 0.426±0.05.

Figure 4-5: The raw O-C plot for WASP-43 b showing the difference between observed midpoint and the calculated midpoint in days vs the Heliocentric Julian date.
4.2.3. WASP-52 b

WASP-52 had a total of 81 transits that had sufficient time resolution for TTV analysis. Of these 81 transits, 80 were obtained from the ETD. My analysis of WASP-52 b’s O-C plot, shown in Figure 4-7, yielded only one TTV period within the acceptable false positive probability range. Using CLEANEST the period is $3.468 \pm 0.001$ days and has a false positive of $0.198 \pm 0.018$ as shown in Figure 4-8.
In addition to the one TTV period that reached the needed threshold one TDV period also met the requirements.

**Figure 4-7:** The unphased O-C chart for WASP-52 b.

**Figure 4-8:** The phased O-C chart for the period of 3.468±0.001 days. The red line represents the fit curve of this data set. The fit curve is the mean curve of the phase dataset using a spline interpolation method (Paunzen, & Vanmunster 2016).
The duration vs Heliocentric Julian date plot for WASP-52 b consists of 77 transits, as some of the light curves were incomplete, making them unusable for TDV analysis. The Duration vs Heliocentric Julian date plot for WASP-52 b can be seen in Figure 4-9.

![Figure 4-9: The Duration vs Heliocentric Julian date plot for WASP-52.](image)

Finally, the TDV analysis of the transits of WASP-52 b revealed one TDV period that had a similar false positive probability as the lone TTV period for WASP-52 b listed above. The TDV period was found using CLEANEST at 5.382±0.002 days with a false positive probability
of 0.198±0.018, shown in Figure 4-10. The overall pattern of this signal is stronger than seen in
the TTV phased O-C diagram and therefore I believe the more likely of the two.

![Figure 4-10: The TDV period estimate of 5.382±0.002 days obtained using CLEANEST for WASP-52. The red line represents the fit curve of this data set. The fit curve is the mean curve of the phase dataset using a spline interpolation method (Paunzen, & Vanmunster 2016).](image)

4.3. Field Variable-Star Period Analysis Results

This section contains the analysis of all 9 field variable stars found while making observations
for my TTV analysis. This includes reanalysis of two previously known variable stars, one star
that has previously been declared a false positive, five new contact binary candidates and one
transit candidate.

4.3.1. V1

Discussed in this section includes the Peranso analysis of both the V-band photometry from
ASAS-SN and my own R-band measurements for V1.
4.3.1.1. **V1 V Band**

V1 had a total of 173 V-band measurements listed for it on ASAS-SN. Each of the previously described period analysis methods were run multiple times, over various period ranges and the results manually inspected. ANOVA and PDM indicated that a period of 0.2739±0.0004 days was the most likely period for this star. Upon manual inspection though it appeared it was combining both the primary and secondary minima into a single event, as seen in Figure 4-11. Further examination with the FALC method presented an alternative period of 0.7544±0.0009 days which presents a more complete light curve which not only shows both minima but also closely matches the ASAS-SN period estimate of 0.7543 days.

![Figure 4-11: shows the folded light curve of V1 with the 0.7544±0.0003-day period estimate from the FALC method.](image)

4.3.1.2. **V1 R Band**

For the R-band analysis of V1, a total of 1110 images were used from the SARA-RM and the BSUO telescopes. From these measurements I estimated the mean apparent R-magnitude to be 14.76±0.02.

The Peranso R-band analysis was completed in several rounds, using both the raw differential photometry flux measurements and the magnitude measurements to find the clearest fit. Manual inspection of the theta values generated from Peranso was necessary as the most
commonly flagged period was 0.38 days and only showed a single minimum. The overall best fit appears as a secondary peak using the ANOVA method at 0.7643±0.0013 days. This phased light curve can be seen in the magnitude-phase plot in Figure 4-12. This period is very close to my estimate of 0.7544 days from the reanalysis of the V-band ASAS-SN data. Because this estimate is made up of significantly more images, and shows cleaner minima I believe this is the correct period for this system.

![Figure 4-12: Shows the folded light curve of the period 0.7643±0.0013 days for the R-band data of V1 using the ANOVA method. It should be noted that the more condensed grouping of data seen in the first minima is due to those observations coming from the single night with SARA-RM which had a much better signal-to-noise-ratio than the observations obtained using BSUO. I believe the gap on the second minima is an indication I am just short of capturing the complete light curve of this system due to its longer period than the other systems.]

4.3.2. V2

Discussed in this section includes the Peranso analysis of both the V-band photometry from ASAS-SN and my own R-band measurements for V2.

4.3.2.1. V2 V band

V2 has 159 measurements listed in the V-band on ASAS-SN. As with V1, each of the previously described period analysis methods were run multiple times, over various period ranges and the results manually inspected. Manual inspection of the phased-light curves was again necessary as the most prominent theta value was for a period which only showed a single
minimum. for example, the peak theta value generated for ANOVA was at a period of 0.3001±0.0004 days.

The analysis with the PDM method provided better period estimates with one being the best obtained during this round of analysis as it had two different periods that appeared to show complete light curves, one with a period of 0.4293±0.0003 days, and a second at a period of 0.8576±0.0004 days. Of these two light curves, shown in Figure 4-13, the second period of 0.8576 days appeared to show a cleaner overall light curve, while the first period of 0.4293 matches closer to the results seen in the R-band analysis, but lacks a clear second minima. It should be noted that both periods differ significantly from the period indicated by the ASAS-SN teams’ analysis at 0.6002 days. I didn’t see a period of 0.60 days for this dataset with any of my analysis the only other periods of note was centered on 0.75 days that was a much weaker signal than both the 0.43-day and 0.86-day periods and a 0.30 day period that only appeared under 1 specific period range examination using the FALC method. It required the search range to be between 0.1 days and 3 days to appear at a high resolution (>2500). The fact this second period is a factor of 2 off from their estimate leads me to believe that it could be an artifact of the timing of their observations since it only appears under one scenario tested.
4.3.2.2. V2 R Band

Because of its smaller field of view the SARA-RM images of the KELT-16 did not include V2. The analysis was based on the 594 R-band images obtained with BSUO. From these 594 images the mean R-magnitude was found to be 14.08±0.02.

The same methodology used in the R-band analysis of V1 was also used here examining both the flux and magnitude measurements in Peranso. Using the ANOVA method from Peranso provided a period estimate of 0.4388±0.0005 days. This period estimate matches up fairly well with the shorter of the two period estimates obtained from the reanalysis of the ASAS-SN V-band photometry. Because of the similarity between the two periods, I believe the closest period for this system is near 0.43 days. More specifically because the R-band analysis involved a larger dataset, with a much clearer secondary minima, as seen in Figure 4-14, I believe the R-band estimate is the closest to the true period of the system.

Figure 4-14: shows the ANOVA method folded light curve of the period 0.4388±0.0005 days for V2.
4.3.3. New Field Variable Star Candidates

<table>
<thead>
<tr>
<th>2MASS designation</th>
<th>My Designation</th>
<th>RA (h,m,s) Gaia</th>
<th>DEC (°,',&quot;) Gaia</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MASS J20564622+3138394</td>
<td>V3</td>
<td>20:56:46.1</td>
<td>+31:38:38.4</td>
</tr>
<tr>
<td>2MASS J20560314+3145505</td>
<td>V4</td>
<td>20:56:03.3</td>
<td>+31:45:50.4</td>
</tr>
<tr>
<td>2MASS J20573379+3146126</td>
<td>V5</td>
<td>20:57:33.8</td>
<td>+31:46:12.0</td>
</tr>
<tr>
<td>2MASS J20562743+3153225</td>
<td>V6</td>
<td>20:56:27.4</td>
<td>+31:53:24.0</td>
</tr>
<tr>
<td>2MASS J20565617+3131253</td>
<td>V7</td>
<td>20:56:56.1</td>
<td>+31:31:26.4</td>
</tr>
</tbody>
</table>

*Table 4-4 contains information on each of the five candidate variable stars discovered in this work. Including their other designations, RA and DEC.*

*Figure 4-15: Marks the positions of the 5 new Variable Star candidates on the night of 8/4/2019 taken with the BSUO telescope. 2MASS J20564622+3138394 is marked as V3, 2MASS J20560314+3145505 is marked as V4, 2MASS J20573379+3146126 is marked as V5, 2MASS J20562743+3153225 is marked as V6, and 2MASS J20565617+3131253 is marked as V7.*
4.3.4. **V3**

2MASS J20564622+3138394, called V3 in this thesis, was near enough to KELT-16 that it was visible in the observations from both SARA-RM and the BSUO telescope, putting the number of R-band measurements available for its analysis at 1110. From these measurements I found that the mean apparent R-magnitude of V3 is 14.0±0.02.

Using the ANOVA method, the best period estimate is at a period of 0.3465±0.0005 days, as seen in Figure 4-16.

![Figure 4-16: Shows the folded light curve of the R-band data of V3 for a period of 0.3465±0.0005 days. The darker region in the first minima is due to SARA-RM observations having a better SNR and so a smaller scatter in the datapoints.](image)

4.3.5. **V4**

The remaining 4 variable star candidates to be discussed are located outside the field of the SARA-RM images. As such 2MASS J20560314+3145505, called V4, only appeared in the larger field of view offered by the BSUO telescope, leaving us with 594 R-band images. This star was much fainter than the previous three stars discussed having a R-band magnitude estimate of 17.08±0.02.

Because the star is so faint the analysis was completed using a flux-phase plot instead of magnitude-phase. The period found by the ANOVA method was 0.3022±0.0006 days as seen in Figure 4-17.
Figure 4-17: Shows the folded light curve of the R-band data of V4 for a period of 0.3022±0.0006 days.

4.3.6. V5

As with V4, the only observations made for 2MASS J20573379+3146126, called V5, were at BSUO. The star’s mean R-magnitude over the course of our observations was found to be 16.41±0.02.

Although it is half a magnitude brighter than the star V4, it was still faint enough that I needed to examine the flux-phase plot instead of the magnitude-phase plot, as seen in Figure 4-18. The estimated period is 0.5403±0.0001 days found using the ANOVA method.

Figure 4-18: Shows the folded light curve of the R-band data of V5 for a period of 0.5403±0.0001 days.
4.3.7. V6

I estimated that 2MASS J20562743+3153225, called V6, has a mean R-magnitude 16.93±0.02. As with the previous two stars the Peranso examination was completed using fluxes instead of magnitudes, as seen in Figure 4-19. This analysis yields a period estimate of 0.2981±0.0004 days using the PDM method.

![Figure 4-19: Shows the folded light curve of the R-band data of V6 for a period of 0.2981±0.0004 days](image)

4.3.8. V7

I estimated 2MASS J20565617+3131253, called V7, has a mean apparent R-magnitude of 17.69±0.02, which makes it the faintest variable star candidate I’ve found in this search by over half a magnitude. Because it is so faint, I am only able to determine that V7 is likely a variable star, though I am less certain of its variability type. Figure 4-20 shows a sinusoidal pattern similar to the other candidate variable stars, though with a much lower signal-to-noise ratio due to how faint the star is. It is possible that this is another contact binary star.
4.3.9. Combined KELT-16 Field Contact Binary Results

Tables 4-5 contains the compiled period and magnitude estimates for each of the variable stars in the field. The R-band images for this analysis coming from my own observations, while the V-band analysis was completed using data listed on the ASAS-SN database. It should be noted that EW stands for the contact binary star classification.

Table 4-5: Combined results for the KELT-16 field variable stars.

<table>
<thead>
<tr>
<th>Designation</th>
<th>R-Band Apparent Magnitude</th>
<th>V-Band Period (Days)</th>
<th>R-Band Period (Days)</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>ASASSN-V J205658.12 +314215.9</td>
<td>14.764 ±0.020</td>
<td>0.7544 ±0.0009</td>
<td>0.7643 ±0.0013</td>
</tr>
<tr>
<td>V2</td>
<td>ASASSN-V J205552.88 +314615.9</td>
<td>14.075 ±0.020</td>
<td>0.8576 ±0.0004</td>
<td>0.4388 ±0.0005</td>
</tr>
<tr>
<td>V3</td>
<td>2MASS J20564622 +3138394</td>
<td>14.003 ±0.020</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V4</td>
<td>2MASS J20560314 +3145505</td>
<td>17.075 ±0.024</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V5</td>
<td>2MASS J20560314 +3145505</td>
<td>16.412 ±0.021</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V6</td>
<td>2MASS J20573379 +3146126</td>
<td>16.940 ±0.024</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V7</td>
<td>2MASS J20565617 +3131253</td>
<td>17.690 ±0.038</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.3.10. WASP 121 Field Variable Candidate

In addition to the seven contact binary candidates in the KELT-16 field, there was one other variable candidate found during my TTV observations, in the field near WASP-121. The star was
listed as a false positive in the ASAS-SN database, under the designation AP44024420, but with my observations I believe it is actually a variable star, Figure 4-21. Unfortunately, I do not have enough observations of the object to perform a period analysis. More information about this system can be found in Table 4-6.

Figure 4-21: The leftmost image is a finding chart for HD 55273 the candidate variable star in the field near WASP-121. The rightmost image shows an AIJ generated light curve of the star HD 55273 and the comparison stars used.

<table>
<thead>
<tr>
<th>Designation</th>
<th>ASAS-SN Designation</th>
<th>RA (h.m.s)</th>
<th>DEC (°,′,″)</th>
</tr>
</thead>
</table>

Table 4-6: Designation and Location of the possible variable star in the WASP-121 b field.

4.3.11. Possible Exoplanet Transit

In addition to the new variable star candidates listed above, there was one additional object of interest found. On the night of 6/7/2019 (UT) one other star in the field near Kelt-16 exhibited a variation in brightness. The location of this star is marked in Figure 4-22. Table 4-7 contains some of the previously known information about the star mostly from the GAIA catalog.
Upon discovering this variation, I examined the 5 nights of observations from BSUO but out of the 6 nights of observations this is the only set of observations in which the star dims. As with the other variable star candidates discussed in the previous sections, I examined the region on the charge-coupled device (CCD) chip near the star’s path, and was able to rule out bad columns or other CCD artifacts affecting our light curve. The examination was completed using both AstroImageJ and VaST.

The shape of the light curve seen in Figure 4-23, suggests the cause for this variation could be a transit of a second body.

If this is indeed a transit, I captured the ingress phase and an addition 100 minutes until the observations were cut short by the approaching dawn. No egress was seen. Based on my observations I have been able to estimate the star’s apparent R-magnitude is 13.58±0.02.

<table>
<thead>
<tr>
<th>Gaia designation</th>
<th>RA (h,m,s)</th>
<th>DEC (º,º,’’)</th>
<th>Parallax (mas) Gaia</th>
<th>Distance (pc)</th>
<th>Temperature K (Gaia)</th>
<th>Radius (R$_{\text{sol}}$) (Gaia)</th>
<th>Luminosity (L$_{\text{sol}}$) (Gaia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaia DR2 186488369 9097368448</td>
<td>20:56:45.6</td>
<td>+31:37:01.2</td>
<td>0.965±0.018</td>
<td>1036.4$^{+19.3}_{-18.6}$</td>
<td>622.4$^{+53}_{-23}$</td>
<td>1.480$^{+0.117}_{-0.030}$</td>
<td>2.962 ±0.153</td>
</tr>
</tbody>
</table>

*Table 4-7: GAIA information on the potential exoplanet host star. (IRSA, GAIA Collaboration 2018)*
Figure 4-22: Shows the location of the additional candidate variable star on the SARA-RM CCD chip.

Figure 4-23: Shows the comparison of the light curve from GAIA DR2-1864883699097368448 and the first 8 of the 15 comparison stars used to obtain these light curves. Binning is set to 2 on AIJ for this plot. As can be seen there is a clear linear trend to all of the stars in this image, which had to be removed to get an accurate measure of the depth seen in the light curve of the target star.
4.3.11.1. Transit Candidate Characteristics

As with the known exoplanets I observed from the TTV portion of my thesis, I was able to estimate the radius of the star using Method 1 along with the SMA and period estimation methods previously discussed.

<table>
<thead>
<tr>
<th>Planet</th>
<th>Date Observed (UT)</th>
<th>Rp/R* Fraction</th>
<th>Planetary Radius ($R_j$) Method 1</th>
<th>Planetary Semi-major Axis (AU)</th>
<th>Planetary Period (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit Candidate</td>
<td>6/7/2019</td>
<td>0.202 ±0.008</td>
<td>2.979 +0.349 -0.089</td>
<td>0.056 +0.004 -0.001</td>
<td>4.17 ±0.34 -0.95</td>
</tr>
</tbody>
</table>

*Table 4-8: Estimates of the observables of the transit candidate.*

One possible explanation for the light curve is a planetary transit as the initial ingress looked very similar to the exoplanet transits I observed for my TTV analysis. But with this estimated radius nearly three times that of Jupiter, it would likely be among the largest of the bloated Hot Jupiter planets discovered; to date only one other is currently listed larger than this estimate. Alternatively, this transit may have been caused by a stellar mass companion instead which would better explain the radius estimate obtained. If this turns out to be a stellar mass companion the period and SMA estimates would need to be updated as they were generated with the assumption that the mass of the primary was much larger than the transiting body.

4.4. 47-Tucanae Results

Tables (4-9-4-13) list the variable stars found in 47-Tucanae. In this table the RA and DEC values are given in equinox J2000.0 equatorial coordinates, and the period estimate is given in days. The three columns titled “Lebzelter and Wood (2005)”, “Weldrake et al. (2004)”, and “Kaluzny et al. (2013)” describes which paper any previously known variable stars were listed in. The index in these columns are the identifiers used in those papers for a given star. Figures
show the finding charts for these variable stars. Light curves of these stars are given in Appendix C.

In total there were 125 possible variable stars in my field out of the over 3000 light curves generated by running the five useable nights of data in a single run with the ISIS program. This includes 37 long period variable star candidates (greater than 5 days), 85 short period candidates (less than 1 day) and 3 stars I have listed in an “Other” category due to their overall strange light curves.

Included in the 85 potential short period candidates are 10 short period candidates that appear to have two different ISIS detections from the same star. The light curve from each detection appears to mirror the other and so it is likely that they are false positives, though they are still being included in the overall count, shown in Table 4-9.

Due to a somewhat worse FWHM during the night of 7/4/2017 than the other four nights, some of the smaller amplitude variable candidates I’m less certain that the July night can be used for the variable candidates with smaller total variations. In many cases it appears that the larger FWHM affected the PSF tracking component of ISIS. This led me to only use four of the five nights in my analysis of many of the smaller amplitude candidate variable stars.

These detections include 27 out of the 34 variables stars listed in Lebzelter and Wood (2005) that fall within my field, and 2 others potential matches to stars listed in their paper, just in slightly different locations (under 5 arcseconds). In the cases of the two possible matches I believe they are the stars listed in Lebzelter and Wood (2005) as they are the closest stars to the coordinates listed in their paper. I also detected one out of the five possible variable stars from Weldrake et al. (2004), and had one other that was a similar case to the two possible matches for Lebzelter and Wood (2005) where my candidate was the closest star to matching the position.
listed in Weldrake’s paper. Finally, I detected one additional variable star listed in Kaluzny et al. (2013), that was not already listed in the 2 previously mentioned papers.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
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*Table 4-9: The known long period variables and new variable candidates in 47-Tucanae*
Of the 37 long period variable stars I detected 14 that appear to be newly discovered long period variable star candidates as they have not appeared in any variable star catalogs examined. Unfortunately, I did not have enough nights to better characterize these systems as half of my nights would not run using ISIS due to having too large of FWHM.

Out of these six matched stars, four appear to show different periods than are listed in their respective papers, with two of the three possible matches also show period discrepancies. The literature periods for each of these stars are between 39 days and 221 days with several having comments noting an even longer second period may also be present. For comparison my period estimates for these stars are between 0.3326 days up to 0.6603 days. Three of these I saw little to no evidence for long term variations while the other three, GC-1, GC-62, and GC-106 appeared to show evidence of both long term and short-term variation in my dataset. The light curves of each of these stars can be seen in Appendix C.
Figure 4-24: A finding chart for the long period variable star candidates. Dark Blue is a variable star that matches one of the three referenced papers, Purple is a new long period variable star candidate, and orange are stars who were listed as long period variable stars but, in my analysis, I only saw short periods.
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<tr>
<td>GC-145</td>
<td>23:53.4</td>
<td>-72:05:08.77</td>
<td>CLEANEST</td>
<td>0.3115</td>
<td>±0.0006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GC-147</td>
<td>24:11.4</td>
<td>-72:05:02.13</td>
<td>CLEANEST</td>
<td>0.4182</td>
<td>±0.0010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GC-153</td>
<td>23:36.4</td>
<td>-72:04:47.50</td>
<td>PDM</td>
<td>0.3572</td>
<td>±0.0011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GC-154</td>
<td>23:26.5</td>
<td>-72:04:43.14</td>
<td>Anova, PDM &amp; CLEANEST</td>
<td>0.4527</td>
<td>±0.0006</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4-11: 69 Short period variable star candidates in 47-Tucanae and short period variable stars that have previously appeared in the literature. * indicates that the overall variation is below the level generally used as a criterion, but was included anyway due to a good overall light curve. Candidate GC-46 appears that it could show both short period and long period variability.

It should also be noted that there are several periods that appear multiple times throughout my data set, they general fall into 5 groupings, centered on 0.311 days (4 stars), 0.332 days (10 stars), 0.357 days (15 stars), 0.414 days (10 stars), 0.452 days (15 stars), each within 0.001 days of the periods listed, and totaling 54 of my 126 candidates. Hettinger (2018) noted a similar issue with 10 RR-Lyrae candidates sharing the same period and attributed it to potential subtraction issues in the dense inner region of the globular cluster he was examining. In my images the issues extend across the entire CCD chip, and unlike in his case my stars show two different patterns, they either tend to increase or decrease. One other thing to note is these short period variable star candidates are clustered more to one side of the CCD chip than the other, the same side that had a dead column running down pixels 574-580 in the x direction, it’s possible that there could be a difference in detection of the CCD chip on either side of this dead column. Another reason for concern for many of these candidates is there are relatively few that show variation in both directions, generally if they are decreasing that is the only direction seen. The same is true for stars that appear to be increasing throughout a night they will only increase and there are few images showing the brightness transitioning downwards again.

For the previously known short period variable and the other likely match for a previously known short period variable, my period estimates closely match the literature values for both GC-21, 0.737 days (Kaluzny et al. 2013) vs 0.7370±0.0026 days and GC-128 and 0.3136 days (Weldrake et al. 2004) vs 0.3112±0.0003 with both being withing 0.025 days of these literature estimates.
Finally, many of the “short” period variable star candidates also appear that they may have an additional long-term trend to them as well. But because of the larger FWHM seen in the July observations it is difficult to determine if that is a true trend or an effect from the larger FWHM. Because of this many of the short period candidates were run with five nights and four nights and then compared to see which had the smoothest period estimate. The fifth night was included if it appeared to help the period estimate or at a minimum returned the same period result as the four-night run.

<table>
<thead>
<tr>
<th>Others</th>
<th>RA (h:m:s)</th>
<th>DEC (°:′:″)</th>
<th>Peranso Period Method</th>
<th>Peranso Period Estimate (Days)</th>
<th>Period Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC-98</td>
<td>23:59.6</td>
<td>-72:01:51.31</td>
<td>CLEANEST</td>
<td>0.8701</td>
<td>±0.0044</td>
</tr>
<tr>
<td>GC-129</td>
<td>24:05.1</td>
<td>-72:00:03.29</td>
<td>CLEANEST</td>
<td>0.3111</td>
<td>±0.0004</td>
</tr>
<tr>
<td>GC-144</td>
<td>00:24:07.85</td>
<td>-72:05:20.6</td>
<td>CLEANEST</td>
<td>0.5672</td>
<td>±0.0029</td>
</tr>
</tbody>
</table>

*Table 4-12: 47-Tucanae variable star candidates with unusual light curves.*

In addition to the more normal light curves there were three that stood out as somewhat strange, GC-98, GC-129, and GC-144, examples of each candidate’s light curve can be seen in Appendix C. GC-129 could be the result of a star being too close to the edge of the CCD chip as the same pattern appears all 4 of the nights examined.
<table>
<thead>
<tr>
<th>Possible False Positives</th>
<th>RA (h:m:s)</th>
<th>DEC (°:'&quot;)</th>
<th>Peranso Period Method</th>
<th>Peranso Period Estimate (Days)</th>
<th>Period Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC--6</td>
<td>00 23 26.84</td>
<td>-72 08 45.49</td>
<td>CLEANEST</td>
<td>0.4524</td>
<td>±0.0005</td>
</tr>
<tr>
<td>GC--7</td>
<td>00 23 26.69</td>
<td>-72 08 45.41</td>
<td>CLEANEST</td>
<td>0.3328</td>
<td>±0.0007</td>
</tr>
<tr>
<td>GC--45</td>
<td>00 24 22.05</td>
<td>-72 04 26.88</td>
<td>CLEANEST</td>
<td>0.5809</td>
<td>±0.0017</td>
</tr>
<tr>
<td>GC--46</td>
<td>00 24 21.71</td>
<td>-72 04 25.02</td>
<td>CLEANEST</td>
<td>0.5323</td>
<td>±0.0007</td>
</tr>
<tr>
<td>GC--70</td>
<td>00 24 49.24</td>
<td>-72 03 13.28</td>
<td>CLEANEST</td>
<td>0.4139</td>
<td>±0.0010</td>
</tr>
<tr>
<td>GC--74</td>
<td>00 24 48.79</td>
<td>-72 03 10.27</td>
<td>PDM</td>
<td>0.4524</td>
<td>±0.0005</td>
</tr>
<tr>
<td>GC--113</td>
<td>00 23 22.73</td>
<td>-72 01 03.84</td>
<td>CLEANEST</td>
<td>0.4523</td>
<td>±0.0007</td>
</tr>
<tr>
<td>GC--114</td>
<td>00 23 23.10</td>
<td>-72 01 02.74</td>
<td>PDM &amp; CLEANEST</td>
<td>0.3568</td>
<td>±0.0007</td>
</tr>
<tr>
<td>GC--133</td>
<td>00 24 36.47</td>
<td>-72 05 39.21</td>
<td>PDM &amp; CLEANEST</td>
<td>0.6672</td>
<td>±0.0026</td>
</tr>
<tr>
<td>GC--134</td>
<td>00 24 36.82</td>
<td>-72 05 37.61</td>
<td>CLEANEST</td>
<td>0.5579</td>
<td>±0.0018</td>
</tr>
</tbody>
</table>

*Table 4-13: Potential false positives due to light curve mirroring*

Each of these 10 candidates appear to come from opposite ends of the same stellar PSF usually with total level of variation, opposite direction, and in each case the best period seen by each member of the pair showed up as one of the top few periods in Peranso.
Figure 4-25: The finding chart for the short period variable star candidates. Red indicates a short period variable star candidate, green indicates a possible false positive due to a mirroring effect between two detections on the same disc, and light blue are “Other” light curves.
5. Conclusions

I have presented R-band photometry of seven transiting exoplanets, providing estimates of their radius, orbital period, and semi-major axis. With the observations of KELT-16, WASP-43 and WASP-52 I was able to perform TTV and TDV analysis with Peranso looking for signs of gravitational interactions with unseen planets in each of these systems with potential TTV signals possible from both KELT-16 and WASP-43 and a possible TDV signal from WASP-52. These observations also yielded five new contact binary systems in the field around KELT-16 for which I was able to perform period analysis with Peranso along with two other previously discovered contact binary systems in this field. Additionally, I was able to provide evidence for a transit of either a bloated Hot Jupiter or a small stellar companion around another field star near KELT-16 and evidence that a previously declared false positive is actually a variable star in the field near WASP-121.

I also have presented R-band photometry and analysis with ISIS of the inner region of the globular cluster 47-Tucanae and detailed the discovery of 13 new long period variable star candidates and 70 possible new short period variable star candidates, along with 13 other short period candidates of lesser quality. New periods were also assigned to six previously discovered variable stars that had been believed to be long period variables but, in my data, they showed short period variability instead. Additional observations may be necessary to verify whether these are long or short period variables. Additional study of the 54 short period variable candidates that fall within five narrow period ranges discussed is also necessary to confirm whether they are the result of a systematic error in the analysis process or not. If the short period variables are confirmed an additional step could be taken to verify the types of variables present. Many of the short period variable candidates fall within the range expected for RR Lyrae.
variables and so could be used to better constrain the distance to 47-Tucanae. Additional observations could also help better constrain the periods of the long-period variable candidates.
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Valdes, Francisco, 1987, The IRAF CCD Reduction Package – CCDRED,


Appendix A

Exoplanet Transit Light Curves

Transit light curves of WASP-52 b and K2-22 b using AstroImageJ. The host star light curve is shown in blue in each image while the other colors below are the comparison stars used.
Transit light curves of WASP-121 b and KPS-1 b using AstroImageJ. The host star light curve is shown in blue in each image while the other colors below are the comparison stars used.
Transit light curves of HATS-24 b using AstroImageJ. The host star light curve is shown in blue in each image while the other colors below are the comparison stars used.
Transit light curves of HATS-24 b and WASP-43 b using AstroImageJ. The host star light curve is shown in blue in each image while the other colors below are the comparison stars used.
Transit light curves of KELT-16 b using AstroImageJ. The host star light curve is shown in blue in each image while the other colors below are the comparison stars used.
Transit light curves of KELT-16 b using AstroImageJ. The host star light curve is shown in blue in each image while the other colors below are the comparison stars used.
Transit light curve of KELT-16 b using AstroImageJ. The host star light curve is shown in blue in each image while the other colors below are the comparison stars used.
Appendix B
Python Plotting Code: plot_lc_PC.py from Dr. Brian Murphy, Butler University via Hettinger (2018)

#!/usr/bin/env python

import pylab
from pylab import *
from matplotlib import *
import numpy as np

#copy to directory with all lc.dat files
#will create all plots in ./lightcurves/

import matplotlib as mpl
import os
import numpy as np
import matplotlib.pyplot as mplplt

#create list of all created lc's
os.system('mkdir lightcurves2')
os.system('ls lc*.data > plot_list.tmp')

plot_list_tmp = open('plot_list.tmp', 'r')

plot=False #boolean to determine whether first plot is finished (used to invert axis)

phot_data_xpix, phot_data_ypix = np.loadtxt ('phot.data', usecols=(0,1), unpack=True) #loads pixel coordinates for each lc*.data

lc_number = 0

for line in plot_list_tmp:
    current_lc_dat = "lc"+str(lc_number)+".data"

    jd, rel_flux, check_rel_flux, col_4, col_5, col_6 = np.loadtxt ('./'+current_lc_dat, unpack=True) #loads pixel coordinates for each lc*.data

    print (lc_number, current_lc_dat, phot_data_xpix[lc_number], phot_data_ypix[lc_number])
mplplt.scatter (jd, rel_flux, c='b', marker='o')
mplplt.xlabel ('JD')
mplplt.ylabel ('Relative Flux')

mplplt.title (current_lc_dat+"\nx, y: "+str(round(phot_data_xpix[lc_number],1))+", "+str(round(phot_data_ypix[lc_number],1))))

if plot==False:     #inverts y-axis for first plot (or else will continue flipping)
    oldymin, oldymax = mplplt ylim()
    mplplt ylim (oldymax, oldymin)
    plot=True
mplplt.savefig('lightcurves2/"+current_lc_dat+.png")

mplplt.cla() #clears axis for next plot

lc_number=lc_number+1

plot_list_tmp.close()
Appendix C

47-Tucanae Variable Star Candidate Light Curves
Unphased light curves of previously known long period variable stars in order of decreasing declination

Light curves of known long period variable stars in 47-Tucanae made using Peranso. These light curves show flux vs Heliocentric Julian Date.
Light curves of known long period variable stars in 47-Tucanae made using Peranso. These light curves show flux vs Heliocentric Julian Date.
Light curves of known long period variable stars in 47-Tucanae made using Peranso. These light curves show flux vs Heliocentric Julian Date.
Light curves of known long period variable stars in 47-Tucanae made using Peranso. These light curves show flux vs Heliocentric Julian Date.
Unphased light curves for my new long period variable star candidates in order of decreasing declination.

Light curves of new long period variable stars candidates in 47-Tucanae made using Peranso. These light curves show flux vs Heliocentric Julian Date.
Light curves of new long period variable stars candidates in 47-Tucanae made using Peranso. These light curves show flux vs Heliocentric Julian Date. The bad column affected GC-50’s light curve, the effects of the column can be seen on the second night of images with the measurements varying widely throughout that night for this star.
Unphased and phased light curves for previously known long-period variable star candidates that I believe show short period variability in my observations in order of decreasing declination.

Light curves of previously known long period variable stars candidates in 47-Tucanae that showed short period variations in my data, made using Peranso. These light curves show flux vs Heliocentric Julian Date. GC-1 appears that it could be either a long period or short period variable. Because the light curve formed matches many of the short period variables it was included in this section.
Light curves of previously known long period variable stars candidates in 47-Tucanae that showed short period variations in my data, made using Peranso. These light curves show flux vs Heliocentric Julian Date.
Unphased and phased light curves for short variable star candidates in order of decreasing declination

Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curve.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curve. GC-21 represents a previously known short period variable star in this field.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curve.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curve.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curve. GC-46 could show either long or short period variations, or even both. I included it in the short period variable section because the folded light curve it resembles many of the short period variables.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curve.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curve.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curves.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curves.

*GC-79 falls short of the variation amount criteria discussed but because there appeared to be a clear variation to its unphased light curve it was included.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curves.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curves.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curves.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curves. *GC-104 is another case where the overall variation level is below the value used as a criterion but included anyway because it appears it is likely varying.
Light curves short period variable stars candidates in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curves.
Other interesting light curves, both phased and unphased in order of decreasing declination

Unusual light curves from stars in 47-Tucanae made using Peranso. The left images show the flux measurements vs Heliocentric Julian Date. The right images show the folded light curves. GC-129 shows an extra light curve so its folded light curve is seen on the next line. The image to the right of the observations for GC-129 is a zoomed in version showing all 4 nights separately.
Potential false positive candidates where the two candidates both appear confined to the same PSF and show opposite variation and nearly the same best period.

Shows the detections that appear to come from the same PSF. Each image shows a flux vs Heliocentric Julian date plot.
Shows the detections that appear to come from the same PSF. Each image shows a flux vs Heliocentric Julian date plot.