Characterizing the Interactions Between Bodies in Exoplanetary Systems

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Physics

By

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ABSTRACT

Characterizing the Interactions Between Bodies in Exoplanetary Systems

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Since the confirmed discoveries of exoplanets orbiting main sequence stars in the late Twentieth Century, the number of exoplanets being discovered has exponentially increased. The properties of these exoplanetary systems vary greatly across their full population. In the present work, two studies have been undertaken to characterize exoplanetary systems through the nature of the interactions between the bodies in these systems. The first study looks at a sub sample of the transiting exoplanet population for trends based on the exoplanet’s Safronov number. No trends in this subsample were found for Safronov numbers calculated for circular orbits nor the eccentric orbits of the planets. The second study investigates interactions between exoplanets and their host stars. Phase resolved observations were conducted for seven stars hosting planets with eccentric orbits to search for modulations in their Ca II H & K (3933.662 Å, 3948.462 Å), Hα (6562.80 Å), and Ca II IRT line at 8662.14 Å; to search for evidence of star-planet interactions. Two of the systems, HD 156279 and HD 118203, show evidence of emission in the core of the Ca II K line and an emerging pattern of activity is seen for the exoplanetary system with the best phase coverage, HAT-P-2. However, no conclusive determination of star-planet interactions can be drawn from these observations thus necessitating follow-up observations to better characterize the nature of star-planet interactions in exoplanetary systems harboring Hot Jupiters in highly elliptic orbits.
Chapter 1

Introduction

1.1 Exoplanetary Systems and Methods of Detection

Exoplanets are celestial bodies similar to the planets found within our Solar System but located orbiting stars outside of our system’s boundaries. In 2006 the International Astronomical Union (IAU) voted to approve resolution 5A subsequently defining a planet located within our Solar System in the following way (1):

A “planet”\(^1\) is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.

While exoplanets are not explicitly defined by the IAU, they can be considered to be celestial bodies meeting criterion (b) above. Criterion (a) and (c) are not considered due to the discovery of “free-floating” planets or planets that are not orbiting a star. An exoplanetary system consists of a celestial body meeting criterion (b) that is in orbit around a stellar body other than the Sun.

The study and detection of exoplanets is a relatively new field. The first planet found orbiting a star other than the Sun, HD 114762 b, was initially miscategorised by its discoverers as a Brown Dwarf (2). In 1992, three years after the detection of HD 114762 b, the first exoplanetary system was discovered around pulsar PSR 1257 + 12 (3). However, the first immediately accepted discovery of an exoplanet around a main

\(^1\) The eight planets located in our Solar System are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.
sequence star, Peg 51 b, was made by Michel Mayor and Didier Queloz in 1995 (4). The discovery of Peg 51 b, a Jupiter mass planet orbiting a star similar to our Sun ignited the field of exoplanetary sciences with teams of astrophysicists developing new techniques to discover exoplanets and searching for evidence of them in ever enlarging swaths of the night sky. As a result, the number of confirmed exoplanet detections has exponential increased. The Exoplanet Encyclopedia lists 1039 confirmed exoplanet detections as of 04 November 2013 (5). The number of exoplanets detected per year by their detection method is shown in Figure 1.1. The most common techniques for detecting exoplanets are discussed in the following two sections.

![Figure 1.1: The number of exoplanets discovered per year since the first discovery of an exoplanet in 1989. The colors correspond to the number of exoplanets discovered with the main five detection methods in a given year. [Figure from (6)]](figure.png)
1.2 Spectroscopy

Electromagnetic radiation is emitted from stars and can be dispersed into various wavelengths (long to short) associated with specific energies (low to high) of the radiation known as a spectrum. The study of the various spectra of electromagnetic radiation is known as spectroscopy. Visible light (3000 Å – 7000 Å, 3 eV – 2 eV) is commonly studied for spectral classification purposes.

1.2.1 Spectroscopic lines

 Electromagnetic radiation emitted from a blackbody can be dispersed into a continuous spectrum. Stars and their intrinsic processes can be classified by this spectrum and the atomic processes associated with it. For instance, when an electron transitions from an excited orbit to one requiring less energy, it will emit a photon, or quantized light containing the energy difference between the two orbits, that will show up as a line at the wavelength in the spectrum associated with that energy. This is known as an emission line and can add to the intensity or an increase in the amount of flux detected in for a specific wavelength in a spectrum. Similarly, if the electromagnetic radiation is incident upon an atom and causes an electron to transition from a low energy orbit to a higher one, the electron will absorb the photon associated with the energy difference between the two orbits and a dark line will show up at the wavelength associated with this energy in the electromagnetic spectrum. The analysis of these dark lines, or absorption lines, is the most common method of spectral classification. Each wavelength in the electromagnetic spectrum is unique to a transition between orbits in the atom of a
specific element. Therefore, by analyzing the absorption lines in a stellar spectrum its composition can be found.

Stellar activity can be analyzed through studying specific wavelengths. For instance, the strength of a star’s magnetic field may be characterized by the equivalent width of the 8542 Å absorption line known to be part of the Calcium II Infrared Triplet (Ca II IRT).

Figure 1.2: (a) The normalized flux of star HD 37605 showing the absorption lines for Ca II K (3933.663 Å) and Ca II H (3968.468 Å). The continuum is the region around the absorption lines and represents the stellar photosphere. The depth of the lines scales with height above the stellar photosphere until the vertex of each absorption line is reached. This is the spectral line core and gives a measurement of the flux from the stellar chromosphere. The spectra above show a modulation in the Ca II K line core when its planet is at an orbital phase of 0.12 compared when the planet is at an orbital phase of 0.01. This emission in the absorption line core is being investigated as evidence of star-planet interactions.
The activity at different heights in a star’s chromosphere is generally studied by looking at the “chromospheric activity indicators” or the Ca II H & K (middle chromosphere, 3968.462 Å and 3933.663 Å), Hydrogen Alpha or Hα (6562.80 Å), and the Ca II IRT 8662.80 (lower chromosphere) spectral lines. Stellar activity is characterized by the S-index or the ratio of flux at the emission cores of the Ca II H & K lines (chromosphere) to the flux at two points in the continuum (photosphere). Activity within the chromosphere can be characterized by determining the star’s log RHK which only utilizes the ratio of the flux in the emission cores of Ca II H & K. Figure 1.2 shows the Ca II H & K absorption lines with emission in their core for the star HD 37605.

1.2.2 Radial Velocity Method

The radial velocity method is thus far the most successful method of detecting planets. Of the 1039 planet detections listed in the Exoplanet Encyclopedia, 533 of these were detected with the radial velocity method. This planet detection technique utilizes the Doppler shifting of the host star’s spectral lines resulting from the star’s orbit around a common barycentre with the planets in its system to detect the radial velocity of the host star through:

\[
\Delta \lambda \over \lambda = \frac{v_r}{c}
\]

where \(\Delta \lambda\) is the shift in a specified wavelength, \(\lambda\) is the lab measured wavelength of the spectral line, \(v_r\) is the radial velocity of the star, and \(c\) is the speed of light. The expected reflex velocity of the planet on its host star ranges from 1 – 10 meters per second depending on the mass of the planet and the semi-major axis of its orbit (7). The radial
velocity method relays information on the period and eccentricity of the exoplanet’s orbit, in addition to the exoplanet’s msini or its mass multiplied by the sine of the angle the orbit is inclined to the normal of the observer’s reference plane (ie. msini ~1 for edge on orbits). Figure 1.3 shows the radial velocity curves for two planets with different orbital eccentricities.

Figure 1.3: (a) The phase folded radial velocity curve for 51 Peg (eccentricity = 0.013) from the observations of Marcy and Butler. (b) The same for HD 156279, which hosts a 9.71 M_{Jup} planet in a 0.708 eccentricity orbit. [Figures from (8) and (9) respectively]

1.3 Photometry

Photometry is the process where the intensity, or brightness, of an object is measured. In astronomy, photometry is used to measure the intensity of the light emitted from a star that is incident on a detector or it is used to measure stellar flux.
Figure 1.4: Transit light curves like the one above for HAT-P-7 depict information about the exoplanet’s orbit but also convey information about the host stars activity through variations in the flux between transits. This can be analyzed for modulations that are in phase with the planet’s orbits. The above transit light curve for HAT-P-7 was constructed from short cadence data obtained during Quarter 2 of the Kepler Space Telescope’s observing cycle.

1.3.1 Light Curves

When a temporal sequence of photometric measurements is plotted with intensity on one axis and time on the other, a light curve is made. Light curves like the one shown in Figure 1.4 can reveal information about stellar activity such as it’s type, magnitude, and period. However, light curves like the one in Figure 1.5 reveal information about the star and the variability of its flux. These light curves help determine information about the star such as its variability class and rotation period. This information can be used to better constrain the exoplanet properties derived with transit photometry.
Figure 1.5: Light curves can give a visual representation of the variability of the star. Analyses of these light curves can reveal information about the properties of the star. The above light curve for KIC 3459297 shows the modulation of different frequencies of oscillations over Kepler Quarters 0-5. The colors identify the data with specific quarters. [Figure from (10)]

1.3.2 Transit Photometry

Figure 1.6: Transit light curves are used for calculating the radii of exoplanets and reveal valuable information about the planet’s orbit. [Figure from (11)]

For exoplanetary systems where an exoplanet crosses our line of sight with its host star, there is a decrease in the incident flux from the host star. This type of study is known as transit photometry and is used for discovering exoplanets. This method of
detection allows properties of the planet, such as its radius (See Figure 1.6), and its orbit to be calculated. The decrease in flux is an areal relationship with the planet’s flux and can be calculated from

$$\Delta F \approx \left( \frac{R_p}{R_*} \right)^2$$

where $\Delta F$ is the transit depth or change in flux as the planet crosses the line of sight with the star, $R_p$ is the exoplanet’s radius, and $R_*$ is the radius of the host star. The exoplanets’ orbital period can be determined from finding the time between the mid-transit points (See Figure 1.4). When this is paired with mass and orbital eccentricity measurements from radial velocity studies, the fundamental parameters of the system are known; thus leading to a better overall understanding of the planetary system.

### 1.4 Hot Jupiters

Hot Jupiters are generally defined as Jupiter sized planets orbiting their host star with a semimajor axis of 0.1 AU or less. These planets currently comprise 152 out of the known 1039 exoplanets listed in the Exoplanet Encyclopedia (5). The existence of Hot Jupiters was perplexing to do the mass of the planets and their proximity to their host star. Their discovery led to new theories of planetary system formation. Many questions still remain about whether these planets formed in situ, migrated to their current location, or if their orbit is a by-product of planet-planet scattering. All three scenarios may contribute to the many planets being discovered on short period orbits. Figure 1.7
The Kepler-11 exoplanetary system where six planets are found in close packed orbits around their host star.

![Image of Kepler-11 system](image.png)

Figure 1.7: Many of the planets discovered are located close to their host star on very short period orbits. The Kepler-11 system is an exoplanetary system where five of the planets are closer to their host star than Mercury is to the Sun and the sixth planet orbits closer to the host star than Venus does to our Sun. Image courtesy of NASA/Tim Pyle. [Figure reproduced from (12)]

### 1.5 Planetary Orbits

The orbital geometry of planetary systems can heavily influence the physical properties experienced by both the planet and the star. Johannes Kepler showed the planets within the Solar System orbit the Sun in elliptically shaped orbits. This orbital geometry is the same for any planet in a stable orbit around its host star.

Planets in elliptical orbits where the eccentricity is either zero (circular) or less than 0.1 are said to be in near circular orbits. Planets in near circular orbits undergo approximately the same interactions throughout their orbits because their distance from
the host star remains approximately the same throughout their orbit. The slight variations in the planet’s distance cause negligible variations in the amount of stellar radiation the planet is exposed to, the gravitational force of the star on the planet, and the interaction between the magnetic field of the star and the magnetosphere of the planet. Additionally, planetary characteristics dependent on the orbital geometry, such as the planet’s orbital velocity, Safronov number, and Hill Sphere; will remain relatively constant.

The eccentricity of a planet’s orbit can greatly affect the interactions it experiences (14). To understand this the orbital geometry must be understood. Figure 1.8 depicts an elliptical orbit as seen in three dimensions. The key terms to note from the diagram are: the exoplanet is at pericentre when it is at the closest point in its orbit to the host star, the apocentre is the point at which the exoplanet is furthest from its host star, the ascending node is when the planet crosses the observer’s line of sight with the host star and begins moving away from the observer (this is also referred to as the sub-planetary point), ω is the argument of periastron or the angle subtended by the planet after it passes through the

Figure 1.8: Diagram of a 3D eccentric orbit [Figure from (13)]
ascending node and reaches pericentre, and \( v(t) \) is true anomaly or the angle between the pericentre and the planet’s location in its orbit. As the eccentricity of the orbit increases, the distance from the star to pericentre will decrease while the distance from the star to apocentre will increase. Thus the planet will experience much larger interactions with its host star while at pericentre, or during periastron passage, then when it is at apocentre.

Table 1.1 demonstrates three different forms of star-planet interactions dependent on a

<table>
<thead>
<tr>
<th>Interaction (Scale)</th>
<th>Eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Radiation ((R_{\text{peri}}/R_{\text{apo}})^2)</td>
<td>1.5</td>
</tr>
<tr>
<td>Tidal ((R_{\text{peri}}/R_{\text{apo}})^3)</td>
<td>1.8</td>
</tr>
<tr>
<td>Magnetic ((R_{\text{peri}}/R_{\text{apo}})^4)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Table 1.1: Planets in elliptical orbits experience a very wide range of stellar environments along their orbit. Here we show the dynamic range for various interaction processes by comparing how different interaction processes scale with increasing orbital separation. Along a planet’s orbit, tidal interaction processes scale by \((r_{\text{peri}}/r_{\text{apo}})^3\) while magnetic interaction processes scale by \((r_{\text{peri}}/r_{\text{apo}})^4\). The average eccentricity of exoplanetary orbits is 0.16.

distance from the host star and how they vary between pericentre and apocentre with increasing eccentricity. Figure 1.9 depicts the orbital geometry for the seven target systems selected for studying star-planet interactions.
Figure 1.9: Many exoplanets are in elliptical orbits around their host stars where the eccentricity is greater then zero. This can affect the interaction scenarios the planet undergoes. Above are the orbital geometries for the seven exoplanets contained in the systems selected for the star-planet interactions study. Three of the images have green rings depicting the habitable zones of their host stars. The target exoplanetary systems are (a) HD 156279, (b) HAT-P-2, (c) 70 Vir, (d) HD 114762, (e) HD 118203, (f) HAT-P-34, and (g) HD 17156. [Figures reproduced from (15)]
1.6 Project Outline

The purpose of this thesis is to characterize the interactions between bodies in exoplanetary systems through analyzing the characteristics of the systems as a whole then examining the interactions between planets and their host stars. A detailed analysis of these procedures can be found in Chapters 2 and 3.
Chapter 2

Observations and Analysis

2.1 Acquiring a Sample Exoplanet Population for Characterization

The current sample of transiting exoplanets (TEPs) includes over 425 exoplanets out of 1039 exoplanets as of 06 November 2013. As the population increases so does the diversity of planets discovered. The current population ranges in mass from the 0.001 $M_{\text{Jup}}$ KOI 1843 b to the 27.38 $M_{\text{Jup}}$ Kelt-1 b while planetary radii range from the 0.027 $R_{\text{Jup}}$ Kepler-37 b to the 2.037 $R_{\text{Jup}}$ Hat-P-32 (See Figure 2.1). The population of TEPs used for this paper was obtained from Exoplanets.org on 21 October 2013. A smaller sample of 229 exoplanets were analyzed were selected for analyzing characteristics in the exoplanet population. From the original sample, TEPs without a measured mass or semi-major axis, or that have a host star without a known effective temperature, were excluded. TEPs without a measured eccentricity were assumed to have an eccentricity of zero for the purposes of our analyses. Additionally, though 13 $M_{\text{Jup}}$ is supposed to be the lower limit for deuterium burning, analysis by Baraffe (16) and Spiegel (17) show higher mass bodies can be considered planets. Thus the planets KOI-423 b and Corot-3 b were included in our analysis though not included in any of the mass specific classes listed above.

Data obtained from the exoplanet archives contained in the Exoplanet Encyclopedia (5), NASA’s Exoplanet Archive (6), and the Exoplanet Orbit Database(18) were used for characterizing exoplanetary systems. Unless otherwise stated, the data obtained from the Exoplanet Orbit Database is analyzed for characterizing the properties of the exoplanet population. This data was chosen for analysis because it uses the lower limit of measured
stellar and exoplanetary properties. By using this data for our statistical analyses the uncertainty of our results are minimized.

Figure 2.1: Stellar surface gravity and the effective temperature of the host star are only known for 676 of the known exoplanets as of 31 October 2013 (18). The lower grouping is main sequence stars while the center top grouping is comprised of subGiants and Giants. The yellow star marks the Sun on the diagram. The blue stars represent the target sample for star-planet interactions to be discussed later while the blue downward triangles are the photometric SPI target stars. The green boxes represent stars where star-planet interactions have already been detected.
2.2 Sub-samples for Characterizing Planet – Planet Interactions

Characterizing planet–planet interactions aids the constraint and comprehension of exoplanetary system formation and evolution. The main planet–planet interactions investigated are the gravitational interactions. A way of probing these interactions is through the planet’s Safronov number; this value gives the efficiency with which a planet can gravitationally scatter another body. A planet’s Safronov number is calculated by:

$$\Theta = \frac{1}{2} \left( \frac{v_{\text{esc, planet}}}{v_{\text{orb, planet}}} \right)^2 = \frac{a}{R_{\text{planet}} M_{\text{star}}} \frac{m_{\text{planet}}}{M_{\text{star}}}$$

where $v_{\text{esc}}$ is the exoplanet’s escape velocity, $v_{\text{orb}}$ is its orbital velocity, $m_{\text{planet}}$, $R_{\text{planet}}$, and $a$ are the planet’s mass, radius, and semi-major axis, respectively; and $M_{\text{star}}$ is the mass of the planet’s host star. In 2007, Barman and Hanson (19) determined there were two distinct classes of exoplanets based on Safronov number that were later confirmed by Torres (20). Class I with Safronov numbers between 0.06 and 0.08, and class II in the range of 0.03 to 0.05. There have also been some criticism of the validity of Safronov numbers (21, 22) and we investigate the usefulness of Safronov numbers and possible correlations with physical parameters in the current work.

A correlation between an exoplanet’s orbital shape and its Safronov number was investigated since the mass of an exoplanet is directly proportional to its Safronov number. Safronov numbers were originally calculated for Keplerian circular orbits (23) from Equation 1. Due to an increasing number of planets fitting the requirements of our sample but that are found to have orbits with non-zero eccentricity, currently 82, we have adapted the Safronov calculations to account for this. The orbital velocity of the planet and resulting Safronov number are calculated from
\[ v_{\epsilon,\text{planet}} = \frac{2\pi a}{T}E(\epsilon) \]

given \( E(\epsilon) = \int_0^{\pi} \sqrt{1 - e^2 \sin^2 \theta} d\theta \) is the complete elliptical of the second kind. The average Safronov number for exoplanets with eccentric orbits can then be found from:

\[ \Theta_\epsilon = \frac{1}{2} \left( \frac{v_{\text{esc},\text{planet}}}{v_{\epsilon,\text{planet}}} \right)^2 \]

where \( v_{\epsilon,\text{planet}} \) is the average orbital velocity of the exoplanet along an elliptical orbit, \( a \) is the semimajor axis, and \( T \) is the orbital period of the exoplanet. A comparison of values for the orbital velocity calculated using both methods was first done for objects within our solar system and the results from the eccentric method are in better agreement with known values.

To achieve a full analysis of characterizing exoplanets based both on their Safronov numbers calculated for both circular and eccentric orbits, we further scrutinized our base sample of exoplanets to only include those with a known stellar mass, planetary radii, and planetary mass given by \( m \sin i \). For the exoplanetary systems where the first two variables are known and the planetary mass is known, but \( m \sin i \) is not, the value of the planetary mass is used for our calculations. Similarly, the TEPs in our sample without known orbital eccentricities were taken to have an eccentricity of zero. After these constraints, a subsample of 229 exoplanets remained for analysis.

The mass-radius relation for TEPs has been explored and modeled by many, including Fortney (24), Baraffe (25), and Mordasini (26). We probed the current sample of TEPs for any correlation between the Class I and Class II Safronov numbers with the plotted distribution on the mass-radius diagram (See Figure 2.2). A comparison to current
models was included in this analysis to see if there were any correlations between core mass models and Safronov classes. The current sample was then investigated for correlations between the masses of the TEPs and radii with other physical parameters independent of Safronov Numbers.

Figure 2.2: Mass-radius correlation for the current sample of TEPs used in this study compared with the exoplanet models of Forney et al (2007) (24). Shown are the mass and radii of the TEPs with masses less than 5 M\textsubscript{J} (as of October 2013). Over-plotted are mass-radius isochrones for planets with core masses of 0, 10 and 100 M\textsubscript{⊕} shown as solid (blue), dotted (pink), and dashed (black) lines, respectively.

The potential distinction of Class I and Class II Safronov numbers prompted a probe into potential correlations between the Safronov numbers and equilibrium temperatures of TEPs with their other physical parameters. Figure 2 shows plots of both Safronov numbers and equilibrium temperature plotted against eccentricity, $\left[\frac{F_e}{H}\right]$, and escape
velocity. Here classes specified by planetary mass based on a modified classification scheme of Torres (27) are used for the analysis. To ensure there was no discrepancy between Safronov numbers calculated for Keplerian circular orbits and the average Safronov number as calculated for elliptical orbits, both were checked for trends with other planetary system properties.

![Figure 2.3: Average Safronov numbers for eccentric orbits and equilibrium temperature compared with eccentricity, $[Fe/H]$ and escape velocity. Symbols are representative of Earth-mass (green triangles), Super Earths (pink triangles), Neptunes (purple squares), Jupiters (light blue circles), and Massive (orange circles) TEPs. Only TEPs with non-zero eccentricities appear in the left plots for Safronov number and equilibrium temperature respectively.]

2.3 Star-planet Interaction Target Criterion

A study was undertaken to determine if the orbital geometry of exoplanets affects the activity of their host stars by observing a sample of planetary systems known to contain massive planets on short period, highly elliptical orbits. While recent studies in the optical, UV, and X-Ray have shown enhanced chromospheric activity for stars hosting
exoplanets with orbital semi-major axes less than 0.1 AU (28, 29, 30, 31), it is not yet clear whether this activity is driven by magnetic or tidal interaction. While many theories predict the existence of SPI (32, 33, 34, 35, 36, 37), only a few instances of SPI have been detected in exoplanetary systems with Hot Jupiters in near circular orbits. For the first portion of the study, the dependence of star-planet interactions (SPI) on the orbital geometry of the planetary systems is being probed by analyzing the Ca II H & K (3933.663 Å and 3968.462 Å, middle atmosphere), Ha (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines for variability phased with the exoplanet's orbit.

The target exoplanetary systems observed in the visual band were selected with the following specific criteria. First, the eccentricity of the exoplanet’s orbit must be greater than 0.2 and the mass or m\text{sini} of the exoplanet in the system must be greater than 0.8 m\text{Jup}. Exoplanetary systems that met these criteria were then scrutinized further. Preference was given to systems where the planet passes closer than 0.1 AU to its host star, has a S-index and/or Log R\text{HK} indicating the star is active, and if the exoplanetary system is listed in Kashyap and Drake’s table of measured X-ray flux (30). To ensure ground based observations of the target systems are possible, stars with a visual magnitude fainter than 13.0 were excluded from our sample. The final requirement is the target system must be visible from Northern Hemisphere observatories. This final requirement was verified by entering the right ascension (RA) and declination (DEC) for each target into the “starobs” program (38) where McDonald Observatory was used for the observatory location since it is the southern most observatory used for this study.

Using the star-planet interaction target sample, observing time was applied for from two different observatories. McDonald observatory allocated time for the nights of 24-28
October 2013 on the 2.1m Otto Struve telescope using their 60,000 resolution echelle spectrograph. The remaining observations of the SPI targets were conducted on the 3.5m telescope at Apache Point Observatory (APO) using the 35,000 resolution “astrophysical research consortium echelle spectrograph (ARCES)” on the nights of 26 and 28 September 2012, 24 December 2012, 25-26 January 2013, 22 and 26 April 2013, 17 June 2013, and the 18 and 23 August 2013. Time on the APO 3.5m is allocated in half nights so a full night’s worth of observations were not possible. Targets to be observed on each of these nights were selected from the star-planet interaction target sample and verified with “staralt” (38) to have an altitude greater than 30° as viewed during from the observatories during the allocated observing window. Information on each of the seven target systems observed can be found in Table 2.1. Data from all the allocated nights was not obtained or utilized either due to inclement weather or instrument malfunction.
Table 2.1: Properties of the exoplanetary systems observed for star-pl
planet in
teractions

<table>
<thead>
<tr>
<th>System</th>
<th>Confirmed SPI</th>
<th>Eccentric SPI Candidates</th>
</tr>
</thead>
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<tr>
<td></td>
<td>HD 179949</td>
<td>HD 189733</td>
</tr>
<tr>
<td>Mass (MSun)</td>
<td>1.181 ± 0.35</td>
<td>0.806 ± 0.048</td>
</tr>
<tr>
<td>Radius (R_s)</td>
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</tr>
<tr>
<td>T_eff(K)</td>
<td>6168 ± 44</td>
<td>5040 ± 50</td>
</tr>
<tr>
<td>S-Index</td>
<td>0.188 ± 0.024</td>
<td>0.525 ± 0.068</td>
</tr>
<tr>
<td>Log (R_HK)</td>
<td>-4.79</td>
<td>-5</td>
</tr>
<tr>
<td>Spectral Type</td>
<td>F8V</td>
<td>K2V</td>
</tr>
</tbody>
</table>

|                  | HD 118203    | HD 114762                |
| Mass (MSun)     | 1.410 ± 0.004 | 1.230 ± 0.03             |
| Radius (R_s)    | 2.079 ± 0.067 | 2.1                      |
| T_eff(K)        | 6429 ± 50     | 5600 ± 150               |
| S-Index         | 0.185 ± 0.032 | 0.052                    |
| Log (R_HK)      | -5           | -4.7                     |
| Spectral Type   | F5 V         | F8                      |

|                  | HD 70 Vir    | HAT-P-34                 |
| Mass (MSun)     | 0.895 ± 0.089 | 1.01 ± 0.012             |
| Radius (R_s)    | 0.859 ± 0.032 | 1.598 ± 0.052            |
| T_eff(K)        | 5953 ± 44     | 6442 ± 88                |
| S-Index         | 0.165         | 0.15                     |
| Log (R_HK)      | -5           | -4.7                    |
| Spectral Type   | K0           | F8                      |

|                  | HAT-P-2      | HD 17156                 |
| Mass (MSun)     | 1.392 ± 0.047 | 1.308 ± 0.083             |
| Radius (R_s)    | 1.20 ± 0.10   | 1.51 ± 0.11              |
| T_eff(K)        | 6290 ± 60     | 6079 ± 56                |
| S-Index         | 0.15 ± 0.020  | 0.15                     |
| Log (R_HK)      | -5           | -5.06                   |
| Spectral Type   | K0           | K0                      |

|                  | HD 156279    |                      |
| Mass (MSun)     | 1.285 ± 0.026 |                      |
| Radius (R_s)    | 1.507 ± 0.012 |                      |
| T_eff(K)        | 5453 ± 40     |                      |
| S-Index         | 0.155 ± 0.020 |                      |
| Log (R_HK)      | -5           | -5.06                  |
| Spectral Type   | K0           |                        |

**Planet Parameters**

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<tr>
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<th>Msin(i) (M_Jup)</th>
<th>Period (d)</th>
<th>Eccentricity</th>
<th>a (AU)</th>
<th>Periastron (R_star)</th>
<th>Apoastron (R_star)</th>
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<td>0.290 ± 0.009</td>
<td>0.677 ± 0.017</td>
<td>0.497</td>
</tr>
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<td>7.46 ± 0.25</td>
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<td>0.441 ± 0.003</td>
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<td>0.144 ± 0.004</td>
<td>0.845 ± 0.026</td>
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<tr>
<td></td>
<td>9.78 ± 0.53</td>
<td>131.05 ± 0.054</td>
<td></td>
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<td>0.170</td>
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</table>
2.4 Analyzing Chromospheric Activity Lines

High resolution spectra of seven systems with the McDonald 2.1m Sandiford echelle spectrograph and ARCES on the APO 3.5m. In addition to the target object spectra, calibration data was also acquired each night in the form of 5-10 bias frames, flat field images, and thorium-argon (ThAr) lamp spectra. The bias frames are calibration images that measure the pixel noise that occurs when a CCD is reading out its data. They are recorded by the CCD as zero second exposures with the shutter closed. Bias frames can be averaged then subtracted from all the remaining images to reduce the noise in the data. The flat fields are calibration images that record variations in the sensitivity of each pixel in the CCD to light. “Sky flats” were taken at McDonald observatory by pointing the telescope at various points in the sky just after sunset, and just before sunrise, when the sky has a greyish hue to it. These flat field frames have the averaged bias frame subtracted from them before being median combined into a “master flat.” A different procedure is used for flat fielding at APO due to the wide range of wavelengths (3200 Å to 10,000 Å) recoded by ARCES. First, the flat fields are done within the instrument by turning on a halogen light and taking ten seven second exposures that give the flat fields for the red portion of the spectrum. The blue portion of the spectrum is much fainter so it needs a longer exposure time. A blue (CuSO₄) filter is used and ten 200 second exposures are taken of the halogen lamp to give the blue flat fields. Each stack of red and blue flatfields are then independently summed and divided by their exposure time, 7 seconds and 200 seconds respectively. The resulting red and blue frames are then median combined to achieve a master flat field. The target image files are divided by the master flat field to normalize the pixel sensitivity, thereby reducing the noise in the finalized
target spectra. The ThAr spectra are taken by turning on a lamp within the instrument then taking an exposure of its spectra to be used to find the wavelength scale for each order in the finalized target spectrum.

The spectra and calibration images were reduced using standard IRAF (Image Reduction and Analysis Facility) routines as specified in the ARCES reduction guidebook (39, 40). The flat field images, ThAr images, and object (target and standard stars) images were first bias corrected by using the CCDPROC package to calculate the bias from the overscan portion of the images then subtracting it from them. Figure 2.7 shows the preprocessed images of the two target spectra. A master flat field image was then produced using the procedures listed above. A master ThAr was developed from averaging the ThAr taken throughout the night. The spectra for the master flat, the master ThAr, and the object frames were extracted using the IRAF routine APALL. A wavelength dispersion correlation was then derived for the full spectrum, across all orders, using the IRAF routine ECIDENTIFY, which builds a reference spectrum to be applied to other images. Any objects with multiple exposures for that night have their spectra combined and averaged to make a mean nightly spectrum for that object with IMCOMBINE. The reference spectrum is then applied to all the mean combined object spectra using the REFSPEC routine. The object images are then divided by the master flat field image then the DISPCOR routine is used to apply the pixel by pixel wavelength dispersion, as calculated for the reference spectrum, to each object image. Figure 2.4 shows the spectra for both a faint and a bright target star at various points in the reduction process. After the wavelength solution is applied to each mean nightly object spectra, the IRAF routine CONTINUUM is run to normalize its continuum flux to one. From the
Figure 2.4: Data from ARCES on the 3.5m at APO during the night of 18 August 2013 is shown at various points in the reduction process for HD 156279 ($V_{mag} = 8.1$) and 70 Vir ($V_{mag} = 5.0$). In each image, the top panel shows the raw spectra, the middle panel shows the extracted spectra, and the lower panel shows flat-field corrected spectra. (a) The order containing the Ca II K line. (b) The order containing the Ca II H line. (c) The order containing the Hα line. (d) The order containing the Ca IRT.

Header information for the RA, DEC, and mid-exposure time (Julian Days), the Barycentric Julian Date (BJD) of the mid-exposure and the barycentric velocity correction are computed using JSkyCalc (41). The normalized mean nightly object
spectra are ready for analysis and are the spectra referred to for the remainder of the analysis.

The first analysis the chromospheric activity indicators undergo is to see if their equivalent width changes over the orbital phase of the planet. This inspection is done by fitting a Gaussian to the four absorption lines being studied, and to the Al I line at 3944 Å (a photospheric line used to verify activity changes), with SPLOT in IRAF. The equivalent width of the Gaussian and its center point are recorded for each line. The orbital phase of the planet is then calculated from the mid-exposure time (BJD), the time of periastron passage of the exoplanet (BJD), the eccentricity of the exoplanet’s orbit, and the exoplanet’s orbital period (days). The phase of the orbit is normalized to one so exoplanet crosses through its periastron point at phase 0.0 and continues along its orbit with increasing phase until it approaches one at the next periastron passage. As the data from the observations spans multiple epochs, the orbits are phase folded for analysis. The equivalent width for each line can then be plotted along its orbital phase.

The remaining analysis of the mean nightly flux for the chromospheric activity indicator absorption lines is conducted in IDL following the same procedures as Shkolnik (42) and Gurdemir (43). With echelle spectrographs, the orders around Ca II H & K normally have a curved continuum so it is difficult to determine a correct value for the flux in the continuum that can be used for normalizing that portion of the spectrum. To overcome this difficulty for the Ca II K absorption line, an ~7 Å window centered on the Ca II K line (3933.663 Å) was used for the analysis. Each of the endpoints of the spectral window was set to one and fitted with a line to normalize the spectrum. This procedure was used for the Ca II H, Hα, and Ca II IRT absorptions lines and centered at 3968.462
Å, 6562.80 Å, and 8662.14 Å respectively. The window for Ca II H is also ~7 Å while the windows for Hα and the Ca II IRT line at 8662.14 Å are ~20 Å and ~11 Å respectively. The procedure was duplicated for all of the absorption lines being viewed to ensure the consistency of our analysis. After the absorption lines were normalized, they were smoothed by three pixels, then a total mean spectra for each absorption line was computed for each of the target stars. The total mean object spectrum is then subtracted from each of the mean nightly spectra. The residuals from each night were used to calculate the mean absolute deviation (MAD) for the absorption line (42). The

\[ \text{MAD} = \frac{1}{N} \sum |data_i - mean| \]

for N spectra and gives an estimate of the overall variability of the star over a specified time period. For the purposes of this research, the MAD is used to track variability of the host star over the multiple epochs of exoplanetary orbits spanned by the observations. The same analysis was conducted for the other three absorption lines known to be chromospheric activity indicators.
Chapter 3

Results

3.1 Safronov Numbers

Safronov numbers were calculated for a sample of 229 transiting exoplanets to first determine separate classes of exoplanets exist and if Safronov numbers and existing planet parameters can be used to constrain planetary formation scenarios. The idea Safronov numbers can be used to distinguish between two classes of Hot Jupiters was tested with the assumption all planets are on circular orbits and for the stated eccentricities of our subsample of planets. To demonstrate the same principle as Hansen and Barman (19), Figure 3.1 shows the Safronov numbers computed for exoplanets assumed to have circular orbits plotted against their equilibrium temperature. Figure 3.2 shows the same plot for the true eccentricities of our subsample.

The Safronov number is plotted as a function of equilibrium temperature for the current sample of TEP in Figure 3.1. Planets such as, HD 189733, TrES-3, HAT-P-7, and XO-3b can be seen in range of Safronov number between ~0.06 to 0.08, noted as Class I. TEPs such as, GJ 436, WASP-11b, HD 209458 b, and OGLE-TR-56 fall in Class II with Safronov number ~0.03 to 0.05. TEPs such as Kepler-11 f, Kepler-10 b, and HAT-P-32 have Safronov numbers below Class II that are shown in Figure 1a. Similarly, there are a handful of planets shown with Safronov numbers higher than those of Class I, including WASP-7b and Kepler-14b, while massive planets such as HAT-P-2 (HD 147506b). From this figure, it is clear there is no longer a distinction between Class I and Class II as there was when only 19 exoplanets could be analyzed. With the discovery of more exoplanets, the gap dividing the classes has filled in.
Figure 3.1: Safronov number versus equilibrium temperature for exoplanets assumed to have circular orbits with a histogram showing the cumulative density of the Safronov distribution.
Figure 3.2: Safronov numbers computed for elliptical orbits versus the equilibrium temperature. The symbols are the same as those in Figure 2.3. For reference, the planets in our solar system are plotted. Mercury is not shown as its Safronov number is just below the lower limit of the plot, but the other Terrestrial planets form our solar system are shown with the asterisk symbol and the "Jovian" planets from our system are plotted with the diamonds and seen grouped in the top left corner of the plot. When the Safronov number is plotted on a log scale a separation into distinct mass-dependent classes becomes apparent.

3.2 Stellar Irradiance

The irradiance of each star at the distance of its planet was calculated from:
\( \langle F_\ast \rangle = \frac{L_\ast}{4\pi a^2 \sqrt{1 - \epsilon^2}} \)

where \( F_\ast \) is the stellar irradiance or average incident flux a planet receives, \( L_\ast \) is the luminosity of the star, \( a \) is the semi-major axis of the planet’s orbit, and \( \epsilon \) is the orbital eccentricity. Evidence for planets being located in a region where the average irradiance of their host star \((2 \times 10^8 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ or } 147 \ F_{\odot\odot})\) is shown in Figures 3.3 (a) and (b).

As many planets are on eccentric orbits, they experience a large variation in the flux they receive from their host star. Figure 3.4 demonstrates the variation in stellar flux the eccentric planets receive between their periastron passage and apoastron passage. The radiative interaction between the planet and its host star decreases with the square of the distance that separates them, thus the larger the eccentricity of the orbit the larger the variation in flux the planet receives.

The largest variation in our sample is for HD 80806 b with a variation of 858x in terms of the ratio of the stellar irradiance at the planet’s periastron and apoastron positions due to its 0.934 eccentricity orbit.

Given the amount of radiation the planet receives, if we consider the planet to be a completely absorbing blackbody (no albedo) the equilibrium temperature of the planet can be calculated. The assumption is also made for perfect thermal redistribution on the planet. Figure 3.5 (a) and (b) demonstrate the radii of the planet versus its equilibrium temperature for circular and eccentric orbits, respectively. The class of Neptune mass planets with Jupiter radii are characterized by their “inflated radii” and are visible in clusters in the center of each plot. However we also see evidence for planets with large or inflated radii with low equilibrium temperatures.
Figure 3.3: (a) The mass-radius diagram for the 229 confirmed exoplanets contained in our sample. The purple circles represent the exoplanets located in an orbit where the stellar irradiance is less than $2 \times 10^8$ ergs cm$^{-2}$ s$^{-1}$ while the blue stars represent the exoplanets located in an orbit of greater stellar irradiance. (b) The radii of our sample of exoplanets versus stellar irradiance. The red triangles represent the eccentric exoplanets at their periastron positions while the blue stars are the same planets at their apoastron distance. Purple circles represent exoplanets on circular orbits.
Figure 3.4: The planet mass - stellar irradiance - planet radius diagram for the 229 confirmed exoplanets contained in our sample. The purple squares represent the exoplanets in circular orbits while the blue triangles represent eccentric exoplanets located at their periastron positions while the red triangles are the same planets at their apoastron distance.
Figure 3.5: Exoplanet radius vs. equilibrium temperature for the current sample of exoplanets. The inflated radii of the gaseous Neptune mass planets are apparent in both. (a) Average equilibrium temperature for all the planets with purple circles representing exoplanets whose orbit is in an area where the stellar irradiance is less than $2 \times 10^8$ ergs cm$^{-2}$ s$^{-1}$. The blue circles are planets exposed to a larger stellar irradiance. A trend is showing for planets with high equilibrium temperatures exposed to high stellar irradiance but with small radii. (b) The same plot but the purple circles represent planets on circular orbits while the blue and red triangles represent the eccentric exoplanets located at their periastron and apoastron positions, respectively.

### 3.3 Star-Planet Interactions

Star planet interactions can be detected through observations of the star. If a hot-spot is generated on the stellar disk due to gravitational perturbations on the star that cause a tidal bulge less dense than lower regions of the stellar atmosphere, it will be phased with half the orbital period of the planet. If this hot-spot is a result of magnetic star-planet interactions, it is expected to be in phase with the planetary orbital period. The spectroscopic data for all target exoplanetary systems was reduced and analyzed as described in Section 2.5 and each of the mean nightly spectra has a signal to noise ratio.
(SNR) of ~95. In the following subsections the results of my observations and analyses for each of our target stars is discussed.

Figure 3.6: (a) The mean Ca II K (3933.663 Å) absorption line from HD 156279 for phases 2.39, 2.70, 2.71, 2.89, and 2.95 as acquired with ARCES on the 3.5m at APO. The mean spectrum for all the observed nights is shown in blue. The lower panel in shows the residual flux given by subtracting the total mean spectra from the mean nightly spectra. The mean average deviation (MAD) is shown as the blue line in the lower panel. The same information is shown for the Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines in panels (b), (c), and (d) respectively. The observed MAD for each line is shown in the lower panels. The MAD is color coded blue for Ca II H and red for both Hα and Ca II IRT.
3.3.1 HD 156279

We obtained five nights of observations of HD 156279, 0.93 M$_\odot$ K0 star hosting a 9.78 m$_{\text{jup}}$ exoplanet on a 131 day orbit with eccentricity of 0.708, between 19 April and 23 August 2013. On each night except 19 August 2013, multiple 1800 second observations of HD 156279 were taken with ARCES on the 3.5m telescope at APO. Figure 3.5 shows the mean nightly flux, the mean total flux, and the calculated residuals for each of the four observed spectral lines.

The observations of HD 156279 do not reveal definitive proof of star-planet interactions. From Figure 3.6 it is evident that the orbital phase of the planet during each observation only spans a range of 0.2 due to the long orbital period of the star and the spacing of the observations. This does not give adequate phase coverage to determine if modulations in the line core are evident over the full orbit. Gaussian fits to the Ca II K line show the variations of the line widths of $\sim$1.8 Å over the observations. Similarly, the Gaussian fits to the Ca II H lines show a variation of $\sim$1.3 Å over the observations while the H$\alpha$ and Ca IRT (8662.14 Å) lines show variations in their equivalent widths of 0.21 Å and 0.25 Å respectively, as depicted in Figure 3.7.

The individual spectral lines reveal information about the chromospheric activity of the star. The Ca II IRT (8662), H$\alpha$, and Ca II H lines are all in absorption as is evident in Figure 3.5. The Ca II K line shows evidence of inversion as emission in the line core is evident. The measured equivalent widths of the emission in the Ca II K line cores for HD 156279 are plotted versus phase in Figure 3.8. The equivalent widths of the emission line cores fail to reveal information about star-planet interactions.
Figure 3.7: Equivalent width of the chromospheric activity indicators versus orbital phase for HD 156279. The blue, pink, green, and red crosses represent the Ca II K (3933.663 Å), Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines respectively.

Figure 3.8: (a) Equivalent widths of the emission in the Ca II K (3933.663 Å) line core plotted versus orbital phase for HD 156279.
3.3.2 HAT-P-2

HAT-P-2 hosts an 8.86 m$_{\text{jup}}$ exoplanet with an orbital eccentricity of 0.517. This target system has the best phase coverage of all the SPI targets but due to its 5.6 day orbital period, most of the observations fall on different epochs. The variations in both the equivalent widths of the lines and the line cores are small. Figure 3.9 depicts the normalized lines and their residuals. Noise due to cosmic ray hits is apparent in the spectra from for a couple of the nights. The intensity of this noise is truncated by the spectra being a mean of the nightly spectra and from smoothing of the spectra. To verify this was an artifact and not true emission, the individual nightly spectra were consulted and the locations of steep flux increases to greater than 3$\sigma$ of the mean intensity for that region were noted. Despite these artifacts, there remains little variability in the Ca II K, Ca II H, H$\alpha$, and Ca II IRT (8662.14 Å).

The equivalent widths of the chromospheric activity indicators for HAT-P-2 show differing degrees in variability based on their relative positions in the visual spectra. For the red portion of the spectrum, the equivalent widths for H$\alpha$ and the Ca II IRT (8662.14 Å) are relatively constant. Four of the measured equivalent widths of H$\alpha$ are closely packed with a variation 0.064 Å but a fifth observed equivalent width is an outlier and brings the spread of the observed equivalent widths to 0.81 Å. The equivalent widths of the Ca II IRT (8662.14 Å) line have a spread of 0.215 Å across the observations. As displayed in Figure 3.11, this is relatively constant. The variability in the blue portion of the spectrum is greater. Ca II H shows a variation in the equivalent widths of ~4 Å while Ca II K has a variability spread of 0.94 Å. No core emission was visible in any of the absorption lines.
Figure 3.9: (a) The mean Ca II K (3933.663 Å) absorption line from HAT-P-2 for phases 0.1, 1.74, 1.90, 2.05, and 2.36 as acquired with ARCES on the 3.5m at APO. The mean spectrum for all the observed nights is shown in blue. The lower panel in shows the residual flux given by subtracting the total mean spectra from the mean nightly spectra. The mean average deviation (MAD) is shown as the blue line in the lower panel. The same information is shown for the Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines in panels (b), (c), and (d) respectively. The observed MAD for each line is shown in the lower panels. The MAD is color coded blue for Ca II H and red for both Hα and Ca II IRT.
Figure 3.10: Equivalent widths of the chromospheric activity indicators versus orbital phase for HAT-P-2. The blue, pink, green, and red crosses represent the Ca II K (3933.663 Å), Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines respectively.

3.3.3 70 Vir

70 Vir is a 1.101 $M_\odot$ star hosting a 7.46 $m_{\text{Jup}}$ exoplanet on a 116 day orbit of eccentricity 0.401. This is the brightest target star observed for SPI and its spectra has the highest SNR for the three nights it was observed. This star shows no activity in the core of Hα nor Ca II IRT (8662.14 Å) as is depicted in Figure 3.12 where the MAD for each line can be seen to have a null value in the position of these line cores. Ca II H & K show slight variability. The two observing nights in April, where the orbital phases are very close together due to 70 Vir b’s 116.68 day orbit, are the two most closely matched spectra but while the greatest variation in phase and residuals occurs for the 17 June 2013 observations.
The equivalent widths of all the absorption lines for 70 Vir are close to constant as the difference between their maximum and minimum values is less than one angstrom (See Figure 3.13). The equivalent widths of the Ca II K, Ca II H, Hα, and Ca II IRT (8662.14 Å) lines have spreads of 0.66 Å, 0.55 Å, 0.057 Å, and 0.019 Å respectively.

Figure 3.11: (a) The mean Ca II K (3933.663 Å) absorption line from 70 Vir for phases 0.47, 2.88, and 2.89 as acquired with ARCES on the 3.5m at APO. The mean spectrum for all the observed nights is shown in blue. The lower panel in shows the residual flux given by subtracting the total mean spectra from the mean nightly spectra. The mean average deviation (MAD) is shown as the blue line in the lower panel. The same information is shown for the Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines in panels (b), (c), and (d) respectively. The observed MAD for each line is shown in the lower panels. The MAD is color coded blue for Ca II H and red for both Hα and Ca II IRT.
Figure 3.12: Equivalent width of the chromospheric activity indicators versus orbital phase for 70 Vir. The blue, pink, green, and red crosses represent the Ca II K (3933.663 Å), Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines respectively.

3.3.4 HD 114762

HD 114762 hosts an 11.64 m\textsubscript{Jup} exoplanet on an 83.9 day orbit with eccentricity of 0.335. This F8 star shows large scale variability in the Ca II H & K lines but no variability in the Hα and Ca II IRT lines. As depicted in Figure 3.14, the MAD is null for the line cores of Hα and Ca II IRT (8662.14 Å). Similar to 70 Vir, the same grouping of the April 2013 observations is apparent while the 17 June observations has a larger measured flux in the Ca II H & K lines.
Figure 3.13: (a) The mean Ca II K (3933.663 Å) absorption line from HD 114762 for phases 2.40, 2.52, and 2.58 as acquired with ARCES on the 3.5m at APO. The mean spectrum for all the observed nights is shown in blue. The lower panel in shows the residual flux given by subtracting the total mean spectra from the mean nightly spectra. The mean average deviation (MAD) is shown as the blue line in the lower panel. The same information is shown for the Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines in panels (b), (c), and (d) respectively. The observed MAD for each line is shown in the lower panels. The MAD is color coded blue for Ca II H and red for both Hα and Ca II IRT.

Analysis of the equivalent widths of the chromospheric activity indicators also shows a similar pattern for HD 114762 as existed for 70 Vir (See Figure 3.15). Hα and Ca II IRT (8662.14 Å), in the red portion of the spectrum, show almost constant equivalent
widths of 0.1 Å and 0.02 Å respectively. Ca II H & K have larger spreads as their maximum and minimum measured equivalent widths are 0.94 Å and 1.44 Å respectively.

![Figure 3.14: Equivalent width of the chromospheric activity indicators versus orbital phase for HD 114762. The blue, pink, green, and red crosses represent the Ca II K (3933.663 Å), Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines respectively.](image)

3.3.5 HD 118203

HD 118203 is a 1.23 M☉ K0 star hosting a 2.136 mJup exoplanet on a 6 day orbit with a 0.309 eccentricity. The analysis of HD 118203 shows very interesting results. The MAD for Hα and Ca II IRT (8662.14 Å) is null thus no variability in the star’s activity is apparent from these lines on the observed date. Just as with the previous two target systems, grouping in the blue portion of the spectra for the April 2013 observations is seen while the 17 June observation has an increased measured flux. Given the short orbital period of 6.133 days for HD 118203 b, these observations are separated by multiple epochs, unlike those of the previous two long period planets. As seen in Figure
3.16, Ca II H shows variation but it is not enhanced in the core. Ca II K shows inversion as emission in the core is apparent in all three night’s observations.

Figure 3.15: (a) The mean Ca II K (3933.663 Å) absorption line from HD 118203 for phases 0.50, 1.33, and 2.59 as acquired with ARCES on the 3.5m at APO. The mean spectrum for all the observed nights is shown in blue. The lower panel in shows the residual flux given by subtracting the total mean spectra from the mean nightly spectra. The mean average deviation (MAD) is shown as the blue line in the lower panel. The same information is shown for the Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines in panels (b), (c), and (d) respectively. The observed MAD for each line is shown in the lower panels. The MAD is color coded blue for Ca II H and red for both Hα and Ca II IRT.

The equivalent widths of the absorption lines are close constant for all the observed nights (See Figure 3.17). In the blue portion of the spectrum, the Ca II K equivalent
widths have a spread of 0.06 Å while the Ca II H equivalent widths have a spread of 0.17 Å. For the red portion of the spectrum, the equivalent widths of Hα span 0.16 Å while those for Ca II IRT (8662.14 Å) span 0.03 Å.

Figure 3.16: Equivalent width of the chromospheric activity indicators versus orbital phase for HD 118203. The blue, pink, green, and red crosses represent the Ca II K (3933.663 Å), Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines respectively.

3.3.6 HAT-P-34

The 10.4 V\textsubscript{mag}, 1.4 M\textsubscript{⊙}, F8 star HAT-P-34 hosts a 3.33 m\textsubscript{Jup} exoplanet that completes a 0.441 eccentricity orbit in a period of 5.45 days. As seen in Figure 3.18, the observed spectra for HAT-P-34 show no variability between the two nights of observations that cannot be attributed to artifacts in the spectra. No definitive results on SPI can be derived for this system.
Figure 3.17: (a) The mean Ca II K (3933.663 Å) absorption line from HAT-P-34 for phases 2.27, and 2.62 as acquired with ARCES on the 3.5m at APO. The mean spectrum for all the observed nights is shown in blue. The lower panel in (a) shows the residual flux given by subtracting the total mean spectra from the mean nightly spectra. The mean average deviation (MAD) is shown as the blue line in the lower panel. The same information is shown for the Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines in panels (b), (c), and (d) respectively. The observed MAD for each line is shown in the lower panels. The MAD is color coded blue for Ca II H and red for both Hα and Ca II IRT.

3.3.7 HD 17156

HD 17156 is a K0 star of 1.285 M_☉ with a 3.3 m_Jup exoplanet traversing a 0.6819 eccentricity orbit over a 21 day period. The observations of HD 17156 took place on the
nights of 24 December 2012 and 25 January 2012. The low SNR of the data seen in Figure 3.18 can be attributed to the poor weather and consistent disruptions in the exposures by thick clouds. From these two data points, no significant results about SPI can be drawn.

Figure 3.18: (a) The mean Ca II K (3933.663 Å) absorption line from HD 17156 for phases 2.04 and 2.97 as acquired with ARCES on the 3.5m at APO. The mean spectrum for all the observed nights is shown in blue. The lower panel in shows the residual flux given by subtracting the total mean spectra from the mean nightly spectra. The mean average deviation (MAD) is shown as the blue line in the lower panel. The same information is shown for the Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines in panels (b), (c), and (d) respectively. The observed MAD for each line is shown in the lower panels. The MAD is color coded blue for Ca II H and red for both Hα and Ca II IRT.
Chapter 4

Discussion

The goal of this research is analyzing various methods to characterize exoplanetary systems through the interactions of the bodies that comprise the systems. A sample of 229 exoplanets from the current exoplanet population was analyzed for means to characterize subsets of exoplanets based on their potential planet-planet interactions. A smaller sample consisting of seven exoplanetary systems with Jupiter mass planets on highly eccentric orbits was selected for ground based observations to probe the existence of star-planet interactions. This subsample was observed for evidence of radiative, gravitational, and magnetic interactions between the host star and its exoplanet. These interactions can yield information about the formation and evolution of planetary systems.

The Safronov number may be a useful property for determining how some planetary systems formed and evolved. The existence of close-in exoplanets with highly elliptic orbits and/or with an orbit inclined to the stellar rotation gives credence to the theory these may be exoplanets that scattered other bodies outside of their planetary systems. This also helps parameterize the size and number of free-floating planets in the Universe. Safronov numbers for scale with mass of the planet thus more massive planets will have larger Safronov number than a less massive planet in the same orbit. An interesting phenomenon happens for the Hot Jupiters with inflated radii. Their increased radii due to an extended envelope will cause these exoplanets to have smaller Safronov number (circular) than a denser but slightly less massive exoplanet in the same orbit. However, the existence of two classes of Hot Jupiters based on their Safronov numbers was a trend
visible when only a small sample of exoplanets had been discovered. With the growing exoplanet population, the gap causing a division between the two classes was soon filled. It can be noted that the average Safronov number for planets increases when the eccentricity of their orbits is considered. This is expected perimeter of the orbit will decrease thus causing the average orbital velocity of the exoplanet to decrease. Since the escape velocity from the planet remains the same, the average Safronov number will be larger for elliptical orbits than for circular ones with the same semi-major axis.

It can confidently be stated that stellar irradiance is a key factor in Neptune Mass planets having inflated radii for systems where the host star’s irradiance is $2 \times 10^8$ ergs cm$^{-2}$ s$^{-1}$ at the location of the exoplanet’s orbit. This confirms the findings of both Fortney and Nettelmann (45) and of Demory and Seager (46). It is dually noted that less massive planets exposed to the same irradiance do not have the mass to gravitationally hold an atmosphere so will appear with very small radii on the mass-radius diagram (See the zoomed in portion of the mass-radius diagram in Figure 4.1.)

With the discovery of an extensive number of small mass and radii planets thanks to exoplanet searches such as those conducted with the Kepler Space Telescope, Hot Jupiters are no longer a dominant phenomenon in exoplanet catalogs. Thus previously stated trends need to be re-analyzed. In 2009, Southworth et al. (47) proposed a possible class distinction between exoplanets based on a correlation between their mass and orbital shape. They found TEPs with masses larger than 3 M$_J$ have a larger subset with significant eccentricities than any class of exoplanets specified with lower masses. While there are 1 Earth-mass, 1, Super-Earth, 1 Neptune-mass, 48 Jupiter-mass, and 3 Massive
Figure 4.1: The portion of the exoplanet mass – radius diagram for the Earth-sized and Super-Earth exoplanets contained in our sample (lower left corner of Figure 3.2). The core composition isochrones for Earth sized planets from Fortney 2007 (24) are shown for comparison. The blue stars represent exoplanets exposed to stellar irradiance greater than $2 \times 10^8$ ergs cm$^{-2}$ s$^{-1}$ while the red dots are exoplanets exposed to a lower irradiance. (a) The diagram for data retrieved from the Exoplanet Orbit Database as used throughout this research. This database uses the minimum values of all exoplanetary properties to be more statistically accurate. (b) For comparison, the same plot using data retrieved from the Exoplanet Archive.

Exoplanets with eccentricities greater than 0.5, the remaining TEPs for each class are distributed below $e < 0.5$. From the current sample, the fraction of TEPs with eccentric orbits to their respective mass-selected class are: Earth-mass – (1/2), Super-Earths – (22/42), Neptunes – (38/47), Jovian – (399/527), Massive – (13/14). (See Figure 3-Right Panel) The following gives the fraction of planets found with significant eccentricities to the number of planets in each class: Earth-mass – (1/2), Super-Earths – (7/42), Neptunes – (16/47), Jupiter – (258/527), Massive – (13/14). Thirty-two of the Earth-mass planets are not included in this analysis because they have a null msini based on the data obtained from the Exoplanet Orbit Database. Only nine of the excluded exoplanets have eccentric
orbits so their exclusion does not change the results. This analysis continues to show the trend suggested by Southworth et al. (47), however Wang & Ford (48) has shown the significance test (49) used may cause exoplanets with low orbital eccentricities to be overly reclassified with eccentricities of zero. Thus, both analyses stated above are used as evidence the mass-eccentricity correlation continues to hold true despite the discovery of a growing number of Earth-size planets.

Figure 4.2: The eccentricity of the sample of 663 exoplanets plotted versus their mass. (a) The majority of the planets discovered have masses less than one Jupiter mass and an eccentricity lower than 0.1. It can be seen that the higher mass planets have fewer points located on the plot for eccentricities equal to zero (circular orbits). (b) For comparison, a log-log plot of eccentricity versus mass for the sub-sample of 482 exoplanets with significant non-zero eccentricities. The pink triangle is the lone Earth-mass planet whereas the green upside down triangles are Super-Earths, the purple squares are Neptunes, the light blue circles are Jupiters, and the dark blue circles are massive planets.
Massive exoplanets on highly eccentric orbits offer an interesting avenue to probe star-planet interactions based on the drastic change in environment the planet will experience throughout its orbit. Given the rates that gravitational and magnetic interactions decrease with increasing distance between the exoplanet and its host star, increases in chromospheric activity are predicted to be strongest when the planet is closest to pericentre. As with exoplanets on near circular orbits, the induced activity will be easiest to detect at the sub-planetary point, but eccentric orbits offer the benefit that due to the decrease in interaction along the orbital path, intrinsic stellar activity will be easier to detect and disregard. Shkolnik et al. (44) and Gurdemir et al. (43) reported the detection of magnetic star-planet interactions on HD 189733, while Fares et al (50) reported evidence for HD 179949, at varying at various points out of phase with the sub-planetary point of its exoplanet’s orbit. The sample of exoplanets chosen to search for evidence of star-planet interactions have various arguments of periastron thus allowing the potential detection of phase-lagged induced activity.

The most successful probe for star-planet interactions is plotting the integrated normalized residuals versus orbital phase. The normalized residuals for each observing night are integrated over the spectral window stated for each of the investigated lines in Section 2.4. To verify the results are not a consequence of noise within the spectral window, such as the remnants of cosmic ray hits, the integrated flux is also calculated for a 1 Å window centered on each line core. The results of both analyses show similar patterns thereby allowing the conclusion that the values for the integrated flux are a result of physical processes within the exoplanetary system and not a byproduct of noise. Figure 4.3 depicts the phase folded integrated flux of the residuals over a 1 Å window.
around the line core of each chromospheric activity indicator. The integrated flux for Ca II H & K peaks at a phase ~0.26 after the sub-planetary point (0.267) for HD 156279.

Figure 4.3: The phase folded integrated flux of the normalized residuals for each of the chromospheric activity indicators as observed in (a) HD 156279, (b) HAT-P-2, (c) 70 Vir, and (d) HD 114762. Activity on the host star induced expected to be in phase with the orbital period of the planet if it is magnetically induced or half an orbit out of phase if it is tidally induced. The dotted line marks the phase of the sub-planetary point where the probability of detecting SPI is highest for systems with circular orbits.
Small scale variability in the integrated flux of Hα and Ca II IRT (8662.14 Å) is also apparent. This differs from the plot of equivalent width versus phase (Figure 3.7) for HD 156279 where it is evident the equivalent widths of the Ca H & K lines peaks at a slightly earlier phase and the equivalent widths of Hα and Ca II IRT remain relatively constant. HAT-P-2 shows the integrated flux of Ca II H & K and Hα peaks just before 0.7, this is an approximate phase lag of ~0.2 from the sub-planetary point (0.4855) while the measured equivalent widths of Ca II H & K are at their minimum at this point. This demonstrates the inverse relationship between the equivalent width and integrated flux expected for Ca II H & K as a star’s chromospheric activity varies. As expected, the integrated flux of each line for HAT-P-2 shows larger variability than the equivalent widths shown in Figure 3.7. Similar behavior is seen for 70 Vir where the integrated flux of the Ca II H & K residuals show behavior opposite that of the equivalent widths for the studied lines. HD 114762 shows a similar inverted pattern but the integrated flux of Hα and Ca II IRT is relatively constant compared to Ca II H & K, just as with the equivalent

Figure 4.4: The same as Figure 4.3 for HD 118203.
Widths. In Figure 4.4, a decreasing trend in integrated flux with orbital phase is seen for Ca II H & K and Ca II IRT. This differs drastically from the relatively constant equivalent line widths observed for HD 118203, but is the expected behavior of the integrated flux for stellar activity induced by interactions between a host star and an

Figure 4.5: (a) The total mean Ca II K (3933.663 Å) absorption lines for each target star being tested for SPI. The same information is shown for the Ca II H (3968.468 Å), Hα (6562.80 Å), and Ca II IRT (8662.14 Å) absorption lines in panels (b), (c), and (d) respectively.
exoplanet in an elliptical orbit. The peak values of the integrated flux for 70 Vir and HD 118203 are well out of phase with their respective sub-planetary points of 0.004 and 0.5675 but are close to that for HD 114762 (0.431). Further observations of these systems are needed before conclusive results about star-planet interactions within these three systems can be made.

The integrated flux was calculated over two spectral windows to minimize the effects of cosmic rays or noise in the portion of the spectra that coincides with the lines. The total mean flux for each of the spectral lines known to be chromospheric activity indicators (3933.663 Å, 3968.468 Å, 6562.80 Å, and 8662.14 Å) is shown in figure 4.5. Variations in the integrated flux may be due to changes in the stellar activity cycle occurring over the multiple epochs of our observations. To better constrain this source of error, observations conducted over consecutive epochs are warranted to better characterize the magnetic activity of the star during the observed period. The emission detected in the Ca II K core for both HD 156279 and HD 118203 call for follow-up observations of these targets to determine the nature of its origin. As more observations of these targets are made, the detection of star-planet interactions will become more definitive and it can be determined whether they are in phase with the orbital period of the system or its beat period.
Chapter 5

Conclusion and Outlook

In summary, the interactions between bodies in exoplanetary systems were interrogated for their ability to characterize exoplanetary systems and reveal potential information about planetary system formation and evolution. It was determined that there is no evidence for two classes of Hot Jupiters based on Safronov numbers thus there is no correlation between the classes and planetary formation via accretion or migration. However, it was confirmed the majority of Hot Jupiters with inflated radii are exposed to a stellar irradiance greater than $2 \times 10^8$ ergs cm$^{-2}$ s$^{-1}$ and the trend that massive planets tend to have eccentric orbits. The fact that a larger fraction of massive planets can be found in eccentric orbits gives credence to the ideas of planet-planet scattering and Kozai migration as processes for exoplanetary system formation. While no concrete evidence for star-planet interactions was found, the fluctuations of the integrated flux in most of the targets, especially HAT-P-2, and the emission in the line core of Ca II K (3933.663 Å) for HD 156279 and HD 118203 warrant follow-up observations of these targets over continuous orbital epochs.
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