ABSTRACT

Planets interact with their host stars through gravity, radiation and magnetic fields, and for those giant planets that orbit their stars within \(~\sim 10\) stellar radii (\(~\sim 0.1\) AU for a sun-like star), star-planet interactions (SPI) are observable with a wide variety of photometric, spectroscopic and spectropolarimetric studies. At such close distances, the planet orbits within the sub-alfvenic radius of the star in which the transfer of energy and angular momentum between the two bodies is particularly efficient. The magnetic interactions appear as enhanced stellar activity modulated by the planet as it orbits the star rather than only by stellar rotation. These SPI effects are informative for the study of the internal dynamics and atmospheric evolution of exoplanets. The nature of magnetic SPI is modeled to be strongly affected by both the stellar and planetary magnetic fields, possibly influencing the magnetic activity of both, as well as affecting the irradiation and even the migration of the planet and rotational evolution of the star. As phase-resolved observational techniques are applied to a large statistical sample of hot Jupiter systems, extensions to other tightly orbiting stellar systems, such as smaller planets close to M dwarfs become possible. In these systems, star-planet separations of tens of stellar radii begin to coincide with the radiative habitable zone where planetary magnetic fields are likely a necessary condition for surface habitability.

**Keywords:** editorials, notices — miscellaneous — catalogs — surveys

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1. INTRODUCTION

Giant planets located < 0.1 AU from their parent star comprise ~7% of the confirmed exoplanets, primarily around FGK stars\(^1\). At such small orbital separations, these hot Jupiters (HJ) provide a laboratory to study the tidal and magnetic interactions between the planet and the star that does not exist in our own solar system. These interactions can be observed because they scale as \(a^{-3}\) and \(a^{-2}\), respectively, where \(a\) is the separation between the two bodies. Although HJs are rare around M dwarfs (only five known), statistics from the Kepler survey have revealed that M stars host on average 0.24 Earth-sized planets in the habitable zone (Dressing & Charbonneau 2015). We can apply the techniques trained on HJs around FGK stars on to small planet + M dwarf systems.

Cuntz et al. (2000a) first suggested that close-in planets may increase and modulate their host star’s activity levels through tidal and magnetic interactions as such effects are readily observed in the comparable cases of tightly orbiting RS CVn binary systems (e.g. Piskunov 1996; Shkolnik et al. 2005b). Variable excess stellar activity with the period of the planet’s orbit rather than with star’s rotation period, indicates a magnetic interaction with the planet, while a period of half the orbit’s indicates a tidal interaction. This suggestion has spurred the search for such interactions as a means of studying the angular momentum evolution of HJ systems and as detecting the magnetic fields of exoplanets (e.g. Cuntz et al. 2000b; Saar et al. 2004; Lanza 2009; Shkolnik et al. 2003, 2005a, 2008; Cohen et al. 2009).

Exoplanetary magnetic fields provide a probe into a planet’s internal dynamics and constraints on its atmospheric mass loss. This fundamental physical property of exoplanets would most directly be detected through the radio emission produced by electron cyclotron maser instability (see review by Treumann 2006 and Chapter 9.6 of this book). Such emission has been detected from all of the solar system’s gas giants and the Earth resulting from an interaction between the planetary magnetosphere and the solar wind. There are no detections to date of radio emission from exoplanets although searches have been typically less sensitive at higher emission frequencies than predicted for exoplanets (e.g. Farrell et al. 1999; Bastian et al. 2000; Lanza 2009; Lazio et al. 2009; Jardine & Collier Cameron 2008; Vidotto et al. 2012 and see review by Lazio et al. 2016).

Even though a radio detection of a planet’s magnetic field \((B_p)\) remains elusive, there have been reported detections through magnetic star-planet interactions (SPI). Nearly twenty studies of HJ systems, varying in wavelengths and observing strategy, have independently come to the conclusion that a giant exoplanet in a short-period orbit can induce activity on the photosphere and upper atmosphere of its parent star. This makes the host star’s magnetic activity a probe of the planet’s magnetic field.

\(^1\) [http://www.exoplanets.org](http://www.exoplanets.org), accessed 2/15/2017
Due to their proximity to their parent star, magnetic SPI in HJ systems can be detected because these exoplanets typically lie within the Alfvén radius of their parent star ($\lesssim 10R_*$ or $\lesssim 0.1$ AU for a sun-like star). At these small separations, the Alfvén speed is larger than the stellar wind speed, allowing for direct magnetic interaction with the stellar surface. If the giant planet is magnetized, then the magnetosphere of the planet may interact with the stellar corona throughout its orbit, potentially through magnetic reconnection, the propagation of Alfvén waves within the stellar wind, and the generation of electron beams that may strike the base of the stellar corona.

In the case of characterizing habitable zone planets, the current favored targets are low-mass stars where the habitable zone is located much closer to the parent star compared to the Earth-Sun separation, making the planet easier to detect and study. Low-mass stars are typically much more magnetically active than solar type stars. It is therefore vital that we understand how this increase in magnetic activity impacts the potential habitability of a planet orbiting close to a low-mass star and what defenses the planet has against it. In order to sustain its atmosphere, a planet around a low-mass star must be able to withstand enhanced atmospheric erosion from extreme stellar wind and also from the impact of coronal mass ejections. Both of these reasons necessitate the push towards the detection and characterization of magnetic SPI in M dwarf planetary systems.

The need to understand magnetic SPI is also driving the modeling effort forward. There have been considerable efforts towards modeling the space weather environments surrounding close-in giant exoplanets and star-planet interactions. The magnetized stellar winds may interact with the close-in exoplanet through the stars’ outflows and magnetospheres, and potentially lead to observable SPI. Observing the stellar winds of stars other than the Sun is difficult and there are very few observational constraints on the winds of low-mass stars (Wood et al. 2005). Star-planet interactions can be simulated by using hydrodynamical (HD) or magnetohydrodynamical (MHD) numerical models. The modeling efforts have not only focused on studying individual systems, but have also been extended to more general scenarios to help aid the interpretation of statistical studies.

MHD models for star-planet interactions require a dynamic model for the stellar corona and wind, and also a model for the planet, which acts as an additional, time-dependent boundary condition in the simulation (Cohen et al. 2011). The standard approach to modeling SPI involves adapting 3D MHD models originally developed for the solar corona and wind. The BATS-R-US (Powell et al. 1999; Tóth et al. 2012) global MHD model forms part of the Space Weather Modeling Framework (Tóth et al. 2005) and is capable of accurately reproducing the large-scale density and temperature structure of the solar corona and has been adapted to model the winds of other stars. This MHD model uses a stellar magnetogram (or solar synoptic map) as input along with other properties of the host star, including the stellar coronal base density ($\rho$),
surface temperature ($T$), mass ($M_*$), radius ($R_*$) and rotation period ($P_*$). The model then self-consistently solves the ideal MHD equations for the stellar corona and wind, which in turn allows the conditions experienced by an exoplanet to be studied (e.g., Cohen et al. 2009, 2011, 2014; Vidotto et al. 2009, 2013, 2014; do Nascimento et al. 2016).

In this chapter, we discuss the observational evidence of magnetic SPI in FGK and M stars plus the array of models produced to explain and characterize this diagnostic, albeit complex, physical phenomenon.

2. PLANET INDUCED AND ORBIT PHASED STELLAR EMISSION

Although no tidally induced variability has yet been reported, magnetic SPI has seen a blossoming of data and modeling over the past 15 years. The strongest evidence for magnetic SPI is excess stellar activity modulated in phase with a planet as it orbits a star with a rotation period significantly different from the planet’s orbital period. Such signatures were first reported by Shkolnik et al. (2003) who observed periodic chromospheric activity through Ca II H & K variability of HJ host HD 179949 modulated on the planet’s orbital period of 3.092 d (Butler et al. 2006) rather than the stellar rotation period of 7 days (Fares et al. 2012). Those data consisted of nightly high-resolution ($\lambda/\Delta\lambda \approx 110,000$), high signal-to-noise (a few hundred per pixel) spectroscopy acquired over several epochs (Figure 1, Shkolnik et al. 2005a, 2008; Gurdemir et al. 2012).

In addition to HD 179949, several other stars with HJs exhibit this kind of Ca II H & K modulation, including $\upsilon$ And, $\tau$ Boo, and HD 189733. Shkolnik et al. (2008) reported that this signature is present roughly \( \sim 75\% \) of the time. During other epochs only rotationally modulated spotting for these stars is observed. This is interpreted as variations in the stellar magnetic field configuration leading to weaker (or no) magnetic SPI with the planet’s field. Simulations of magnetic SPI using magnetogram data of the varying solar magnetic fields confirm this to be a likely explanation of the intermittent effect (Cranmer & Saar 2007). As another example, the large scale magnetic field of the planet-host star HD 189733 has been observed over multiple years using Zeeman-Doppler Imaging (ZDI) and the field shows structural evolution between observations (Moutou et al. 2007; Fares et al. 2010, 2013). In this case, the SPI diagnostics in the HD 189733 system must vary with the stellar magnetic field.

3. SCALING LAW TO MEASURE PLANETARY MAGNETIC FIELD STRENGTHS

In the solar system, there is a strong correlation between the magnetic moment of a body and the ratio of its mass to its rotation period (Figure 2). Analogously, a similar relationship has emerged for exoplanets. Figure 3 shows $M_p \sin i / P_{\text{orb}}$ against the stellar magnetic activity measure, $<\text{MADK}>$, the average of the Mean Absolute Deviation of Ca II K line variability per observing run. Note that the planet is assumed to be tidally locked such that $P_{\text{orb}}$ equals the rotation period of the planet.
Signatures of star-planet interactions

Figure 1. Integrated Ca II K residual flux of HJ host HD 179949 as a function of orbital phase where \( \varphi = 0 \) is the sub-planetary point (or inferior conjunction). The symbols are results from six individual epochs of observation collected from 2001 to 2006 by Shkolnik et al. (2003, 2005b, 2008) and Gurdemir et al. (2012). The spot model shown is fit to the 2001-2005 data and shows a persistent region of excess chromospheric activity peaking at the planet’s orbital phase of \( \sim 0.75 \).

Lanza (2009) and Lanza (2012) provided a straightforward formalism with which to scale the expected power emitted from magnetic SPI (\( P_{SPI} \)):

\[
P_{SPI} \propto B_\star^{4/3} B_p^{2/3} R_p^2 v
\]

where \( B_\star \) and \( B_p \) are the magnetic field strengths of the star and planet, respectively, \( R_p \) is the planet’s radius, and \( v \) is the relative velocity between the two bodies. This implies that systems with stars that are tidally locked to their HJs, i.e. stellar rotation period equals the orbital period as is the case for HJ host \( \tau \) Boo, should produce weak \( P_{SPI} \) (Figure 3; Shkolnik et al. 2008; Walker et al. 2008; Fares et al. 2013).

The strength of the planetary magnetic field for tidally locked planets has been a subject of debate but scaling laws presented by Christensen et al. (2009) and others reviewed in Christensen (2010) predict that the planet’s field strength depends primarily on the internal heat flux, and not on electrical conductivity nor the rotation speed. This same energy scaling can simultaneously explain the observed field strengths of Jupiter, Earth and rapidly rotating low-mass stars.

Using the formalism of Lanza (2009) above with the measured stellar magnetic fields from spectropolarimetric observation of these targets (e.g., Donati et al. 2008; Fares
et al. 2009, 2013; Jeffers et al. 2014; Hussain et al. 2016; Mengel et al. 2017), it is possible to use this correlation to estimate the relative magnetic field strengths of the planets, exhibiting a range of planetary magnetic field strengths of the HJs in these systems. For example, the HJ around HD 179949 appears to have a field strength seven times that of the HJ around HD 189733.

There are stars for which no planet phased activity is reported, e.g. HD 209458 (Shkolnik et al. 2008) and WASP 18 (Miller et al. 2015; Pillitteri et al. 2014b). In these cases, the central stars are particularly inactive with very weak fields and measurable SPI is not unexpected according to Lanza’s formalism as both the star and the planet require strong enough magnetic fields for an observable interaction. In addition, in many cases, the data collected were of too low S/N to detect any induced modulations caused by the planet and/or lacked phase coverage of the planetary orbit making it difficult to disentangle planet induced activity from stellar rotational modulation. The star may also have a highly variable magnetic field. If the stellar magnetic field is highly complex in structure then it may be that the magnetic field lines simply do not reach the orbit of the planet (Lanza 2009). Finally, the planet itself may have a weak magnetic field or no field at all.

4. MODELS AND OBSERVATIONS OF PLANET INDUCED VARIABILITY AT MANY WAVELENGTHS
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Figure 3. $M_p \sin i / P_{\text{orb}}$, which is proportional to the planet’s magnetic moment (Figure 2), plotted against the mean night-to-night Ca II K chromospheric activity (assuming the planet is tidally locked, $P_{\text{orb}} = P_{\text{rot}} \ast$). The green squares show systems where SPI has been detected. Note that τ Boo, for which $P_{\text{orb}} = P_{\text{rot}} \ast$ does not follow the trend. This is evidence in support of a model (Lanza 2009) where near-zero relative motion of the planet through the stellar magnetosphere produces minimal magnetic SPI effects (Shkolnik et al. 2008).

In addition to Ca II H & K observations, planet phased modulation has been reported in broadband optical photometry from space for τ Boo (Walker et al. 2008) and CoRoT-2 (Pagano et al. 2009) and in X-ray for HD 17156 (Maggio et al. 2015). Tentative evidence of planet phased X-ray modulation of HD 179949 was reported by Scandariato et al. (2013). They find an activity modulation period of $\sim 4$ days (with a false alarm probability of 2%), which is longer than the orbital period of 3.1 days, but may be tracing the synodic period of the planet with respect to the star ($P_{\text{syn}} = 4.7$–5.6 days for $P_{\text{rot}} = 7$–9 days). Clearer planet phased X-ray and far-UV modulation has also been reported for HD 189733 (Pillitteri et al. 2011, 2015).

From a modeling perspective, the combined flux at all wavelengths is needed to assess the total power emitted from such an interaction adding value to these higher energy observations. Ideally, simultaneous observations across optical, UV and X-ray activity indicators would be scheduled but has proven to be challenging to accomplish. From this and other perspectives discussed below, statistical studies of a large sample of monitored stars for planet phased stellar activity is the necessary path forward.
The HD 189733 system is one of the most studied as it is a bright K2V dwarf at a distance of 19.3 pc, hosts a transiting hot Jupiter at a distance of only 0.03 AU (Bouchy et al. 2005), and exhibits planet induced Ca II H & K variations (Shkolnik et al. 2005a, 2008). It has been the subject of multiple searches for X-ray flares that coincide with the orbit of the planet. Transit observations of HD 189733b, with phase coverage from $\phi = 0.52 - 0.65$ have shown that the X-ray spectrum softened in strict correspondence with the transit event, followed by a flaring event when the planet was at $\phi = 0.54$ (Pillitteri et al. 2010, 2011, 2014a). This phase offset for the beginning of the flare event corresponds to a location of 77° forward of the sub-planetary point, as is also the case for the HD 179949 system. This phased emission is best interpreted as the observational signature of an active spot on the surface of the star that is connected to, and co-moving with, the planet (Pillitteri et al. 2014a). Such a hot spot has been analytically derived by modeling the link between an exoplanet and the star (Lanza 2012). These authors calculated that if the planet is sufficiently close to the star (as is the case for hot Jupiters) the magnetic field lines that connect the star to the planet would produce such a phase offset owing to the relative orbital motion of the planet.

Simulations are also helping to understand SPI and planet phased emission through modeling studies aimed not at reproducing individual systems but rather at the general conditions that favor SPI. The first generation of SPI models focused primarily on recovering the phase offset between the sub-planetary point and the chromospheric hot spot rather than explaining the spot’s energy dissipation (McIvor et al. 2006; Preusse et al. 2006; Lanza 2008). The next generation of models explicitly included the planet and were able to show that the power generated in a reconnection event between the stellar corona and the planet can reproduce the observed hot spots (Lanza 2009; Cohen et al. 2011; Lanza 2013).

An investigation by Cohen et al. (2011) using the MHD code BATS-R-US showed that HD 189733b orbited in-and-out of the variable Alfvén radius and that when the planet was within the Alfvén radius its magnetosphere would reconnect with the stellar coronal field resulting in enhanced flaring from the host star. In their simulations the planet was implemented as an additional boundary condition representing HD 189733b’s density, temperature, and magnetic field strength. They found that SPI varies during the planetary orbit and is highly dependent on the relative orientation of the stellar and planetary magnetic fields.

A recent study by Matsakos et al. (2015) was aimed at categorizing various types of SPI using the 3D MHD PLUTO code (Mignone et al. 2007, 2012). They ran 12 models in total, detailed in Table 2 of Matsakos et al. (2015). Since they were seeking to explore the parameter regime over which the observational signature of SPI changes, they chose to explore various parameters for the planet and star, rather than adopting the parameters for a known system. They classify star-planet interactions into four types illustrated in Figure 4. Types III and IV describe scenarios where an
accretion stream forms between the planet and the star. For these interactions, the authors find that the ram pressure from the stellar wind must be greater than the magnetic and tidal pressures from the planet. The accretion stream arises through Kelvin-Helmholtz and Rayleigh-Taylor instabilities and is triggered by the interaction between the stellar wind and the denser planetary material. These simulations showed that the location where the accretion stream typically impacts the stellar surface is dependent on the parameters of the system but is typically $\sim 45 - 90^\circ$ in front of the planet. This finding is in good agreement with the observed SPI phase offsets discussed above.

![Figure 4](image)

**Figure 4.** The four types of star-planet interaction as described in Matsakos et al. (2015). In Type I, the ram and magnetic pressure of the stellar wind is greater than the planetary outflow, confining the material and leading to the formation of a bow shock (e.g., Vidotto et al. 2010; Llama et al. 2011). In Type II, the planetary outflow is stronger than in Type I resulting in material being swept back into a tail. The interactions of Types III and IV, the ram pressure of the stellar wind is greater than the tidal pressure of the planet, resulting in the formation of a tail behind the planet and an accretion stream onto the star. The accretion stream typically impacts the stellar surface $\sim 90^\circ$ ahead of the sub-planetary point, in agreement with observations of magnetic SPI.

5. **STATISTICAL STUDIES OF MAGNETIC SPI**

As the number of known exoplanets continuously rises, statistical studies are becoming an effective way to study the properties of exoplanetary systems. An effi-
cient strategy with which to study planet induced stellar emission is by analyzing single-epoch observations of a statistical sample in search of a significant difference in emission properties of stars with and without close-in giant planets.

From a sample of stars with Ca II H & K observations, Hartman (2010) showed a correlation between planet surface gravities and the stellar log $R'_{HK}$ activity parameter for 23 systems with planets of $M_p > 0.1 M_J$, $a < 0.1$ AU orbiting stars with $4200$ K $< T_{\text{eff}} < 6200$ K, with a weaker correlation with planet mass. In another study of 210 systems, Krejčová & Budaj (2012) found statistically significant evidence that the equivalent width of the Ca II K line emission and log $R'_{HK}$ of the host star correlate with smaller semi-major axis and larger mass of the exoplanet, as would be expected for magnetic and tidal SPI.

The efficiency of extracting data from large photometric catalogs has made studying stellar activity of many more planet hosts possible in both the ultraviolet (UV) and X-ray. A study of 72 exoplanet systems by Poppenhaeger et al. (2010) showed no significant correlation between the fractional luminosity ($L_X/L_{\text{bol}}$) with planet properties. They did, however, report a correlation of stellar X-ray luminosity with the ratio of planet mass to semi-major axis ($M_p \sin i/a$), suggesting that massive, close-in planets tend to orbit more X-ray luminous stars. They attributed this correlation to biases of the radial velocity (RV) planet detection method, which favors smaller and further-out planets to be detected around less active, and thus X-ray faint, stars.

A study of both RV and transit detected planets by Shkolnik (2013) of the far-UV (FUV) emission as observed by the Galaxy Evolution Explorer (GALEX) also searched for evidence of increased stellar activity due to SPI in $\sim$300 FGK planet hosts. This investigation found no clear correlations with $a$ or $M_p$, yet reported tentative evidence for close-in massive planets (i.e. higher $M_p/a$) orbiting more FUV-active stars than those with far-out and/or smaller planets, in agreement with past X-ray and Ca II results (Figure 5). There may be less potential for detection bias in this case as transit-detected planets orbit stars with a more normal distribution of stellar activity than those with planets discovered with the RV method. To confirm this, a sample of transiting small and distant planets still needs to be identified.

The first statistical SPI test for lower mass (K and M) systems was reported by France et al. (2016) in which they measured a weak positive correlation between the fractional N V luminosity, a transition region FUV emission line, with $M_p/a$ for the most massive planet in the system. They found tentative evidence that the presence of short-period planets (ranging in $M_p \sin i$ from 3.5 to 615 $M_{\text{Earth}}$) enhances the transition region activity on low-mass stars, possibly through the interaction of their magnetospheres (Figure 6).

Cohen et al. (2015) modeled the interaction between an M-dwarf and a non-magnetized planet like Venus. Their work shows very different results for the localized space-weather environments for the planet for sub- and super-Alfvénic stellar wind conditions. The authors postulate that these dynamic differences would lead to
additional heating and additional energy being deposited into the atmosphere of the planet. In all their simulations they find that the stellar wind penetrates much deeper into the atmosphere than for the magnetized planets simulated in Cohen et al. (2014), suggesting that for planets orbiting M dwarfs a magnetosphere may be necessary to shield the planet’s atmosphere.

Vidotto et al. (2014) modeled the stellar wind of six M stars ranging from spectral type M0 to M2.5 to study the angular momentum of the host star and the rotational evolution of the star. They found the stellar wind to be highly structured at the orbital separation of the planet, and found that the planetary magnetospheric radii could vary by up to 20% in a single orbit. This will result in high variability in the strength of SPI signatures as the planet orbits through regions of closed and open magnetic field, implying that a larger, statistical study may be the most efficient path forward, especially for M dwarfs.

6. PLANETARY EFFECTS ON STELLAR ANGULAR MOMENTUM EVOLUTION

As the evidence continues to mount that star-planet interactions measurably increase stellar activity, and now for a wider range of planetary systems, there remains an ambiguity in the larger statistical, single-epoch studies as to whether or not this effect is caused by magnetic SPI, tidal SPI or planet search selection biases. Although no tidal SPI has been observed as stellar activity modulated by half the planet’s orbital period (Cuntz et al. 2000a), there may be other effects due to the presence of the planets or planet formation process on the angular momentum evolution of the
Figure 6. Fractional N V (at 1240 Å) luminosity from a sample of 11 K and M dwarf planet hosts is weakly correlated with a measure of the star-planet interaction strength $M_p/a$, where $M_p$ is the mass of the most massive planet in the system (in Earth masses) and $a$ is the semi-major axis (in AU). The Pearson coefficient and statistical likelihood of a null correlation is shown at the top. This provides tentative evidence that the presence of short-period planets enhances the transition region activity on low-mass stars, possibly through the interaction of their magnetospheres (France et al. 2016).

stars, which might increase the stellar rotation through tidal spin-up or decrease the efficiency of stellar magnetic breaking (Lanza 2010; Cohen et al. 2011). In both cases, the star would be more active than expected for its mass and age.

For main sequence FGK stars, the magnetized stellar wind acts as a brake on the stellar rotation, decreasing the global stellar activity rate as the star ages. This well observed process has given rise to the so-called “age-rotation-activity” relationship. However, the presence of a short-period giant planet may affect the star’s angular momentum. Under this scenario, the age-activity relation will systematically underestimate the star’s age, potentially making “gyrochronology” inapplicable to these systems. This poses an issue for evolutionary studies of exoplanets and their host stars, including planet migration models and planet atmospheric evolution.

Several studies have found that stars hosting giant planets rotate faster than the evolutionary models predict. This increase in rotation rate is thought to be the direct consequence of tidal spin-up of the star by the planet. Additional evidence for the
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Tidal spin-up of stars by giant planets has been found using two hot Jupiter systems by Schröter et al. (2011) and Pillitteri et al. (2011). These studies searched for X-ray emission from M dwarf companions to the active planet hosts CoRoT-2 and HD 189733. Both systems showed no X-ray emission indicating the age of the systems to be > 2Gyr; however, the rotation-age relation places these systems between 100-300 Myr for CoRoT-2 and 600 Myr for HD 189733.

A study by Lanza (2010) showed that tides alone cannot spin-up the star to the levels seen in CoRoT-2 and HD 189733. Rather, his study postulated that the excess rotation is a consequence of interactions between the planetary magnetic field and the stellar coronal field. He proposed that these interactions would result in a magnetic field topology where the majority of the field lines are closed. This configuration would therefore limit the efficiency of the stellar wind to spin-down the star through angular momentum loss. By computing a simple linear force-free model, Lanza (2010) was able to compute the radial extension of the stellar corona and its angular momentum loss. He found that stars that host hot Jupiters show a much slower angular momentum loss rate than similar stars without a short-period giant planet, similar to Cohen et al. (2011).

In order to disentangle the possible causes of the observed increased stellar activity of HJ hosts observed from single-epoch observations, it is necessary to monitor the activity throughout the planet’s orbit and over the stellar rotation period. Such studies can better characterize the star’s variability, generate firmer statistical results of any planet induced activity, and assess the underlining physical processes involved. The first and only attempt to date of this was reported by Shkolnik et al. (2008) in which they monitored 13 HJ systems (all FGK stars) in search of orbit phased variability and then found a correlation between the median activity levels modulated by the planet and the $M_p \sin i/P_{orb}$ (Figures 3 and 2). In the case of multi-planet systems, the planet with the largest $M_p \sin i/P_{orb}$ should have the strongest SPI effects.

7. SUMMARY

Detecting exoplanetary magnetic fields enables us to probe the internal structures of the planets and to place better constraints on their atmospheric mass loss through erosion from the stellar wind. Searching for the observational signatures of magnetic SPI in the form of planet induced stellar activity has proved to be the most successful method to date for detecting magnetic fields of hot Jupiters.

Single-epoch statistical studies in search SPI signatures show that indeed there are significant differences in the activity levels between stars with close-in giant planets compared to those without. However, the cause of this remains ambiguous with four possible explanations.

- Induced stellar activity in the form of interactions between the stellar and planetary magnetic fields.
• The inhibition of magnetic breaking and thus faster than expected stellar rotation and increased stellar activity.

• Tidal spin-up of the star due the presence of the close-in planet.

• Lastly, the selection biases of planet hunting techniques.

These potential underlying causes of such a result highlight the need for further monitoring campaigns across planetary orbit and stellar rotation periods to clearly identify planet-induced excess stellar activity.

The vast majority of SPI studies, both individual monitoring as well as larger single-epoch statistical studies, have concentrated on main sequence FGK stars as they are the dominant hosts of hot Jupiters. These stars have the advantage of being relatively quiescent compared to M dwarfs, and thus teasing out signals produced by magnetic SPI from intrinsic stellar activity is simpler. But they also have the disadvantage of lower stellar magnetic field strengths compared to M dwarfs, lowering the power produced by the interaction.

The modeling of magnetic SPI, especially with realistic stellar magnetic maps from ZDI surveys, continues to advance and aid in the interpretation of observed planet phased enhanced activity across the main sequence. Additional models enable quantitative predictions of the radio flux density for stars displaying signatures of SPI. Radio detections of at least a few of these systems will help calibrate the relative field strengths, and provide for the first time, true magnetic field strengths for hot Jupiters.

Ongoing and future studies of magnetic SPI in a large sample of systems are necessary for improved statistics and distributions of magnetic fields of exoplanets. Extensions of these techniques to other tightly orbiting stellar systems, such as smaller planets close to M dwarfs, are challenging but possible. In these systems, star-planet separations of tens of stellar radii begin to coincide with the radiative habitable zone where planetary magnetic fields are likely a necessary condition for surface habitability. As more close-in planets around relatively bright M dwarfs are discovered by missions such as TESS, the search for magnetic star-planet interactions will be extended to these low-mass stars.
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