ON THE DETECTABILITY OF STAR–PLANET INTERACTION

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Abstract

Magnetic (or tidal) interactions between “hot Jupiters” and their host stars can potentially enhance chromospheric and coronal activity. An ideal test bed for investigating this effect is provided by the extreme WASP-18 system, which features a massive (~10 times Jupiter) close-in (~1 day period) transiting planet orbiting a young F6 star. Optical and X-ray observations of WASP-18 were conducted in 2011 November. The high-resolution echelle spectrograph Magellan Inamori Kyocera Echelle was used on the 6.5 m Magellan Clay Telescope to obtain 13 spectra spanning planetary orbital phases of 0.7–1.4, while the X-ray Telescope on Swift provided contemporaneous monitoring with a stacked exposure of ~50 ks. The cores of the Ca II H and K lines do not show significant variability over multiple orbits spanning ~8 days, in contrast to the expectation of phase-dependent chromospheric activity enhancements for efficient star–planet interaction. The star is also X-ray faint, with log $L_X < 27.6$, indicating that coronal activity is likely low. The lack of detectable star–planet interaction in this extreme system requires that any such effect here must be transient, if indeed present. We demonstrate that searches for Ca II H and K variability can potentially mistake a stellar hotspot, if observed over a short segment of the rotation period, for planet-induced activity. Taken together, these results suggest that the utility of star–planet interaction as a robust method of estimating exoplanet magnetic field strengths may be limited.

Key words: planetary systems – stars: activity – stars: individual (WASP-18) – stars: magnetic field

Online-only material: color figures

1. INTRODUCTION

The possibility of magnetic star–planet interactions was initially explored by Cuntz et al. (2000; see also Rubenstein & Schaefer 2000), and this and subsequent work has indicated that reconnection events could be an important effect in “hot Jupiter” systems, acting to produce enhancements in chromospheric and coronal activity corotating with the planet rather than with the stellar rotation. It has been conjectured that the energy available from reconnection events should scale with the product of the stellar and planetary magnetic field strengths, as well as the relative velocity of the magnetic field lines, and inversely with approximately the square of the orbital semimajor axis (Cuntz et al. 2000; Kashyap et al. 2008). Consequently, a calibrated relationship between the amplitude of star–planet interaction and stellar and orbital parameters could permit estimation of exoplanet magnetic field strengths. Throughout this work, we quantify interaction strength in otherwise similar systems as $M_P/a^2$, where $a$ is the semimajor axis in AU and the planetary magnetic field strength is taken to scale with the planetary mass $M_P$ (e.g., Arge et al. 1995; Stevens 2005); this is broadly consistent with the various proposed trends investigated (e.g., Kashyap et al. 2008; Shkolnik et al. 2008; Scharf 2010; Poppenhager et al. 2010). Numerical studies suggest that star–planet interactions can potentially generate sufficient energy to be observable as, e.g., phase-variable core Ca II H and K or X-ray emission (probing chromospheric and coronal activity, respectively) in monitoring of individual hot Jupiter systems, or as a greater average level of activity in systems with more massive or closer-in planets. For example, Lanza (2008) and Lanza et al. (2011) modeled chromospheric hot spots in several systems (offset from the subplanetary point by varying degrees) as arising from star–planet magnetic reconnection events, and Cohen et al. (2009, 2011) carried out three-dimensional magnetohydrodynamic simulations demonstrating that close-in giant planets can produce an increase in overall stellar activity and generate (non-persistent) coronal hot spots that rotate synchronously with the planet (albeit potentially shifted in phase); see also Pillitteri et al. (2010).

Observational evidence of magnetic star–planet interaction has now been presented for several individual systems. For example, Shkolnik et al. (2005) examined 10 stars (K1 to F7) known at the time to possess massive, close-in planets (median minimum planetary mass $M_P \sin i = 0.6 M_{\text{Jup}}$, median orbital period $P = 3.4$ days), in low-eccentricity orbits, and claimed evidence of star–planet interaction in HD 179949 and $\nu$ And (both F8) based on slight Ca II H and K emission variability synchronized with the planetary period (see also discussion in Gu et al. 2005), although this synchronization is apparently transient (Shkolnik et al. 2008). Chandra observations of HD 179949 showed variable X-ray emission with an apparently maximum near the phase associated with Ca II H and K enhancement (Saar et al. 2008). Fares et al. (2012) carried out spectropolarimetric observations of HD 179949, finding that the stellar magnetosphere is highly tilted (producing two maxima per rotation period) and that chromospheric activity is primarily linked to stellar rotation, although low-level fluctuations near the beat period could be planet induced (see also Guerdemir 2012).
field strengths in hot Jupiter systems, additional convincing instances, beyond the handful suggested to date, must be identified. Observations of a strongly interacting system could constitute a contextual template to guide interpretation of results in more weakly interacting systems (including those already studied). Additionally, a robust measurement of star–planet interaction in an extreme high-mass, short-period system would supply productive leverage for uncovering and later quantifying scaling relations. Conversely, a failure to detect planet-induced stellar activity in an extreme system would severely constrain the practical relevance of star–planet interaction and could impact theoretical understanding and numerical modeling of this effect.

1.1. WASP-18 in Context

We identified WASP-18 as the potentially most strongly interacting system among currently discovered exoplanets, a distinction it retains as of 2012 April. We obtained a list of all confirmed planets with $M_p > 0.1 M_J$ (i.e., planetary mass greater than 10% that of Jupiter), orbital period $P < 100$ days, and $V < 15$ from the Exoplanet Orbit Database7 (Wright et al. 2011). As may be seen in Figure 1, WASP-18b (Hellier et al. 2009; Southworth et al. 2009), with $M_p = 10.4 M_J$, $P = 0.941$ days, and $a = 0.020$ AU, has the largest value of the interaction strength proxy $M_p/a^2$ within this sample (and would also rank first for other plausible parameterizations of interaction strength). More specifically, after excluding brown dwarfs (with $M_p > 13 M_J$), of the 551 entries in the Exoplanet Orbit Database, the $M_p/a^2 \simeq 50,000 M_J$ AU$^{-2}$ for WASP-18 is nearly 2.5 times greater than the next largest value (CoRoT-14b), and only five systems have $M_p/a^2 > 5000 M_J$ AU$^{-2}$. Because WASP-18 is a transiting system, the planetary properties are securely established by light curve and radial velocity measurements. The values of $M_p/a^2$ are also labeled for several systems described in Section 1; for example, HD 179949 has $M_p/a^2 \simeq 500 M_J$ AU$^{-2}$.

The stellar and planetary properties for the WASP-18 system are given in Table 1, as are those for previously identified star–planet interaction candidates HD 179949, $\upsilon$ And, and $\tau$ Boo (but recall $\tau$ Boo is tidally locked, with stellar and orbital periods of $\sim 3.2$ days, which may suppress magnetic interaction). The value of $M_p/a^2$ for WASP-18b exceeds that for the other candidate systems by one to two orders of magnitude. Such extreme planetary systems are difficult to maintain, and WASP-18b itself is expected to have a short lifetime against infall from tidal drag (Hellier et al. 2009). The star WASP-18 has spectral type F6, effective temperature $T_{\text{eff}} = 6400 \pm 100$ K, and stellar mass $M_* = 1.22 \pm 0.03 M_\odot$ (values from the Exoplanet Orbit Database, from which original references may be obtained); conversely, these are similar to the properties of HD 179949 (F8, 6170 K, 1.18 $M_\odot$), $\upsilon$ And (F8, 6210 K, 1.31 $M_\odot$), and $\tau$ Boo (F7, 6390 K, 1.34 $M_\odot$). WASP-18 is slightly hotter than HD 179949 and $\upsilon$ And, and consequently likely possesses a slightly shallower outer convection zone. On the other hand, the stellar rotation period is shorter, at $\sim 5.6$ days, estimated from $v \sin i = 11$ km s$^{-1}$; the orbit and stellar rotation are aligned8 (Triaud et al. 2010). HD 179949 and $\upsilon$ And have rotational periods of 7.6 days (Fares et al. 2012) and $\sim 12$ days (Shkolnik et al. 2008), respectively. Further, WASP-18 appears

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7 Available at http://www.exoplanets.org.
8 All four of these systems are near the $T_{\text{eff}} \sim 6250$ K border above which hot Jupiter hosts tend to have high stellar obliquities (Winn et al. 2010), but the spin–orbit alignment in WASP-18 is more characteristic of cooler hot Jupiter hosts.

In this paper, we present a sensitive search for star–planet interaction in the extreme WASP-18 system. If star–planet interaction is to become a useful probe of exoplanet magnetic
to be a younger star, with an age of \sim 500–700 Myr (Hellier et al. 2009; Brown et al. 2011). The age–rotation-activity relation would then predict relatively greater intrinsic activity in WASP-18, apart from any planet-induced modulation or enhancement (but see Section 3.2 for caveats). Observationally, WASP-18 has other appealing features: the star is among the brighter transit-detected systems, and the short planetary period facilitates rapid accumulation of phase coverage across multiple orbits. Due to its extreme properties, WASP-18 has been studied at a range of frequencies; for example, Nymeyer et al. (2011) used Spitzer observations of secondary eclipse to infer that the planet has \( T \sim 3100 \) K with near-zero values for both albedo and day/night side energy redistribution. However, high-resolution, high signal-to-noise Ca\( ^{\text{ii}} \) H and K spectroscopy, and sensitive X-ray observations have not been published prior to the observations presented here.

## 2. OBSERVATIONS

### 2.1. Data Acquisition and Reduction

Optical spectroscopy was carried out with the 6.5 m Clay Telescope on 2011 November 6–7 and 10–13 using the Magellan Inamori Kyocera Echelle (MIKE), a high-throughput double echelle spectrograph. A \( 0^\circ 7 \times 5^\prime \) slit was used throughout, providing a resolution of \( R \sim 40,000 \) near the Ca\( ^{\text{ii}} \) H and K lines. A communication board failure prevented use of the blue-side CCD on November 10 and bad weather limited observing on November 11. In total, 13 visits to WASP-18 were obtained.

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**Table 1: Candidates for Star–Planet Interaction**

| Star   | Type | V   | B−V | d      | \( M_P \) | \( P \) | \( a \) | Age (Gyr) | \( M_P/a^2 \) | \( R_{\text{HK}} \) | log \( L_X \) | log \( (L_X/L_{\text{bol}}) \) |
|--------|------|-----|-----|--------|----------|-------|-------|-----------|-------------|-------------|-----------|----------------|
| WASP-18| F6   | 9.39| 0.49| 100    | 10.4     | 0.94  | 0.0201| 0.6       | 25700       | <−5.0       | <27.6     | <−6.2        |
| τ Boo  | F7   | 4.50| 0.51| 15.62  | 4.1      | 3.31  | 0.0480| 2.5       | 1780        | −4.73       | 28.8      | −5.3         |
| HD 179949 | F8 | 6.25| 0.55| 27.5   | 0.95     | 3.09  | 0.0439| 2.1       | 490         | −4.80       | 28.6      | −5.3         |
| \( \upsilon \) And | F8 | 4.10| 0.54| 13.49  | 0.69     | 4.62  | 0.0594| 3.8       | 200         | −5.07       | 27.6      | −6.5         |

**Notes.** Data are taken from the Exoplanet Orbit Database (http://www.exoplanets.org), except for planetary mass and system age which are from the Extrasolar Planets Encyclopedia (http://www.exoplanet.eu), and log \( L_X \) which is from this work, Poppenhaeger et al. (2012), Kashyap et al. (2008), and Poppenh"ager et al. (2010) for WASP-18, τ Boo, HD 179949, and \( \upsilon \) And, respectively; log \((L_X/L_{\text{bol}})\) is calculated.

\( a \) Estimated from our measured log \( L_X < 27.5 \text{ erg s}^{-1} \) and the \( R_{\text{HK}} \sim \log (L_X/L_{\text{bol}}) \) correlation in Mamajek & Hillenbrand (2008). See also footnote 15.

\( b \) The potential strength of magnetic star–planet interaction in the τ Boo system is reduced due to the apparent tidal locking of the star to the planet; see Section 1.
with combined exposure times of 20–40 minutes per visit. The planetary orbital phase coverage (Figure 2) spans 0.7–1.4 and includes one visit at central planetary transit.

The XRT observations were initially planned for similar phase-resolved analysis, but the star proved to be unexpectedly X-ray faint (see also Section 3.2) and so all sequences were combined for an effective exposure of ~50 ks. WASP-18 is not detected by XRT in the stacked exposure, in either the soft (Figure 4) or the full bands. Specifically, within an aperture of 20″ centered on the SIMBAD optical position of WASP-18, there are 3.8 counts in the 0.3–2 keV band, where the expected background is 3.7 counts. The 95% upper limit on the source counts within 20″ is <5.9 net counts (from Kraft et al. 1991), corresponding to <8.1 total net counts after accounting for the XRT point-spread function (Moretti et al. 2005). For a coronal model with $kT = 1$ keV and solar abundances, the unabsorbed 0.3–2 keV X-ray flux is $<3.3 \times 10^{-15}$ erg s$^{-1}$, calculated using the Portable Interactive Multi-Mission Simulator for a plasma/APEC model presuming an intervening column of $N_H = 10^{18}–10^{19}$ cm$^{-2}$; other plausible models give similar.

10 This may be verified through comparison to the residuals near photospheric absorption features, which should not show any variability phased with the planetary orbit.

11 http://cxc.harvard.edu/toolkit/pimms.jsp
results to within \( \lesssim 30\% \) (or 0.1 dex). At the Hipparcos distance to WASP-18 of 100 \( \pm 10.6 \) pc, this corresponds to a limiting X-ray luminosity of \( \log L_X < 27.6 \) erg s\(^{-1}\) (0.3–2 keV).

3. DISCUSSION

We compare the observed persistent low activity in WASP-18 to expectations for planet-induced variability, as well as to the intrinsic properties of similar stars, and additionally explore the general possibility of stellar hotspots acting to mimic star–planet interaction.

3.1. Expected Variability in WASP-18

Past work would seem to suggest that the degree of planet-induced Ca \( \Pi \) H and K variability expected for WASP-18 could be substantial. For example, Shkolnik et al. (2005, 2008) report “on/off” Ca \( \Pi \) H and K variability phased with the planetary...
orbital period in HD 179949 and \( \nu \) And (see also Poppenh"ager et al. 2011), which have stellar types of F8 and do not show obvious core emission within the deep photospheric absorption (similar to WASP-18). The amplitude of residual flux associated by Shkolnik et al. (2008, Figure 3; Shkolnik et al. 2005, Figure 6) with star–planet activity in HD 179949 (\( \nu \) And) is \( \lesssim 0.017 \) (\( \approx 0.008 \)). The value of \( M_p/a^2 \) for WASP-18 could suggest an effect 50 (130) times greater than for HD 179949 (\( \nu \) And). In contrast to such predictions, the level of phase-binned variability observed for WASP-18 is \( \lesssim 0.003 \) (Figure 3; Section 2.2), below the levels detected in HD 179949 and \( \nu \) And.

The degree of X-ray variability expected in WASP-18 is more difficult to estimate, as only a handful of X-ray-brightening events have been attributed to potential star–planet interaction. For example, HD 179949 displayed an increase in X-ray emission by \( \sim 30\% \) near the phase associated with the Ca II H and K enhancement (Saar et al. 2008); with a stellar X-ray luminosity of \( \log L_X = 28.6 \) erg s\(^{-1} \) (Kashyap et al. 2008), this is an increase of \( \log L_X = 28.1 \) erg s\(^{-1} \). HD 189733 showed two X-ray flares near phase 0.53 (i.e., shortly after occultation), peaking at twice the baseline count rate (Pillitteri et al. 2011); with a stellar X-ray luminosity of \( \log L_X = 28.4 \) erg s\(^{-1} \) (Kashyap et al. 2008), this is an increase of \( \log L_X = 28.4 \) erg s\(^{-1} \). Cohen et al. (2011) used their MHD modeling of the HD 189733 system to estimate that the energy available from magnetic reconnection to accelerate particles into the stellar corona is \( \sim 10^{26} \) erg s\(^{-1} \) (after applying conservative efficiency assumptions). From these examples, WASP-18 might be expected, taking into account its exceptional value of \( M_p/a^2 \), to possess interaction energy available for coronal activity enhancement sufficient to generate absolute increases in its X-ray luminosity by several times \( 10^{26} \) erg s\(^{-1} \). However, the observed XRT upper limit of \( \log L_X < 27.6 \) erg s\(^{-1} \) indicates that the X-ray luminosity did not achieve this level for any more than \( \lesssim 10\% \) of the Swift coverage. Without even a stacked X-ray detection it is not possible to evaluate the relative amplitude of phase-dependent X-ray variability, if any, in WASP-18.

The scaling of star–planet interaction strength with \( M_p/a^2 \) that we (and others; Section 1) have adopted approximately holds for otherwise similar systems. We briefly consider the impact upon the energy available for star–planet interaction due to potentially differing planetary or stellar magnetic field strengths in WASP-18 compared to HD 179949 and \( \nu \) And. The planetary magnetic field strength depends most relevantly upon \( M_p \) but also scales inversely with the planetary rotational period. For tidally locked planets, as all these are believed to be (out to \( \sim 0.15 \) AU; Bodenheimer et al. 2001), the planetary rotation period is identical to the orbital period, and both are substantially shorter for WASP-18 than for HD 179949 or \( \nu \) And. This suggests (Arge et al. 1995; Sánchez-Lavega 2004; Stevens 2005) an increase in baseline planetary magnetic field strength by a factor of a few, which would enhance any star–planet interaction. The relative velocity between magnetic field lines, which is governed by the difference between the planetary and stellar rotation rates, is \( v_{\text{rel}} = K(R_*/a) - v_{\text{rot}} \) for tidally locked planets, where \( K \) is the orbital velocity and \( v_{\text{rot}} \) is the equatorial stellar rotational velocity (Cuntz et al. 2000). This would suggest a further increase in interaction strength by a factor of a few. On the other hand, the interaction strength approximately scales with the stellar magnetic field, \( B_\star \) (Cuntz et al. 2000; Kashyap et al. 2008; see Lian 2009 and Scharf 2010 for slightly different formulations), which appears to be substantially weaker in WASP-18 than in at least HD 179949 and perhaps also \( \nu \) And. This is evident by the X-ray nondetection of WASP-18, as \( B_\star \) is observed to depend approximately linearly upon \( L_X \) (Pevtsov et al. 2003). That log (\( L_X/L_\odot \)) is at least one order of magnitude lower in WASP-18 than HD 179949 possibly offsets any gains in interaction strength due to faster planetary rotation, although the difference in inferred stellar magnetic field strengths is less between WASP-18 and \( \nu \) And. However, since the observed amplitude of Ca II H and K variability in WASP-18 is already \( \gtrsim 5 \) times lower than that suggested to arise from star–planet interaction in HD 179949, \( B_\star \) would need to be \( \gtrsim 50 \) times lower in WASP-18 than in HD 179949 to explain our nondetection for a similar interaction efficiency, which seems implausible given their similar stellar spectral types.

The lack of evidence for star–planet interaction in WASP-18 is unexpected given that we selected it as the system with the greatest predicted interaction strength (based on planetary mass and semimajor axis) and given the broad similarity in stellar properties between WASP-18 and other systems (notably HD 179949 and \( \nu \) And) for which star–planet interaction has been claimed. Star–planet interaction in WASP-18 would seem to be at best highly transient as it was not demonstrably present during our observations. For reference, Ca II H and K variability has been described as phased with the planetary orbit in \( \lesssim 50\% \) of the epochs at which HD 179949 and \( \nu \) And have been observed. Further, the timescale for a magnetic reconnection event in the simulations of Cohen et al. (2011) is short, \( \sim 0.25 \) orbits. On the other hand, our spectroscopic coverage of WASP-18 extends over eight complete planetary orbits, and the X-ray observations cover many more (albeit at a lower sensitivity per orbit). To the extent that star–planet interactions are transient, they should intuitively occur with greater frequency in extreme systems such as WASP-18, which contrasts (if not definitively) with our findings. It might be alternatively suggested that, if our observations did not simply happen to take place within a period of relative quiescence, the efficiency of star–planet interaction

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12 The ratio of residuals for HD 179949 and \( \nu \) And is \( \sim 2 \), while the ratio of \( M_p/a^2 \) is \( \sim 2.5 \). However, given the dissimilarity of other parameters, such as intrinsic stellar activity, and the apparent variability of any star–planet interaction in these systems, we do not consider this necessarily informative.

13 While less physically motivated, alternative scalings with either separately \( 1/a^2 \) or \( M_p \) would still predict a substantially greater effect for WASP-18, by a factor of 4.8 (8.7) or 11 (15) compared to HD 179949 (\( \nu \) And).
for WASP-18 could be lower than has been identified in the past for less extreme systems. However, we emphasize again that WASP-18 is not notably distinctive in terms of stellar properties from HD 179949 and ν And. (Below, we explore the possibility that the particularly massive and close-in planet in WASP-18 actually acts to suppress stellar activity.)

Regardless of its underlying cause, this lack of observed variability in WASP-18 demonstrates that even extreme systems, arguably the best candidates to display planet-induced activity enhancements, challenge prevailing ideas concerning star–planet interaction. The appealing prospect of calibrating star–planet interactions to estimate exoplanet magnetic field strengths would currently appear to require additional unambiguous evidence of such interactions occurring.

3.2. Expected Intrinsic Activity in WASP-18

We next consider the overall baseline level of chromospheric and coronal activity in WASP-18, to provide context for the nondetection of planet-induced variability. WASP-18 shows atypically low Ca II and coronal activity in WASP-18, to provide context for the which is not based on Ca II activity, main-sequence F, G, K, or M stars with inferred activities occurring.

The appealing prospect of calibrating star–planet interactions to estimate exoplanet magnetic field strengths would currently appear to require additional unambiguous evidence of such interactions occurring.

3.3. An Additional Challenge to Observations of Star–Planet Interaction

Here, we explore the possibility that a hotspot rotating upon the stellar surface can potentially mimic a shorter-period signature of star–planet interaction if only observed over a small fraction of the stellar rotation. Figure 5 shows simulated examples for HD 179949 and ν And, which have stellar planetary periods of 7/3.09 and 14/4.618 days, respectively (Shkolnik et al. 2008). The half and full sinusoidal models for planet-induced activity chosen for these examples are similar to those applied by Shkolnik et al. (2005, 2008) to these systems, but here for an edge-on inclination and with arbitrary (2009) encompass ≥1 Gyr, and the Brown et al. (2011) estimate depends upon complicated planet–star interactions. If the planet has acted to spin up the star (recall the orbital plane and the stellar rotation axis are aligned), the current relatively rapid stellar rotation rate would not be reflective of true age. Stellar age has proven difficult to determine in some other hot Jupiter systems; for example, Schröter et al. (2011) find that CoRoT-2a is X-ray bright and young but a late-K companion is X-ray undetected, inconsistent with the inferred system age, and a similar situation may apply for HD 189733 (Pillitteri et al. 2011). If WASP-18 were two to three times older than current estimates, the intrinsic activity would still be somewhat low but to a much less unusual degree. If the age is indeed correct, it is natural to consider whether the extremely massive and close-in planet could act to suppress, rather than enhance, stellar activity. The tidal force exerted by WASP-18 upon its parent star is much greater than is typical even for hot Jupiter systems, and in fact Arras et al. (2012) note that the small but apparently non-zero eccentricity indicated by radial velocity data is likely due to tidal fluid motion on the star. Mid-type F stars have shallow outer convective zones; perhaps the tidal pull is sufficient to repress dynamo activity in WASP-18 or comparably extreme systems (of which none are, however, currently known). This possibility could be assessed through magnetohydrodynamic simulations.

14 The age of WASP-18 is estimated as 630+950−530 Myr by Hellier et al. (2009) based on stellar isochrones, and as 570+375−560 Myr by Brown et al. (2011) based on tidal interaction modeling.

15 A recent high signal-to-noise Keck/HIRES spectrum of WASP-18, calibrated as described in Wright et al. (2004), gives $R_{\text{HK}} = -5.15$ (H. Isaacson 2012, private communication).
normalizations. (By construction the stellar hotspot amplitude is taken as unity, and the relative amplitude of the interaction model is then greater for HD 179949 than for \upsilon\ And, also qualitatively similar to the published models.) The probability of the stellar and planetary phases co-aligning to mimic star–planet interaction for these particular models is not very large (e.g., \(\lesssim 3\%\) of 10,000 random phase offsets for each example yield total squared residuals less than 0.1), but with additional freedom to adjust the relative amplitudes, or to consider additional parameters (such as spot latitude or system inclination, within a limited range) or to choose from alternative model functional forms, or with a greater tolerance for (apparent) outliers, this effect could potentially present a significant source of contamination within a large sample of tested stars. For the particular cases of HD 179949 and \upsilon\ And, it must be emphasized that several observing runs were conducted, and in some (but not all) of those runs variability of similar amplitude similarly phased with the planetary orbit was observed (Shkolnik et al. 2005, 2008; Poppenhäger et al. 2011), which clearly decreases the probability of mistaking a stellar hotspot for one corotating with the planet.

We note that, in general, searches for star–planet interaction based on Ca\textsc{ii} core variability can guard against this type of false positive at a given epoch through obtaining coverage over at least one complete stellar rotation and over multiple planetary orbits (as was done with our coverage of WASP-18). If searches over multiple epochs find some instances in which core variability phases with the stellar rotation and others in which it apparently matches the orbital period, a comparison of the amplitudes can also check whether the observed activity is likely to arise from distinct (intrinsic versus planet-induced) sources. It would be odd if the activity in the “off” state (phased with stellar rotation rather than orbital period) had a similar amplitude to that seen in the “on” state, during which there is no obvious physical reason that the star should otherwise go silent. It is not clear to us that the current data for HD 179949 and \upsilon\ And can definitively pass this test, but see, e.g., Fares et al. (2012). In any case, the conclusion is that complete and extended coverage, preferably across multiple epochs and multiple orbits per epoch, is essential for high-confidence detections of star–planet interaction.

4. CONCLUSIONS

We have carried out a sensitive search for planet-induced stellar activity within the extreme WASP-18 system, selected as an ideal test bed for investigating potential magnetic (or tidal) interactions between “hot Jupiters” and their host stars. High-resolution spectroscopy of the Ca\textsc{ii} H and K lines was conducted with the 6.5 m Magellan Clay Telescope and contemporaneous X-ray monitoring was obtained with the Swift satellite. Our primary results are the following.

1. The Ca\textsc{ii} H and K cores do not show significant variability over \(\sim 8\) days. Stacking residual spectra from 13 visits into phase bins of 0.70–0.93, 0.99–1.19, and 1.21–1.41 does not show any significant structural changes that could be attributed to planetary influence.

2. WASP-18 is not detected in a stacked 50 ks XRT exposure, constraining the X-ray luminosity to be unusually low for a young F6 star, with log \(L_X\) < 27.6.

3. The lack of observed variability phased with the planetary orbit suggests that any magnetic star–planet interaction in WASP-18 must be transient, if present at all.

4. The low level of chromospheric and coronal activity is consistent with an intrinsically weak magnetic field on WASP-18, perhaps indicating that the inferred young stellar age is not reliable, or alternatively potentially related to particularly strong planetary tidal effects.

5. It is demonstrated that a stellar hotspot can potentially mimic star–planet interaction, for observations truncated to a short segment of the rotation period.

6. Current ideas concerning star–planet interaction do not appear to be supported by the above results; therefore, it may be optimistic at present to conceive of star–planet interaction as a robust estimator of exoplanet magnetic field strengths.

Further high-quality Ca\textsc{ii} H and K spectroscopy (as in Shkolnik et al. 2005, 2008) of previously monitored and newly discovered systems would refine understanding of the observational signatures of star–planet interaction. In addition, we are currently carrying out a Chandra survey of solar analogs to check whether stars with close-in planets are systematically enhanced in X-ray luminosity, and this experiment has been designed to sidestep many of the selection biases that necessarily challenged previous large-sample X-ray studies. That investigation will help further clarify whether the difficulties in establishing observational evidence of star–planet interaction in WASP-18 are anomalous or typical.

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REFERENCES

Arge, C. N., Mullan, D. J., & Dolginov, A. Z. 1995, ApJ, 443, 795

Arras, P., Burkart, J., Quataert, E., & Weinberg, N. N. 2012, MNRAS, 422, 1761

Bodenheimer, P., Lin, D. N. C., & Mardling, R. A. 2001, ApJ, 548, 466

Brown, D. J. A., Collier Cameron, A., Hall, C., Hebb, L., & Smalley, B. 2011, MNRAS, 415, 605

Buccino, A. P., & Manas, P. J. D. 2008, A&A, 483, 903

Canto Martins, B. L., Das Chagas, M. L., Alves, S., et al. 2011, A&A, 530, A73

Cohen, O., Drake, J. J., Kashyap, V. L., et al. 2009, ApJ, 704, L85

Cohen, O., Kashyap, V. L., Drake, J. J., et al. 2011, ApJ, 733, 67

Cuntz, M., Saar, S. H., & Musielak, Z. E. 2000, ApJ, 533, L151

Fares, R., Donati, J.-F., Moutou, C., et al. 2010, MNRAS, 406, 409

Fares, R., Donati, J.-F., Moutou, C., et al. 2012, MNRAS, 423, 1006

Freire Ferrero, R., Frasca, A., Marilli, E., & Catalano, S. 2004, A&A, 413, 657

Gu, P.-G., Shkolnik, E., Li, S.-L., & Liu, X.-W. 2005, Astron. Nachr., 326, 909

Gudrenrik, L., Redfield, S., & Cuntz, M. 2012, PASA, 29, 141

Hellier, C., Anderson, D. R., Collier Cameron, A., et al. 2009, Nature, 460, 1098

Henry, T. J., Soderblom, D. R., Donahue, R. A., & Baliunas, S. L. 1996, AJ, 111, 439

Kashyap, V. L., Drake, J. J., & Saar, S. H. 2008, ApJ, 687, 1339

Kraft, R. P., Burrows, D. N., & Nousek, J. A. 1991, ApJ, 374, 344

Krejčíová, T., & Budaj, J. 2012, A&A, 540, A82

Lanza, A. F. 2008, A&A, 487, 1163

Lanza, A. F. 2009, A&A, 505, 339

Lanza, A. F., Bonomo, A. S., Pagano, I., et al. 2011, A&A, 525, A14

Lenz, L. F., Reiners, A., & Küster, M. 2011, in ASP Conf. Ser. 448, 16th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. C. Johns-Krull (San Francisco, CA: ASP), 1173

Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264
Moretti, A., Campana, S., Mineo, T., et al. 2005, Proc. SPIE, 5898, 360
Nymeyer, S., Harrington, J., Hardy, R. A., et al. 2011, ApJ, 742, 35
Pevtsov, A. A., Fisher, G. H., Acton, L. W., et al. 2003, ApJ, 598, 1387
Pillitteri, I., Günther, H. M., Wolk, S. J., Kashyap, V. L., & Cohen, O. 2011, ApJ, 741, L18
Pillitteri, I., Wolk, S. J., Cohen, O., et al. 2010, ApJ, 722, 1216
Poppenhäger, K., Günther, H. M., & Schmitt, J. H. M. M. 2012, Astron. Nachr., 333, 26
Poppenhäger, K., Lenz, L. F., Reiners, A., Schmitt, J. H. M. M., & Shkolnik, E. 2011, A&A, 528, A58
Poppenhäger, K., Robrade, J., & Schmitt, J. H. M. M. 2010, A&A, 515, A98
Poppenhäger, K., Robrade, J., Schmitt, J. H. M. M., & Hall, J. C. 2009, A&A, 508, 1417
Poppenhäger, K., & Schmitt, J. H. M. M. 2011, ApJ, 735, 59
Preibisch, T., & Feigelson, E. D. 2005, ApJS, 160, 390
Rubenstein, E. P., & Schaefer, B. E. 2000, ApJ, 529, 1031
Saar, S. H., Cuntz, M., Kashyap, V. L., & Hall, J. C. 2008, in IAU Symp. 249, Exoplanets: Detection, Formation and Dynamics, ed. Y.-S. Sun, S. Ferraz-Mello, & J.-L. Zhou (Cambridge: Cambridge Univ. Press), 79
Sánchez-Lavega, A. 2004, ApJ, 609, L87
Scharf, C. A. 2010, ApJ, 722, 1547
Schmitt, J. H. M. M. 1997, A&A, 318, 215
Schmitt, J. H. M. M., & Liefke, C. 2004, A&A, 417, 651
Schröter, S., Czesla, S., Wolter, U., et al. 2011, A&A, 532, A3
Shkolnik, E., Bohlender, D. A., Walker, G. A. H., & Collier Cameron, A. 2008, ApJ, 676, 628
Shkolnik, E., Walker, G. A. H., Bohlender, D. A., Gu, P.-G., & Kürster, M. 2005, ApJ, 622, 1075
Southworth, J., Hinse, T. C., Dominik, M., et al. 2009, ApJ, 707, 167
Stelzer, B., & Neuhauser, R. 2001, A&A, 377, 538
Stevens, I. R. 2005, MNRAS, 356, 1053
Triaud, A. H. M. J., Collier Cameron, A., Queloz, D., et al. 2010, A&A, 524, A25
Walker, G. A. H., Croll, B., Matthews, J. M., et al. 2008, ApJ, 682, 691
Winn, J. N., Fabrycky, D., Albrecht, S., & Johnson, J. A. 2010, ApJ, 718, L145
Wright, J. T., Fahourti, O., Marcy, G. W., et al. 2011, PASP, 123, 412
Wright, J. T., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2004, ApJ, 152, 261