A CORRELATION BETWEEN STELLAR ACTIVITY AND THE SURFACE GRAVITY OF HOT JUPITERS

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ABSTRACT

Recently, Knutson et al. have demonstrated a correlation between the presence of temperature inversions in the atmospheres of hot Jupiters and the chromospheric activity levels of the host stars. Here, we show that there is also a correlation, with greater than 99.5% confidence, between the surface gravity of hot Jupiters and the activity levels of the host stars, such that high surface gravity planets tend to be found around high-activity stars. We also find a less significant positive correlation between planet mass and chromospheric activity, but no significant correlation is seen between planet radius and chromospheric activity. We consider the possibility that this may be due to an observational bias against detecting lower mass planets around higher activity stars, but conclude that this bias is only likely to affect the detection of planets much smaller than those considered here. Finally, we speculate on physical origins for the correlation—including the possibility that the effect of stellar insolation on planetary radii has been significantly underestimated, that strong UV flux evaporates planetary atmospheres, or that high-mass hot Jupiters induce activity in their host stars—but do not find any of these hypotheses to be particularly compelling.

Key words: methods: statistical – planetary systems – stars: activity

1. INTRODUCTION

With more than 70 transiting exoplanets (TEPs) now known, it has become possible to detect statistically robust correlations between the parameters of TEPs and their host stars, which in turn yields insights into the processes that are important for determining the physical properties of exoplanet systems. Several correlations have already been noted, including correlations between the masses and orbital periods of TEPs (Gaudi et al. 2005; Mazeh et al. 2005; Torres et al. 2008), between their surface gravities and orbital periods (Southworth et al. 2007; Torres et al. 2008), between the inferred core mass of planets and the metallicity of their host stars (Guillot et al. 2006; Burrows et al. 2007), between Safronov number and the host star metallicity (Torres et al. 2008), and between the radii of planets and their average equilibrium temperature and host metallicity (Enoch et al. 2010).

Very recently, Knutson et al. (2010, hereafter KHI10) have demonstrated a correlation between the emission spectra of TEPs and the chromospheric activity levels of their host stars, as measured from the strength of the emission lines at the Ca ii H and K line cores. Planets with spectra consistent with noninverted temperature models appear to be found around high-activity stars, while planets with spectra consistent with temperature inversions are found around low-activity stars. In demonstrating this correlation KHI10 also published a catalog of log \( R'_{HK} \) values for 39 TEPs. This new, homogenous sample enables statistical studies of the relationships between stellar activity and the physical properties of TEPs.

In this Letter, we use the sample of log \( R'_{HK} \) values from KHI10 to investigate correlations between stellar activity and other TEP parameters. We find that there is a significant correlation between log \( R'_{HK} \) and the planet surface gravity log \( g' \). A similar correlation between stellar activity (as traced by the temporal variation in an index related to log \( R'_{HK} \)) and the minimum planetary mass \( M_P \sin i \) was previously noted by Shkolnik et al. (2005) for a sample of 10 radial velocity (RV) planets, though the authors deemed the correlation to be only suggestive. Here, we demonstrate that the log \( R'_{HK} - \log g' \) correlation is robust with greater than 99.5% confidence.

The structure of this Letter is as follows, In Section 2, we describe the data and conduct the statistical analysis to establish the correlation. In Section 3, we discuss a potential observational bias which might lead to this correlation. In Section 4, we speculate on possible physical origins of this correlation.

2. DATA AND STATISTICAL ANALYSIS

Table 1 gives the log \( R'_{HK} \) and log \( g' \) values adopted for planets with both parameters measured, together with the sources from the literature for the surface gravity measurements. In all cases we take log \( R'_{HK} \) from KHI10. In general, we take the surface gravity of planets from studies that calculated it directly from observable parameters (the transit duration, depth, and impact parameter, together with the RV semiamplitude, eccentricity, and orbital period; see Southworth et al. 2007) in a Markov-Chain Monte Carlo simulation, or we calculate it ourselves from the given observable parameters.

Figure 1 shows the relation between log \( R'_{HK} \) and log \( g' \); the existence of a correlation is readily apparent. To determine the statistical significance of this correlation, we use the Spearman rank-order correlation test (see Press et al. 1992), finding \( r_S = 0.45 \). The probability that a random sample of size \( N = 39 \) drawn from an uncorrelated population would have either \( r_S \geq 0.45 \) or \( r_S \leq -0.45 \) is only 0.4%, so the significance of the correlation is 99.6%. If we exclude the two hot Neptunes GJ 436b and HAT-P-11b, which one might expect to have atmospheric properties that are different from more massive planets, the two long period planets HD 80606b and HD 17156b, and also exclude planets orbiting stars which have temperatures outside the range over which log \( R'_{HK} \) has been calibrated (4200 K < \( T_{\text{eff}} \) < 6200 K; Noyes et al. 1984), we find a stronger correlation of \( r_S = 0.68 \), with a false alarm probability (FAP) of 0.032%. The sample size in this case is \( N = 23 \).

We have also searched for correlations between log \( R'_{HK} \) and other parameters such as planetary mass \( M_P \), planetary radius \( R_P \), the RV semiamplitude \( K \), stellar mass \( M_S \), planetary density

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1. e.g., http://exoplanets.org.
Table 1

Adopted Values for the Stellar Activity Index and Planetary Surface Gravity

| Planet          | log $R'_{\text{HK}}$ | log $g_P$ (cgs) | Ref. log $g_P$ |
|-----------------|----------------------|-----------------|---------------|
| CoRoT-1b        | -5.312               | 3.0266          | 10            |
| CoRoT-2b        | -4.331               | 3.6157          | 1             |
| GJ 436b         | -5.298               | 3.1070          | 8             |
| HAT-P-10/WASP-11b | -4.823             | 3.0800          | 16            |
| HAT-P-11b       | -4.567               | 3.0500          | 3             |
| HAT-P-12b       | -5.104               | 2.7500          | 19            |
| HAT-P-13b       | -5.138               | 3.1088          | 21,22         |
| HAT-P-14b       | -4.855               | 3.6200          | 27            |
| HAT-P-1b        | -4.984               | 2.9570          | 8             |
| HAT-P-2b        | -4.780               | 4.2260          | 29            |
| HAT-P-3b        | -4.904               | 3.3100          | 9             |
| HAT-P-4b        | -5.082               | 3.0200          | 1             |
| HAT-P-5b        | -5.061               | 3.2190          | 3             |
| HAT-P-6b        | -4.799               | 3.1710          | 3             |
| HAT-P-7b        | -5.018               | 3.3406          | 15,30         |
| HAT-P-8b        | -4.985               | 3.2300          | 18            |
| HAT-P-9b        | -5.092               | 2.9910          | 12            |
| HD 149026b      | -5.030               | 3.1320          | 17            |
| HD 17156b       | -5.022               | 3.8810          | 15            |
| HD 189733b      | -4.501               | 3.3099          | 11            |
| HD 209458b      | -4.970               | 2.9630          | 3             |
| HD 80606b       | -5.061               | 4.0202          | 28            |
| TrES-1b         | -4.738               | 3.2200          | 3             |
| TrES-2b         | -4.949               | 3.2980          | 3             |
| TrES-3b         | -4.549               | 3.4250          | 13            |
| TrES-4b         | -5.104               | 2.8580          | 13            |
| WASP-12b        | -5.500               | 2.9900          | 14            |
| WASP-13b        | -5.263               | 2.8500          | 9             |
| WASP-14b        | -4.923               | 4.0100          | 24            |
| WASP-17b        | -5.331               | 2.5600          | 26            |
| WASP-18b        | -5.430               | 4.2810          | 20            |
| WASP-19b        | -4.660               | 3.1900          | 25            |
| WASP-1b         | -5.114               | 3.0100          | 3             |
| WASP-2b         | -5.054               | 3.2870          | 3             |
| WASP-3b         | -4.872               | 3.4200          | 2             |
| XO-1b           | -4.958               | 3.2110          | 3             |
| XO-2b           | -4.988               | 3.1680          | 3             |
| XO-3b           | -4.459               | 4.2950          | 6             |
| XO-4b           | -5.292               | 3.3316          | 7             |

Notes.

* $\log R'_{\text{HK}}$ values are taken from KH110.

* Calculated from $K$, and a combination of $a/R_\star$, $T_{\text{eff}}$, $\rho_\star$, $b$, $i$, and $R_p/R_\star$ from the given source(s).

References. (1) Alonso et al. 2008; (2) Gibson et al. 2008; (3) Torres et al. 2008; (4) Pál et al. 2008; (5) Welsh et al. 2010; (6) Winn et al. 2008; (7) McCullough et al. 2008; (8) Southworth 2008; (9) Skillen et al. 2009; (10) Gillon et al. 2009; (11) Triaud et al. 2009; (12) Shporer et al. 2009; (13) Sozzetti et al. 2009; (14) Hebb et al. 2009; (15) Winn et al. 2009b; (16) Bakos et al. 2009a; (17) Carter et al. 2009; (18) Latham et al. 2009; (19) Hartman et al. 2009; (20) Southworth et al. 2009; (21) Bakos et al. 2009b; (22) Winn et al. 2010; (23) Bakos et al. 2010; (24) Joshi et al. 2009; (25) Hebb et al. 2010; (26) Anderson et al. 2010; (27) Torres et al. 2010; (28) Hebrard et al. 2010; (29) Pál et al. 2010; (30) Winn et al. 2009a.

$\rho_P$, the Safronov number $\theta$ (Hansen & Barman 2007), planetary equilibrium temperature ($T_{\text{eq,P}}$; assuming zero albedo), average stellar flux incident on the planet ($F_P$), orbital period $P$, stellar metallicity [Fe/H], and stellar effective temperature $T_{\text{eff}}$. Table 2 summarizes the strengths of each correlation for three separate samples:

1. $M > 0.1 M_J$, $a < 0.1$ AU, and $4200 K < T_{\text{eff}} < 6200 K$.
2. $4200 K < T_{\text{eff}} < 6200 K$.
3. No restrictions.

In addition to the $\log R'_{\text{HK}}$–log $g_P$ correlation, positive correlations with > 99% confidence are also seen between $\log R'_{\text{HK}}$ and $\theta$ and between $\log R'_{\text{HK}}$ and $\rho_P$. All three parameters (log $g_P$, $\theta$, and $\rho_P$) scale as $M_P/R_P^n$ ($n = 1$ for $\theta$, $n = 2$ for log $g_P$, and $n = 3$ for $\rho_P$). The correlations seen between these parameters and $\log R'_{\text{HK}}$ most likely have the same origin. We focus on log $g_P$ here both because the correlation is slightly more significant for this parameter than it is for $\theta$ or $\rho_P$ and because for TEPs log $g_P$ can be determined directly from measurable parameters (Southworth et al. 2007), while the other two parameters are dependent on stellar models, which could conceivably introduce a bias if there is a systematic error in the stellar models which depends on activity.

By checking several different parameters for correlations with $\log R'_{\text{HK}}$, we have conducted several independent trials, and must therefore increase the FAPs to account for this. Several of the parameters are strongly correlated (log $g_P$, $\theta$, and $\rho_P$, as well as $K$ and $M_P$, and $T_{\text{eq,P}}$ and $F_P$), so these are not completely independent trials; we estimate that the
We note from Table 2 that while the planet mass $M_P$ shows a positive correlation with $\log R'_{HK}$ with $\sim 97\%$ confidence, there is no significant correlation detected between $\log R'_{HK}$ and the planet radius $R_P$.

3. POTENTIAL SELECTION EFFECTS

The observed correlation between $\log R'_{HK}$ and $\log g_P$ may potentially be due to observational biases rather than physical effects. Most of the transiting planets in this sample were initially discovered by photometric transit surveys, which are sensitive only to the planet radius. Enhanced stellar activity may lead to photometric variability which reduces the sensitivity to lower radius planets. However, this effect would result in a correlation between $\log R'_{HK}$ and $R_P$, which is not observed.

Another potentially relevant observational bias is the relative difficulty of obtaining high-precision RV observations for high-activity stars. These observations are required to confirm candidate planets identified by transit surveys, so it is conceivable that lower mass transiting planets will not be confirmed if they are orbiting high-activity stars. Indeed, as seen in Table 2, the correlation between RV semiamplitude $K$ and $\log R'_{HK}$ has a FAP of $\sim 1.5\%$. Figure 2 (top) shows the relation between these two parameters. If this correlation were due only to an observational bias, however, we would expect the correlation to continue to hold when low mass and long period planets are also included (Sample 2). The fact that the correlation is reduced to $r_S = 0.28$ with an FAP of $17\%$ in this case is evidence that this relation is most likely not due to a selection effect. In practice most transit surveys follow-up targets regardless of the stellar activity. In fact, the lowest $K$ planet in this sample, HAT-P-11, was discovered around one of the most active stars in the sample. Moreover, while a selection effect might explain the absence of Sample 1 planets in the lower right corner of Figure 2 (top) or Figure 1 (bottom), it does not explain the absence of Sample 1 planets in the upper left corners of these figures, unless high $\log g_P$ planets are intrinsically less common than low $\log g_P$ planets and low $\log R'_{HK}$ hot Jupiter host stars are intrinsically less common than high $\log R'_{HK}$ host stars. Finally, because the FAP for the $\log g_P$–$\log R'_{HK}$ correlation is more than an order of magnitude lower than the FAP for the $K$–$\log R'_{HK}$ correlation, it is unlikely that the former correlation is a by-product of the observational bias.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Top: RV semiamplitude of TEPs vs. the chromospheric activity of the stellar hosts, as measured with $\log R'_{HK}$. Symbols are the same as in Figure 1. Bottom: same as above, here we only show TEPs with $M > 0.1 M_J$, $a < 0.1$ AU orbiting stars with $4200$ K $< T_{\text{eff}} < 6200$ K (filled black circles).

| Parameter | Sample 1 | Sample 2 | Sample 3 |
|-----------|----------|----------|----------|
| $\log g_P$ | 0.68 | 0.47 | 0.45 |
| $\theta$ | 0.62 | 0.36 | 0.41 |
| $\rho_T$ | 0.66 | 0.53 | 0.43 |
| $M_P$ | 0.45 | 0.22 | 0.23 |
| $K$ | 0.50 | 0.28 | 0.28 |
| $R_P$ | $-0.031$ | $-0.053$ | $-0.21$ |
| $M_S$ | 0.19 | 0.15 | 0.30 |
| $T_{\text{eff}}$ | $-0.19$ | $-0.16$ | $-0.19$ |
| $(P)_T$ | $-0.21$ | $-0.18$ | $-0.21$ |
| $P$ | $-0.29$ | $-0.23$ | 0.0096 |
| $[\text{Fe/H}]$ | $-0.19$ | $-0.18$ | $-0.059$ |
| $T_{\text{eff,S}}$ | $-0.31$ | $-0.32$ | $-0.18$ |

**Notes.**

- The Spearman nonparametric rank-order correlation coefficient.
- False alarm probability. These have not been corrected for the total number of independent trials conducted by searching for correlations between different parameter combinations.
latter correlation. To quantify this, we simulated 10,000 samples with \( K \) and \( \log g_p \) pairs taken from the observed data set and \( \log R'_{\text{HK}} \) for each pair, \( i \), given by

\[
\log R'_{\text{HK},i} = a \log K + b + e_i, \tag{1}
\]

where \( a \) and \( b \) are the parameters from fitting a line to the observed \( \log R'_{\text{HK}}-K \) relation, and \( e_i \) is a Gaussian random variable with unit mean and variance equal to the variance of \( \log R'_{\text{HK}}-\log K-b \). Only 0.07% of the trials have \( \text{FAP} > 1.5\% \) for the \( \log R'_{\text{HK}}-\log K \) correlation and FAP < 0.032% for the \( \log R'_{\text{HK}}-\log g_p \) correlation. This all suggests that poorer RV precision due to increased stellar activity is unlikely to explain the absence of low surface gravity (or low \( K \)) hot Jupiters around active stars.

4. DISCUSSION

Assuming that the observed correlation between \( \log R'_{\text{HK}} \) and \( \log g_p \) is not due to an observational bias, it is not obvious what physical processes might give rise to it. It is well known that \( \log R'_{\text{HK}} \) is a decreasing function of age for FGK stars (e.g., Soderblom et al. 1991), but the \( g_p \)-age relation implied from the \( \log g_p-\log R'_{\text{HK}} \) relation is opposite of what is expected—that planets should contract with age, and not expand with age. For example, by interpolating the Fortney et al. (2007) models while accounting for the increase in stellar luminosity over time, we find that a coreless 1.0 \( M_J \) planet orbiting a 1.0 \( M_\odot \) star on a 2.5 day period should decrease in radius from 1.22 \( R_J \) to 1.13 \( R_J \) between 300 Myr and 4.5 Gyr. Models such as these, however, are known to under-predict the radii of many hot Jupiters. If the effect of insolation on planetary radii is substantially larger than anticipated, so that the inflation due to the increase in stellar luminosity with time is greater than the gravitational contraction of the planet over time, the result would be a positive \( \log g_p - \log R'_{\text{HK}} \) correlation.

Another possibility is that strong stellar UV flux increases the evaporation of hydrogen from the atmospheres of hot Jupiters (e.g., Lecavelier des Étangs et al. 2010, and references therein). For gas giant planets, the radius is not a strong function of planetary mass (see Fortney et al. 2007), as a result the mass-loss process is expected to decrease the surface gravity of the planet. A possible explanation for the correlation could be that planets orbiting older, less active stars, have undergone more total mass loss than planets orbiting younger stars, and therefore have lower surface gravities. Alternatively, if the mass-loss process is rapid and \( \log R'_{\text{HK}} \) for these stars does not depend significantly on stellar age (due, for example, to star–planet interactions as discussed below), planets with surface gravities below a threshold that increases with stellar activity could be evaporated to below the 0.1 \( M_J \) cutoff used in defining the data sample, yielding an absence of planets in the lower right corner in the bottom panel of Figure 1.

Alternatively, the presence of hot Jupiters may induce activity on the host star, either by tidally spinning-up the star’s convection zone, or via a magnetic star–planet interaction (see the review by Shkolnik et al. 2009). In this case, stars with high \( \log R'_{\text{HK}} \) may not necessarily be younger than stars with lower \( \log R'_{\text{HK}} \). Evidence that the presence of a hot Jupiter is correlated with increased stellar X-ray activity has been presented by Kashyap et al. (2008), while Pont (2009) found that hot Jupiter host stars may exhibit excess rotation. Other investigations have found evidence of magnetic activity variations correlated with planet properties (e.g., Shkolnik et al. 2005; Lanza et al. 2009). For both tidal and magnetic star–planet interactions, the strength of the interaction increases with planet mass. If the \( \log R'_{\text{HK}}-\log g_p \) correlation is a by-product of a more fundamental \( \log R'_{\text{HK}}-M_p \) correlation, one might wonder why the former is detected with higher significance than the latter. A possible explanation is that \( \log g_p \) is determined directly from measurable parameters while \( M_p \) is directly proportional to the stellar mass \( M_* \), which in turn is dependent on stellar models. As a result \( \log g_p \) is generally determined with better precision, and presumably with better accuracy, than \( M_p \) for TEPs. However, by simulating data sets with the observed \( M_p-\log R'_{\text{HK}} \) correlation and \( M_p-\log g_p \) correlations, assuming the scatter about these relations is intrinsic, and assuming the observational errors for \( M_p \) and \( \log g_p \) are realistic, we find that there is only an \( \sim 1\% \) probability of the FAP of \( \log g_p-\log R'_{\text{HK}} \) being less than 0.1% while the FAP of \( M_p-\log R'_{\text{HK}} \) is greater than 1%. Even if we assume the true observational error on \( M_p \) is \( \sim 0.5 M_p \), the probability is only \( \sim 6\% \). It is therefore unlikely that the \( \log R'_{\text{HK}}-M_p \) relation is driving the \( \log R'_{\text{HK}}-\log g_p \) relation.

In summary, we have identified a significant positive correlation between stellar activity and planetary surface gravity. As far as we are aware this correlation is unanticipated, and its cause is unclear.

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