HOT JUPITERS AND HOT SPOTS: THE SHORT- AND LONG-TERM CHROMOSPHERIC ACTIVITY ON STARS WITH GIANT PLANETS

E. SHKOLNIK AND G. A. H. WALKER
Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road,
Vancouver, BC V6T 1Z1, Canada; shkolnik@physics.ubc.ca, gordonwa@uvic.ca

D. A. BOHLENDER
Herzberg Institute for Astrophysics, National Research Council of Canada, Victoria,
BC V9E 2E7, Canada; david.bohlender@nrc-cnrc.gc.ca

P.-G. GU
Institute of Astronomy and Astrophysics, Academia Sinica, Taipei 11529, Taiwan; gu@asiaa.sinica.edu.tw

AND

M. KÜRSTER
Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; kuerster@mpia-hd.mpg.de

Received 2004 August 20; accepted 2004 December 10

ABSTRACT

We monitored the chromospheric activity in the Ca ii H and K lines of 13 solar-type stars (including the Sun): 8 of them over 3 years at the Canada-France-Hawaii Telescope (CFHT) and 5 in a single run at the Very Large Telescope (VLT). A total of 10 of the 13 targets have close planetary companions. All of the stars observed at the CFHT show long-term (months to years) changes in H and K intensity levels. Four stars display short-term (days) cyclical activity. For two, HD 73256 and κ1 Cet, the activity is likely associated with an active region rotating with the star; however, the flaring in excess of the rotational modulation may be associated with a hot Jupiter. A planetary companion remains a possibility for κ1 Cet. For the other two, HD 179949 and v And, the cyclic variation is synchronized to the hot Jupiter’s orbit. For both stars this synchronicity with the orbit is clearly seen in two out of three epochs. The effect is only marginal in the third epoch at which the seasonal level of chromospheric activity had changed for both stars. Short-term chromospheric activity appears weakly dependent on the mean K line reversal intensities for the sample of 13 stars. In addition, a suggestive correlation exists between this activity and the $M_p \sin i$ of the star’s hot Jupiter. Because of their small separation (≤0.1 AU), many of the hot Jupiters lie within the Alfvén radius of their host stars, which allows a direct magnetic interaction with the stellar surface. We discuss the conditions under which a planet’s magnetic field might induce activity on the stellar surface and why no such effect was seen for the prime candidate, τ Boo. This work opens up the possibility of characterizing planet-star interactions, with implications for extrasolar planet magnetic fields and the energy contribution to stellar atmospheres.

Subject headings: planetary systems — radiation mechanisms: nonthermal — stars: activity — stars: chromospheres — stars: late-type

Online material: color figure

1. INTRODUCTION

In the past decade, ≈140 extrasolar planets have been discovered as companions to late-type dwarfs, mostly from precise radial velocities (PRVs; e.g., Walker et al. 1995) from which the Keplerian orbital parameters and minimum planetary masses can be derived. From transiting planets, of which five are known, true planetary masses, radii, densities, and albedo-dependent estimates of surface temperature are available. To date, a handful of experiments have led to further information about these planets, including Lyγ (Vidal-Madjar et al. 2003) and sodium detections (Charbonneau et al. 2002) in the atmosphere of the transiting planet around HD 209458. A current review of follow-up techniques to probe planetary characteristics has been presented by Charbonneau (2003).

The presence of a giant planet likely influences its parent star beyond the dynamical perturbations measured by the PRV method. Robinson & Bopp (1987) caught the signatures of “superflares” with energies of $\sim 10^{35}$ ergs (Schaefer et al. 2000) on nine solar analogs that have no otherwise unusual properties such as very rapid rotation or very high chromospheric activity. Rubenstein & Schaefer (2000) suggested that these anomalous superflares were stimulated by an unseen close-in extrasolar giant planet (CEGP, also known as a “hot Jupiter”). They explored the possibility of magnetic reconnection events occurring between both the star’s and the planet’s entangled magnetic fields. Cuntz et al. (2000) suggested a more consistent observable interaction between a parent star and its hot Jupiter in the form of enhanced stellar activity of the star’s outer atmosphere. This interaction can take the form of tidal and/or magnetic heating of the plasma. Both the star and its planet experience strong tidal forces, as well as repeated magnetic reconnection with a large planetary magnetosphere. If such planet-induced heating of the star is confined to a narrow range in stellar longitude, the heated...
regions likely track the planet as it orbits. This implies that the period of any observed activity would be correlated with the planet’s orbital period \( P_{\text{orb}} \), such that tidally induced activity has a period of \( \sim P_{\text{orb}}/2 \) and magnetic activity a period of \( P_{\text{orb}} \). In the simplest configuration of magnetic interaction, the expected enhancement would occur near the subplanetary point, which defines orbital phase \( \phi = 0 \) at the time when the planet is in front of the star relative to the line of sight.

A partial analogy can be made to the Jupiter-Io system (Zarka et al. 2001) where the volcanically active moon of Jupiter, orbiting at a distance of 5.9 \( R_J \), constantly couples with Jupiter’s magnetosphere, leaving two footprints at high positive and negative latitudes on the planet’s surface. Plasma flows along the magnetic field lines, making up the Io flux tube, as these footprints follow Io in its orbit. Even though the analogy is limited, a similar phenomenon may occur between CEGPs and their stars such that coupling between the magnetic fields of the planet and the star may cause footprints or “hot spots” on the star’s surface that follow the planet and have a period close to the planet’s orbital period. Similarly, auroral emission may be stimulated on the planet’s atmosphere (Zarka et al. 2001), but no searches for planetary radio emissions have yet been successful (e.g., Bastian et al. 2000; Farrell et al. 2003; Ryabov et al. 2003).

More recently, Santos et al. (2003) observed cyclic photometric variations with a period very similar to that of the radial velocity (RV) curve for the K dwarf HD 192263. The stability of the 24.4-day periodic RV through almost 4 yr of data (Santos et al. 2000; Henry et al. 2002) rules out the interpretation that stellar activity alone is the cause of the RV curve and supports the existence of a planetary-sized companion around the star. However, they question what might cause a quasi-stable photometric period that coincides with the planetary orbit. They offered planet-induced magnetic activity offset by 90° from the subplanetary point as an explanation.

Even though the interpretations of Rubenstein & Schaefer (2000) and Santos et al. (2003) are uncertain, there exists ample observational evidence of such tidal and magnetic interactions in the exaggerated case of the RS Canum Venaticorum (RS CVn) stars, which are tightly orbiting binary systems consisting of two chromospherically active late-type stars. For example, Catalano et al. (1996) found as many starspots and plages within 45° of the sub-binary point as on the rest of the stellar surface for several RS CVn systems. And, a relatively long period system \( P_{\text{orb}} = 20.1 \text{ days} \) (Walker 1944), shows modulation of the Mg II UV chromospheric emission lines with a period of 10 days, half the orbital period. Glebocki et al. (1986) interpreted this as a tidal heating of the primary by its companion, possibly a brown dwarf (Donati et al. 1995). In addition, in our own Ca II H and K observations of ER Vul, an RS CVn system with two G V dwarfs and \( P_{\text{orb}} = 0.69 \text{ days} \), we see clear enhancements near the sub-binary longitudes (E. Shkolnik et al. 2005, in preparation).

With these scenarios in mind, we searched for periodic chromospheric heating by monitoring the Ca II H and K emission in stars with giant planets within a few stellar radii. We chose to study the tightest observable systems since the tidal and magnetic interactions depend on the distance from the planet to the star as \( 1/r^3 \) and \( 1/r^2 \) (or as \( 1/r^3 \); see § 4), respectively. Of the known extrasolar planets, about 20% have semi-major axes of less than 0.1 AU and masses comparable to Jupiter’s (Schneider 2004). It is expected that these planets also have magnetic fields similar to Jupiter’s (4.3 G).\(^3\) It is also reasonable to assume that any magnetic interaction would be greatest in the outermost layers of the star, namely, the chromosphere, transition region, and the corona, owing to their proximity to the planet, low density, and nonradiative heat sources. The broad, deep photospheric absorption of the Ca II H and K lines allows the chromospheric emission to be seen at higher contrast. Because of this and the accessibility from the ground, the H and K reversals are an optimal choice with which to monitor chromospheric heating of these Sun-like stars.

Our program stars have orbital periods between 2.5 and 4.6 days, eccentricities \( \leq 0 \), and semimajor axes \( < 0.06 \text{ AU} \). These systems offer the best chance of observing upper atmospheric heating. The first five systems we observed were \( \tau \) Boo, HD 179949, HD 209458, 51 Peg, and \( \upsilon \) And from the Canada-France-Hawaii Telescope (CFHT). The first results from 2001 and 2002 observations, including the first evidence of planet-induced magnetic heating of HD 179949, were published in Shkolnik et al. (2003). We later extended the experiment at the Very Large Telescope (VLT) to include five southern targets, HD 46357, HD 73256, HD 75289, HD 76700, and HD 83443. The system parameters for the program stars are listed in Table 1 along with our two standards, \( \tau \) Cet and the Sun.

In this paper we compile our 2003 CFHT data with those of previous years and include the recent VLT observations. A broader understanding of stellar activity, its cycles, and planet-induced chromospheric heating emerges. We also observed \( \kappa^1 \) Cet, a young (650–750 Myr old), chromospherically active, solar analog. It was one of the nine stars reported to have anomalous superflare activity by Robinson & Bopp (1987) possibly caused by magnetic interactions with a close-in giant planet (Rubenstein & Schaefer 2000). Of their sample, only \( \kappa^1 \) Cet has been looked at by the PRV planet searches of Walker et al. (1995), Cumming et al. (1999), and Hallwachs et al. (2003), none of which have detected a planet. Interestingly, however, Walker et al. (1995) observed a rapid RV change of 80 m s\(^{-1}\) in 1988 that could have been caused by a planet in highly elliptical orbit. However, it coincided with an equally sharp increase in the Ca II chromospheric activity indicator at 8662 Å, implying that the RV jump was likely due to changes intrinsic to the star. We may have observed this same phenomenon in our Ca II data.

The details of our CFHT and VLT observations are outlined in § 2. We briefly discuss the precise differential radial velocities that yielded updated ephemerides for the planetary systems such that orbital phases could be determined to better than 0.02. In § 3 we discuss our analysis and results of the Ca II H and K measurements including long-term, short-term, and rotational modulation. A theoretical discussion of the physical requirements for magnetic interactions between stars and their hot Jupiters is presented in § 4, with future experiments suggested in § 5.

2. THE SPECTRA

2.1. CFHT Observations

The observations were made with the 3.6 m CFHT on 3.5, 4, 2, and 5 nights in 2001 August, 2002 July, 2002 August, and 2003 September, respectively. We used the Gecko échelle

\(^3\) However, if tidally locked, the planets’ rotation rates may be much lower than Jupiter’s, possibly causing their magnetic fields to be substantially smaller (e.g., Sánchez-Lavega 2004).
spectrograph fiber fed by the Cassegrain Fiber Environment (CAFE) from the Cassegrain to coude focus (Baudrand & Vitry 2000). Spectra were centered at 3947 Å, which was isolated by a UV grism (300 lines mm\(^{-1}\)) with \(\lesssim 60\) Å intercepted by the CCD. The dispersion was 0.0136 Å pixel\(^{-1}\), and the 2.64 pixel FWHM of the thorium-argon (Th/Ar) lines corresponded to a spectral resolution of \(R = 110,000\). The detector was a back-illuminated EEV CCD (13.5 \(\mu\)m pixels, 200 \(\times\) 4500 pixels) with spectral dispersion along the rows of the device.

To remove the baseline from each observation, the appropriate mean darks were subtracted from all the exposures. Flat fields were then normalized to a mean value of unity along each row. All the stellar exposures observed on a given night were combined into a mean spectrum to define a single aperture for the extraction of all stellar and comparison exposures, including subtraction of residual background between spectral orders (prior to flat-fielding). This aperture was ultimately used to extract one-dimensional spectra of the individual stellar and comparison exposures and of the mean, normalized flat field. This one-dimensional flat was used to obtain the most consistent flat-fielded spectra possible. All the data were processed with standard IRAF routines.\(^4\) Wavelength calibration was done using the Th/Ar arcs taken before and after each spectrum. We required frequent arcs in order to track the CCD drift or any creasing in the system throughout the night. Heliocentric and differential RV corrections were applied to each stellar spectrum using IRAF’s \textit{recorrect} routine. A specimen, flat-fielded spectrum of \(\nu\) And is shown in Figure 1. The \(\text{Ca} \& \text{H} \& \text{K}\) spectrum of \(\nu\) And is shown in Figure 1. The \(\text{Ca} \& \text{H} \& \text{K}\) core. These values are relative to the normalization points near 3930 and 3937 Å, which are at approximately \(\frac{1}{3}\) of the continuum at 3950 Å.

\(^a\) The first five periods are from this work (see \S\ 2.1.1). See footnote b for the last five.

\(^b\) Published orbital solutions: \(\tau\) Boo and \(\nu\) And (Butler et al. 1997), HD 179949 (Tinney et al. 2001), 51 Peg (Marcy et al. 1997), HD 209458 (Charbonneau et al. 2000), HD 46375 (Marcy et al. 2000), HD 73256 (Udry et al. 2003), HD 75289 (Udry et al. 2000), HD 76700 (Tinney et al. 2003), HD 83443 (Mayor et al. 2004), Sun (Marcy et al. 1995). The Ca/H & K core. These values are relative to the normalization points near 3930 and 3937 Å, which is isolated by a UV grism (300 lines mm\(^{-1}\)).

\(^c\) Total integrated intensity bounded by the K1 features of the mean normalized Ca/H & K core. These values are relative to the normalization points near 3930 and 3937 Å, which is isolated by a UV grism (300 lines mm\(^{-1}\)).

\(^d\) We subtracted the photospheric emission from \((\text{K})\) in order to measure the mean integrated chromospheric emission \((\text{K}')\) using data from Wright et al. (2004); see text for more details.

\(^e\) Average integrated “intensity” of the mean absolute deviation (MAD) of the K residuals, per observing run.

\(^f\) Henry et al. (2000).

\(^g\) Mazeh et al. (2000).

\(^h\) Closest of three known planets in the system.

\(^i\) Derived from empirical fits (Noyes et al. 1984) of the Ca/H & K index (Wright et al. 2004).

\(^j\) (MAD K) was corrected for a \(\approx 30\%\) variable contribution by telluric Ca/H & K emission (also referred to as “airglow”) since it was the first star observed after sunset.

\(^k\) Udry et al. (2003).

\(^l\) Value corrected to remove modulation due to rotation. For HD 73256 the noncorrected value is 0.0155, and for \(\kappa\) Cet, 0.0182.

\(^m\) Rucinski et al. (2004).

\(^n\) Fekel (1997).

\(^o\) François et al. (1996).

\(^p\) Average integrated “intensity” of the mean absolute deviation (MAD) of the K residuals, per observing run.

\(^q\) Henry et al. (2000).

\(^r\) Mazeh et al. (2000).

\(^s\) Closest of three known planets in the system.

\(^t\) Derived from empirical fits (Noyes et al. 1984) of the Ca/H & K index (Wright et al. 2004).

\(^u\) (MAD K) was corrected for a \(\approx 30\%\) variable contribution by telluric Ca/H & K emission (also referred to as “airglow”) since it was the first star observed after sunset.

\(^v\) Udry et al. (2003).

\(^w\) Value corrected to remove modulation due to rotation. For HD 73256 the noncorrected value is 0.0155, and for \(\kappa\) Cet, 0.0182.

\(^x\) Rucinski et al. (2004).

\(^y\) Fekel (1997).

\(^z\) François et al. (1996).
Fig. 2.—Differential radial velocities for the five “51 Peg” stars measured in 2003 September, plotted as a function of relative orbital phase, and the unvarying star, $\tau$ Cet, as a function of time. Each sine curve has the planetary orbital period from Table 1 and published amplitude for the star and has been shifted in phase to give the best fit to the $\Delta$RVs. The measurement error of the individual points is $<5$ m s$^{-1}$. The $\sigma_{\Delta RV}$ of the $\Delta$RV are listed in Table 2. Note that $\tau$ Cet’s $\Delta$RVs are plotted on a much smaller scale than the others and have a $\sigma_{\Delta RV}$ of 7 m s$^{-1}$, making the average $\sigma_{\Delta RV}$ for all the data 17 m s$^{-1}$.
Spectra with comparable S/N were taken of two stars known not to have close-in giant planets, τ Cet and the Sun (sky spectra were taken at dusk). Table 2 of Walker et al. (2003a) lists the five CFHT program stars plus τ Cet, including their U magnitudes, exposure times, and typical S/N.

2.1.1. Precise Differential Radial Velocities

Differential radial velocities (∆RVs) were measured with the fxcor routine in IRAF (version PC-IRAF V2.12), which performs a Fourier cross-correlation on dispersion-corrected spectra. We used the first spectrum in the series for each star as the template; hence, all ∆RVs are relative to the first spectrum on the first night of the run. Both the template and the input spectrum were normalized with a low-order polynomial. The correlation used only the ~20 Å region between the H and K lines, part of the spectrum bounded by (and including) the two strong Al ii lines (3942–3963 Å) as shown in Figure 1.

The ∆RVs measured during the 2002 July run for the five “51 Peg” stars can be found in Walker et al. (2003a). The ∆RVs from 2003 September are plotted in Figure 2. After the orbit is removed, the average σRV is 17 m s⁻¹. The two stars observed at the highest S/N have σRV of 7 and 9 m s⁻¹. This precision may be the best achievable for a single spectrum with this spectrograph. The excellent ∆RVs yield current orbital ephemerides and hence accurate phases (±0.02) for each observation. Using the ephemerides of the planets’ discovery orbits, we tabulated the 2003 September times of subplanetary position (ϕ = 0) with revised orbital periods. These are listed in Table 2.

2.2. VLT Observations

We obtained high-resolution spectra through Visitor mode using the VLT’s Ultraviolet and Visual Echelle Spectrograph (UVES) mounted on the 8.2 m Kueyen (UT2) over four photometric half-nights (2004 April 4–7). The standard blue arm setting was used, centered on 4370 Å, giving a wavelength range of 3750–4990 Å. We used the CD2 cross disperser grating (660 g mm⁻¹) with a CCD of 2048 × 3000 pixels of 15 μm². Image Slicer 2 with a slit width of 0.544 resulted in a resolution of R ≈ 75,000.

The data were reduced on site by the UVES data reduction pipeline that uses the ESO-MIDAS software package within the UVES content. The data processing consisted of standard procedures: bias subtraction, interorder background correction, cosmic-ray hit removal, flat-fielding, and wavelength calibration. The data were wavelength calibrated with Th/Ar arcs attached at the beginning and end of each set of 8–10 stellar exposures. The exposure times, number of exposures, and S/N for each star are listed in Table 3.

3. A COMPARISON OF Ca ii EMISSION

3.1. Extracting the H, K, and Al i Lines

The very strong Ca ii H and K photospheric lines suppress the stellar continuum, making it difficult to normalize each 60 Å spectrum consistently. For this reason, a careful analysis by which to isolate any modulated Ca ii emission was devised. Figure 1 shows a flat-fielded spectrum of υ And with the normalization levels marked by dashed lines. The normalization wavelengths were constant for all spectra of a given star. The 7 Å spectral ranges, centered on the H and K lines, were chosen to isolate the H and K reversals while minimizing any apparent continuum differences induced by varying illumination of the CCD. This window is, however, wide enough that a few photospheric absorption features appear that could be tested for variability as well. The mean Ca ii K cores for the program stars are shown in Figures 3 and 4. In addition, 7 and 2 Å cuts, centered on the strong photospheric Al i line at 3944 Å, were used as internal standards since the line has comparable depth and S/N to the Ca ii lines.

To normalize each subspectrum, the end points were set to 1 and fitted with a straight line. The spectra were grouped by date and a nightly mean was computed for each of the three lines. The rms of the Al i residuals for each CFHT target star is less than 0.0005 of the normalized mean. This is representative of the Al i residuals for all stars in all four runs. The Al i line of

---

**Table 2**

| Star      | ∆RV  | HJD at ϕ = 0 | δ(HJD) | Revised Porb | δ(Porb) |
|-----------|------|-------------|--------|--------------|---------|
| τ Boo     | 33   | 2452892.864 | 0.066  | 3.31250      | 0.00026 |
| HD 179949 | 19   | 2452894.114 | 0.062  | 3.09246      | 0.00031 |
| HD 209458 | 17   | 2452893.653 | 0.070  | 3.52940      | 0.00020 |
| 51 Peg    | 15   | 2452895.868 | 0.085  | 4.23092      | 0.00014 |
| υ And     | 9    | 2452892.615 | 0.092  | 4.61750      | 0.00052 |

* Uncertainties in the respective measurements.

**Table 3**

| Star        | U   | B   | Exposure Time (s) | n² | S/N Continuum | S/N Core |
|-------------|-----|-----|-------------------|----|---------------|---------|
| HD 46375    | 9.33| 8.7 | 300               | 8  | 510           | 150     |
| HD 73256    |     | 8.86| 300               | 9 x 2 | 520          | 150     |
| HD 75289    | 7.04| 6.94| 120               | 10 | 790           | 230     |
| HD 76700    | 9.17| 8.76| 300               | 8  | 540           | 160     |
| HD 83443    | 9.54| 9.03| 300               | 8  | 420           | 120     |

* Number of spectra taken per night. We observed HD 73256 twice per night for a total of 18 exposures.
  b Nightly average per 0.015 Å pixel⁻¹ in the continuum near 3950 Å and in the Ca ii K core.
the VLT data varies with an average rms of 0.0006. These values demonstrate both the level of stellar photospheric stability and the reliability of the data reduction and analysis. For all stars observed, the H and K emission was nonvarying at the 0.001 level on a given night, likely as a result of intranight (statistical) noise.

3.2. Long-Term Variability

With four CFHT observing runs spanning a baseline of over 2 yr, we can compare the long-term variations in the chromospheric levels of the stars. We measure emission strength by integrating across the normalized K cores bounded by the K1

Fig. 3.—Mean normalized Ca H K cores for the CFHT program stars.
features (Montes et al. 1994). Each star’s average integrated K emission (K) for each observing run is plotted in Figure 5 along with its fractional variation relative to the overall average emission. This is a good start to tracking the intrinsic stellar activity cycles of these stars. In the case of the Sun, we see the decrease from 2001 August to 2003 September as it declines from solar maximum. However, we also observed the naked-eye sunspot grouping of 2002 August that appeared in our data as a ≈2% increase in the Ca ii emission relative to the other years. Since the variability from run to run may also be an

Fig. 4.—Mean normalized Ca ii K cores for the VLT program stars plus κ1 Cet, which we observed at the CFHT.
indication of active regions on the disk of the star, we require more frequent monitoring over several more years to firmly say anything about the activity cycle of any individual program star.

3.3. Short-Term Variability

When monitoring Ca II emission, intrinsic stellar activity modulated by stellar rotation will appear along with any possible activity stimulated by the planet. The orbital periods of the planets are well known and uniquely established by the PRV and transit discovery methods. The rotation periods of the stars are much harder to determine in part because of stellar differential rotation, which yields nonunique periods. For our work, it is key to distinguish between the rotational and orbital modulation of chromospheric emission.

To isolate the chromospheric activity within the reversals, we took nightly residuals from the average stellar spectrum of all data. Each residual spectrum had a broad, low-order curvature removed that was an order of magnitude less than the variations in the H and K lines discussed below. The residuals of the normalized spectra (smoothed by 21 pixels) were used to compute the mean absolute deviation (MAD) of the Ca II K core of the And. The units are intensity as a fraction of the normalization level at 1/3 of the continuum. Overlaid (dashed line) is the mean spectrum (scaled down) indicating that the activity on and is confined to the K reversal. [See the electronic edition of the Journal for a color version of the top panel of this figure.]

Ca II H emission and activity levels are ≃2/3 that of Ca II K (Sanford & Wilson 1939).

The star with the shortest rotation period in our sample is τ Boo. It has the largest $v \sin i$ (=14.8 m s$^{-1}$; Gray 1982) and is believed to be in synchronous rotation with its tightly orbiting planet ($P_{\text{rot}} = 3.2 \pm 0.5$ days, Henry et al. 2000; $P_{\text{orb}} = 3.31250 \pm 0.00026$ days, this paper). If τ Boo is tidally locked to its planet, the planet-star interaction may be minimal (Saar et al. 2003) as a result of the fact that there is near-zero relative velocity (see § 4 for theoretical discussion). The integrated residuals from the mean normalized K core are plotted against orbital phase in the left panel of Figure 7. Looking at the individual observing runs in the plot for τ Boo, the two nights of observation in 2001 August did not show much variation when the star was somewhat less active. The 2002 July data showed an increase in activity near the subplanetary point relative to the other observations in their respective runs. However, in 2002 August and 2003 September observations show a relative enhancement at $\phi \approx 0.4$–0.5 modulated with a period near $P_{\text{rot}}$ and $P_{\text{orb}}$. This chaotic activity does not allow us to draw any conclusions about planet-induced heating.

Similar to τ Boo, the K emission of HD 209458 showed night-to-night modulation, but with a smaller amplitude during most runs and without any phase coherence, as shown in the right panel of Figure 7. In 2001 August, we caught the system immediately after transit, at which time we observed a slight enhancement in the Ca II emission relative to all other observations. In the 2002 July run, an increase in emission occurred at
\( \phi \sim 0.25 \) with no apparent rise toward \( \phi = 0 \). Because of the relatively low S/N of these data and the large intranight deviations, we cannot form any conclusions.

As seen in Figures 7 and 8, four of the five CFHT stars show significant chromospheric variation throughout a single observing run. The standards, \( \tau \) Cet and the Sun, show no such modulation. One consistent result for the "active" stars (\( \tau \) Boo, HD 179949, HD 209458, and \( \upsilon \) And) is their night-to-night modulation of H and K emission. Furthermore, unlike the case for HD 73256 (see \( \S \) 3.4), the night-to-night variations of these stars do not increase or decrease monotonically throughout an observing run, implying that the variability cannot be explained exclusively with starspots rotating into or out of view. Another mechanism is necessary. The night-to-night variations may indicate planet-induced activity or sporadic flaring from hot spots. If coupled to the planet, the localized activity would be traveling on the stellar surface faster than the star is rotating as it tracks the planet in its orbit.

Other than for \( \tau \) Boo, the timescale of activity is short compared to the stellar rotation period. Unfortunately, because of the large uncertainties in the rotation periods of the other stars, phasing with rotation is uninformative at this stage. However, we do know that \( \upsilon \) And and HD 209458 both have \( P_{\text{rot}} > 3P_{\text{orb}} \) and rotate only \( \pm 20^\circ \) per day. Wolf & Harmanec (2004) recently made UBV photometric observations of HD 179949 at our request from the SAAO Sutherland Observatory. When they combined their V observations with those from Hipparcos (converted to V), they detected a rotation period of 7.07 days but with an amplitude of only 0.008 mag. Given that the rms of the V observations was 0.006 mag, this periodicity is at the limit of detection. Indirect indications of the rotation rate of HD 179949 imply \( P_{\text{rot}} \approx 9 \) days and are presented in Shkolnik et al. (2003; see also Saar et al. 2003). These include a high X-ray luminosity for the star, a very long tidal synchronization timescale, and a moderate \( S_{\text{HK}} \) index. While more photometry is needed to determine a rotation period conclusively, it is highly unlikely that HD 179949 is tidally locked to its planet at 3.092 days.

### 3.3.1. Planet-induced Activity on Two Stars

In Shkolnik et al. (2003) we presented the first evidence of planet-induced heating on HD 179949. The effect lasted for over a year and peaked only once per orbit, suggesting a magnetic interaction. We fitted a truncated, best-fit sine curve with \( P = P_{\text{orb}} = 3.092 \) days corresponding to the change in projected area of a bright spot on the stellar surface before being occulted by the stellar limb. The left panel of Figure 8 updates the integrated K residuals to include the 2003 September data. The spot model is a remarkable fit for the 2001 and 2002 data.

![Fig. 7](image1.png)

**Fig. 7.**—Integrated flux of the K line residuals from a normalized mean spectrum of \( \tau \) Boo and HD 209458 as a function of orbital phase. The symbols distinguish data from different observing runs: 2001 August (circles), 2002 July (squares), 2002 August (triangles), 2003 September (diamonds). Units of the integrated flux are in equivalent angstroms relative to the normalization level, which is approximately \( \frac{1}{4} \) of the stellar continuum. The error bars in residual flux are \( \pm 1 \sigma \) as measured from the intranight variations. The size of the phase error is within the size of the points.

![Fig. 8](image2.png)

**Fig. 8.**—Integrated flux of the K line residuals from a normalized mean spectrum of HD 179949 and \( \upsilon \) And as a function of orbital phase. The solid lines are best-fit spot models. For HD 179949, we used a truncated sine curve fitted to the 2001 and 2002 data, and for \( \upsilon \) And, we fitted the curve to the 2002 and 2003 data.
peaking at $\phi = 0.83$ with an amplitude of 0.027. Clearly, the average K emission is higher during the latest run (as shown in Fig. 5) with a much smaller level of variability. It is interesting to note that the 2003 data still peak between $\phi = 0.80$ and 0.95, consistent with the previous results.

The second convincing case of magnetic interaction is between $\nu$ And and its innermost giant planet.\(^5\) In the right panel of Figure 8, the 2002 July, 2002 August, and 2003 September runs show good agreement in phase-dependent activity with an enhancement at $\phi = 0.53$. The best-fit sine curve has an amplitude of 0.0032. The 2001 August fluxes are lower than the mean of all four observing runs by almost 3% and still display a significant ($>2\sigma$) modulation like the quiescent epoch of HD 179949. Again, even the low-amplitude modulation has a rise and fall with a period consistent with $P_{\text{orb}}$ and peaks near $\phi = 0.5$.

For these two cases, the peak of the emission does not directly coincide with the subplanetary point, $\phi = 0$. For HD 179949, it leads the planet by $60^\circ$ in phase, and for $\nu$ And, the Ca ii emission is $169^\circ$ out of phase with the subplanetary point. Santos et al. (2003) also observed a $90^\circ$ lag from the sub-binary point in the periodic activity indicated by the photometric variations for HD 192263. The phase lead or lag may help identify the nature of the interaction. For example, the phase offset of a starspot or group of starspots can be a characteristic effect of tidal friction, magnetic drag, or reconnection with off-center stellar magnetic field lines, including a Parker spiral-type scenario (Weber & Davis 1967; Saar et al. 2003). In any case, the phasing, amplitude, and period of the activity have persisted for over a year between observations. For HD 179949, this equals 108 orbits or at least 37 stellar rotations, and for $\nu$ And, the time spans 88 orbits or approximately 29 rotations.

The observations are consistent with a magnetic heating scenario as the chromospheric enhancement occurred only once per orbit. We estimated the excess absolute flux released in the enhanced chromospheric emission of HD 179949 by calibrating the flux with that of the Sun. The flux was the same order of magnitude as a typical solar flare, $\sim 10^{27}$ ergs s$^{-1}$ or $1.5 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$. This implies that flarelike activity triggered by the interaction of a star with its hot Jupiter may be an important energy source in the stellar outer atmosphere. This also offers a mechanism for short-term chromospheric activity on the stars with close-in Jupiter-mass planets.

3.3.2. The Nonvarying Program Stars

Of the 10 program stars we monitored for H and K variability, 5 of them showed no changes down to the 0.001 level: 51 Peg, HD 46375, HD 75289, HD 76700, and HD 83443. There are two reasons we offer to explain the relative quiescence of these stars. It was well known through the many years of the Mount Wilson $\Delta$HK survey that there is a strong correlation between rotation rate (or inversely with rotation period) and Ca ii emission (Noyes et al. 1984; Pasquini et al. 2000). This is a likely contributor although it is not obviously clear in our sample set as shown in the left panel of Figure 9, where the inverse of the rotation period is plotted against the mean chromospheric emission of the Ca ii K line ($\langle K \rangle$). The photospheric contribution to the emission was removed from $\langle K \rangle$ using $\langle K \rangle = \langle K \rangle - R_{\text{phot}}/R_{\text{HK}}$, where $R_{\text{phot}} = R_{\text{HK}} - R_{\text{phot}}$, and is an empirical function of $(B-I)$ and $S_{\text{HK}}$ taken from Hartmann et al. (1984). The chromospheric contributions $R_{\text{HK}}$ are from Wright et al. (2004).\(^6\) In Table 1 we list $\langle K \rangle$, $\langle K \rangle$, and $\langle \text{MAD K} \rangle$ for all the stars. From the right panel of Figure 9, we deduce that the higher a star’s chromospheric emission, the more night-to-night activity it displays. Radick et al. (1998) show the same effect for a much larger sample. This is akin to shot noise since the flaring or stochastic noise associated with the activity will increase with the activity level.

Secondly, a recent calculation of the magnetic fields in giant extrasolar planets (Sánchez-Lavega 2004) looked at the internal structure and the convective motions of these planets in order to calculate the dynamo-generated surface magnetism. Given the same angular frequency (which is a reasonable approximation for the short-period planets in question), the magnetic dipole moment, and hence the magnetospheric strength, increases with planetary mass. This is observed in our own solar system for the magnetized planets where the magnetic moment grows proportionally with the mass of the planet (Arge et al. 1995). Since only lower limits exist for most of the hot Jupiters, we can only plot $M_p \sin i$ against $\langle \text{MAD K} \rangle$ in Figure 10, where we still see an intriguing correlation. The dashed circles for HD 179949

\(^5\) $\nu$ And has three known Jupiter-mass planets at 0.059, 0.829, and 2.53 AU (Butler et al. 1999).

\(^6\) For those few stars that were not in Wright et al. (2004), we removed the photospheric contribution as tabulated from stars in the Wright et al. (2004) sample of the same spectral type and log $g$. 

---

**Fig. 9.—Left:** $1/P_{\text{rot}}$ in days plotted against $\langle K \rangle$, the mean chromospheric emission in the K line, for all stars except HD 76700, for which no $P_{\text{rot}}$ is published. **Right:** $\langle K \rangle$ as a function of the mean MAD K values per run for all the stars. The dashed circles are $\langle \text{MAD K} \rangle$ for HD 179949 and $\nu$ And with the orbital (geometric) modulation removed. Units for $\langle K \rangle$ and $\langle \text{MAD K} \rangle$ are in equivalent angstroms relative to the normalization level. All values are listed in Table 1.
and $v$ And are their (MAD K) values $0.0021$ and $0.0011$, respectively) with the orbital modulation removed. Of our sample, $\tau$ Boo has the most massive planet and yet falls well below the correlation. As we discuss further in §4, if the star and planet are tidally locked, as is thought to be the case for $\tau$ Boo, then there is little or no free energy left from the orbit and we would expect weak, if any, magnetic coupling.

3.4. Modulation by Rotation

For most of our target stars, rotation periods are not well enough known to accurately phase the Ca ii data with $P_{\text{rot}}$. There is even ambiguity in $P_{\text{rot}}$ of the often-observed $\kappa^{1}$ Cet. In late 2003, $\kappa^{1}$ Cet was monitored continuously for 30.5 days by the Microvariability and Oscillations of Stars (MOST) microsatellite. This best light curve ever obtained for $\kappa^{1}$ Cet necessitates a non-zero eccentricity, while a sine curve is sufficient for HD 73256. We observed periodic Ca ii H and K variability in the chromosphere of $\kappa^{1}$ Cet during our 2002 and 2003 CFHT runs from which we determined a rotation period of $9.332 \pm 0.035$ days. The results were first published in Rucinski et al. (2004), where we compared the activity seen in Ca ii with MOST’s light curve showing that the chromospheric activity coincided with the low-latitude spot such that the maxima of the two curves agree. The (MAD K) given for these two stars in Table 1 are corrected for the rotational modulation resulting in activity levels comparable to HD 179949. The integrated residual K fluxes for $\kappa^{1}$ Cet and HD 73256 are plotted against relative rotational phase in Figure 11. For completeness, we plot the residual K fluxes of HD 73256 as a function of orbital phase in Figure 12, where the flare is apparent at $\phi_{\text{orb}} = 0.03$. There is no clear signature of the planet in the activity.

In both cases, $\kappa^{1}$ Cet ($M_{\text{J}} = 4.92$) and HD 73256 ($M_{\text{J}} = 5.27$) show sporadic flaring beyond the clear rotational modulation. The periodic best-fit curve for $\kappa^{1}$ Cet necessitates an energy of $2.8 \times 10^{9}$ ergs cm$^{-2}$ s$^{-1}$ (again, measured by comparing with solar absolute flux). We estimate the absolute flux emitted from HD 73256’s flare at $\phi_{\text{orb}} = 0.15$ to be $4.9 \times 10^{8}$ ergs cm$^{-2}$ s$^{-1}$ (or $>2.9 \times 10^{8}$ ergs cm$^{-2}$ if the flare lasted for at

in $P_{\text{rot}}$ from the space observations of $\kappa^{1}$ Cet demonstrates the difficulty in measuring $P_{\text{rot}}$ for most stars.

Nonetheless, two stars do exhibit clear rotational modulation: $\kappa^{1}$ Cet, a star with no confirmed planet (Halbwachs et al. 2003), and HD 73256, a star with a $1.85 M_{\text{J}}$, planet orbiting at 0.037 AU (Udry et al. 2003). The Ca ii emission from $\kappa^{1}$ Cet has been monitored by Baliunas et al. (1995) through the narrow-band filter of the Mount Wilson survey from 1967 to 1991. These data show long-term stability of a period of $9.4 \pm 0.1$ days. Close to the photometric rotation period of $9.214$ days published by Messina & Guinan (2002). The rotation period for HD 73256 is photometrically determined to be $14$ days (Udry et al. 2003), consistent with the $13.9$ days derived from the $R'_{\text{IR}}$ activity index (Donahue 1993).

We observed periodic Ca ii H and K variability in the chromosphere of $\kappa^{1}$ Cet during our 2002 and 2003 CFHT runs from which we determined a rotation period of $9.332 \pm 0.035$ days. The results were first published in Rucinski et al. (2004), where we compared the activity seen in Ca ii with MOST’s light curve showing that the chromospheric activity coincided with the low-latitude spot such that the maxima of the two curves agree. HD 73256 was observed twice per night for four nights at the VLT. The mean K cores of these two stars are shown at the top of Figure 4 where their similarly strong emission is evident. The high level of chromospheric emission points to a young age for both of these stars: $650–750$ Myr for $\kappa^{1}$ Cet (Gu¨del et al. 1997; Dorren & Guinan 1994) and $830$ Myr for HD 73256 (Donahue 1993). The (MAD K) given for these two stars in Table 1 are corrected for the rotational modulation resulting in activity levels comparable to HD 179949. The integrated residual K fluxes for $\kappa^{1}$ Cet and HD 73256 are plotted against relative rotational phase in Figure 11. For completeness, we plot the residual K fluxes of HD 73256 as a function of orbital phase in Figure 12, where the flare is apparent at $\phi_{\text{orb}} = 0.03$. There is no clear signature of the planet in the activity.

In both cases, $\kappa^{1}$ Cet ($M_{\text{J}} = 4.92$) and HD 73256 ($M_{\text{J}} = 5.27$) show sporadic flaring beyond the clear rotational modulation. The periodic best-fit curve for $\kappa^{1}$ Cet necessitates a non-zero eccentricity, while a sine curve is sufficient for HD 73256. The largest excursion from the rotation curve of $\kappa^{1}$ Cet has an energy of $2.8 \times 10^{9}$ ergs cm$^{-2}$ s$^{-1}$ (again, measured by comparing with solar absolute flux). We estimate the absolute flux emitted from HD 73256’s flare at $\phi_{\text{orb}} = 0.15$ to be $4.9 \times 10^{8}$ ergs cm$^{-2}$ s$^{-1}$ (or $>2.9 \times 10^{8}$ ergs cm$^{-2}$ if the flare lasted for at

The MOST microsatellite is a Canadian photometric telescope recently launched to observe $p$-mode oscillations on Sun-like stars (Walker et al. 2003b).

Fig. 10.—Minimum planetary mass (in Jupiter masses) plotted against the average MAD of the K line per observing run. The dashed circles are (MAD K) for HD 179949 and $v$. And with the orbital (geometric) modulation removed. All data are listed in Table 1.

![Graph showing minimum planetary mass](image1.png)

---

![Graph showing integrated K line residuals](image2.png)

---

![Graph showing integrated K line residuals](image3.png)

---

![Graph showing integrated K line residuals](image4.png)
least the hour for which we observed it). The modulation of the K emission due to rotation is ≈6%, indicating that the emission is dominated by a large hot spot on the stellar surface. As we have seen on HD 179949 and \( \upsilon \) And, planet-induced variations are at the level of 1%–2%, suggesting that the reigning hot spot could have diluted any heating caused by the hot Jupiter.

The \( \Delta \text{RVs} \) for \( \kappa^1 \) Cet are plotted in Figure 13 against the 9.332 day phase determined from the K line residuals; the open symbols correspond to data from 2002 and the filled squares to 2003. From the 2002 data we derive \( \sigma_{\text{RV}} = 21.8 \, \text{m} \, \text{s}^{-1} \) and 23.6 m s\(^{-1} \) when combined with 2003. These values are very similar to \( \sigma_{\text{RV}} = 24.4 \, \text{m} \, \text{s}^{-1} \), found over 11 yr by Cumming et al. (1999). In 2003 the \( \Delta \text{RVs} \) appear significantly different between the two nights, something that seems to be reinforced by the consistency within the pairs of \( \Delta \text{RVs} \). While a planetary perturbation cannot be ruled out by the 2002 data and other PRV studies, the difference in 2003 might be associated with the velocity field of the star itself. The increase of velocity with increasing K line strength at \( \phi_{\text{tan}} \approx 0.7 \) is consistent with the extreme event in 1988 seen by Walker et al. (1995). However, it should be emphasized, the possibility remains of a close giant planet around \( \kappa^1 \) Cet. For instance, a planet inducing a reflex RV variation <50 m s\(^{-1} \) and tidally synchronized with the star would have \( M_p \sin i \approx 0.74 M J \) and \( a = 0.084 \, \text{AU} \).

4. A PHYSICAL SCENARIO

The enhancements of chromospheric activity on HD 179949 and \( \upsilon \) And appear only once per orbit, implying a magnetic, rather than tidal, interaction between the star and its hot Jupiter. The two stars are F-type stars with higher X-ray luminosity than the solar value. The \( \text{ROSAT} \) catalog of bright main-sequence stars lists HD 179949 as having at least double the X-ray luminosity (a measurement independent of \( i \)) of most other single F8–F9 dwarfs (Hünsch et al. 1998). \( \text{Yohkoh} \) solar X-ray observations (e.g., Yokoyama & Shibata 2001) have shown that the energy release at the site of magnetic reconnection during a solar flare generates a burst of X-ray–emitting gas. This hot plasma is funneled along the magnetic field lines down to the surface producing “footprints” through anomalous heating of the Sun’s chromosphere and transition region. It is this same phenomenon that is likely occurring between hot Jupiters and their host stars through the reconnection of their magnetic fields. Observationally, companion-induced activity is unambiguously observed on RS CVn stars, as discussed in § 1.

The hot Jupiter of \( \upsilon \) And is located farther out from the host star than that of HD 179949, implying that the magnetic interaction between the star and its hot Jupiter is diminished. This would result in less Ca ii enhancement as is shown in our data. \( \tau \) Boo is also an F-type star with intense X-ray emission, but its magnetic influence is likely reduced by the small relative motion in the azimuthal direction between the planet and the stellar magnetosphere in an almost final equilibrium state in which the star and the planet are tidally locked to each other. While more data are required to truly verify whether the variability of Ca ii emission is correlated to the apparent position of the hot Jupiter in these systems, we explore and review a few theoretical aspects of planet-induced heating scenarios in this section.

The location of the hot Jupiter relative to the Alfvén radius (the distance from the star at which the RV of the wind \( V_{\text{r, wind}} \) equals the local Alfvén velocity \( V_A \)) plays a significant role in transporting energy toward the star against the stellar winds. Since the Alfvén radius of the Sun is about 10–20 \( R_\odot \) at solar minimum and 30 \( R_\odot \) at solar maximum (e.g., Lotova et al. 1985), the small distance ≤0.1 AU of hot Jupiters from their host stars suggests that unlike our Jupiter, surrounded by a bow shock, some of these hot Jupiters are located inside the Alfvén radius depending on the magnetic strength of their host stars (Zarka et al. 2001; Ip et al. 2004). Therefore, the direct magnetic interactions between a hot Jupiter and its star without a bow shock might resemble the Io-Jupiter interactions (Zarka et al. 2001) or the RS CVn binaries (Rubenstein & Schaefer 2000). Most of the theoretical models applied to these two cases have focused on the geometry of intertwined magnetic fields, as well as the energy transport through Alfvén waves and/or induced currents.

Alfvén waves cannot propagate along the stellar field lines toward the star in the region outside the Alfvén radius where the group velocity of Alfvén waves is always in the positive radial direction (e.g., Weber & Davis 1967). Other means of inward...
energy transport require their energy flux to be at least larger than the energy flux carried by the stellar winds.

Ip et al. (2004) estimate the input magnetic power due to the relative motion between the synchronized hot Jupiter and the stellar magnetosphere to be $\sim 10^{27}$ ergs s$^{-1}$, the same order of magnitude of a typical solar flare. A similar amount of power might be obtained based on the induced current model (Zarka et al. 2001) if the radius of the ionosphere of an unmagnetized hot Jupiter in the induced current model can be approximated by the radius of the magnetopause of a magnetized hot Jupiter. The observed excess energy flux from an unresolved disk of the star is equal to this input magnetic power averaged over the disk of the star. That is, the energy flux is roughly equal to

$$\left( \frac{B_m^2}{8 \pi} \right) \left( V_{\text{orb}} - V_{\phi, \text{wind}} \right) \left( \frac{r_m}{R_p} \right)^2 = \left( \frac{B_p^2 (1-1/q)}{8 \pi} \right) \left( \frac{2 \pi}{P_{\text{orb}}} - \frac{2 \pi}{P_{\text{rot}}} \right) \left( \frac{R_p}{a} \right)^2 \left( \frac{R_p}{R_p} \right)^2 \ .$$

(1)

where $r_m$ is the radius of the planet’s magnetopause, $B_m$ is the magnetic field at the magnetopause, $R_p$ is the radius of the star, $R_p$ is the radius of the planet, $a$ is the distance between the star and the planet, $V_{\text{orb}}$ and $P_{\text{orb}}$ are the orbital velocity and period, respectively, $P_{\text{rot}}$ is the rotation period of the star, $V_{\phi, \text{wind}}$ is the azimuthal component of the stellar wind velocity, and $B_a$ and $B_p$ are the mean magnetic field on the surface of the star and the planet, respectively. In deriving the above equation, we have assumed that the stellar magnetic field decays as $r^{-p}$, the planetary field decays as $r^{-q}$, $r_m$ was determined by equating the stellar and planetary fields at the magnetopause [i.e., $B_a(R_p/a)^p = B_p(R_p/r_m)^q$], and the stellar magnetosphere inside the Alfvén radius is nearly corotating with the stellar rotation (i.e., $V_{\phi, \text{wind}} \approx \Omega a$). The radial component of the stellar wind $V_{\text{r, wind}}$ is left out from the above estimate as long as the condition $V_{\text{r, wind}} < V_{\text{orb}} - V_{\phi, \text{wind}}$ is valid. The energy flux in equation (1) should be regarded as the maximal input energy from the planet’s orbital energy because only some fraction of this amount of energy is transferred to the Ca II emissions. For $p = 2$ (Vrsnak et al. [2002] for the case of our Sun, and Weber & Davis [1967] for the case of open fields), $q = 2$, $a = 0.045$ AU, $R_p = 1.3$ $R_\odot$, $P_{\text{rot}} = 1.1$ $R_\odot$, $P_{\text{rot}} = 9$ days, $B_a = 200$ G, and $B_p = 10$ G, the energy flux given by equation (1) is roughly equal to $10^5$ ergs cm$^{-2}$ s$^{-1}$, a value comparable to the differential intensity from our data of Ca II K emission from HD 179949. The same amount of energy flux can also be achieved for the case of a dipole field for the hot Jupiter ($p = 2$, $q = 3$) where $a = 0.045$ AU, $B_a = 250$ G, and $B_p = 10$ G. If both the star and the planet have dipole fields ($p = q = 3$), very strong fields $B_a = 1000$ G and $B_p = 30$ G are required to generate the same energy flux. Therefore, the tight energy budget constrained by the synchronous Ca II emission from HD 179949 strongly suggests that the mean global fields of this F-type star are not likely in a dipole field configuration at the location of the planet but have the radial, open structure (i.e., $p = 2$) just like the solar fields have as a result of the outflowing winds.

The argument that hot Jupiters might have weaker fields than our Jupiter owing to slower spin rates and weaker convection (Sánchez-Lavega 2004) should be treated with caution since in addition to the uncertainty in the interior structure of the metallic hydrogen region of a hot Jupiter, the response of slow convection to various rotation rates in the dynamo process is not well understood. If $p = 2$ and $B_p \lesssim 1$ G (Sánchez-Lavega 2004) for HD 179949b, then equation (1) indicates that $B_a = 300$ G is required to generate the energy flux $10^5$ ergs cm$^{-2}$ s$^{-1}$ and in this case the stellar field dominates over the planetary field even on the surface of the hot Jupiter (i.e., $q = \infty$ in eq. [1]).

The observational constraints on the strength of the stellar magnetic fields such as the field versus Ca II relation (Schrijver et al. 1989, 1992), along with the radio cyclotron emissions from the hot Jupiter’s magnetosphere,9 should help to narrow down the field strength of hot Jupiters in the magnetic interaction scenario, therefore improving our knowledge of the interior structure and the dynamo processes of gaseous planets.

Now we turn our attention to the variation of Ca II level, the phase coverage of additional emission, and the phase lead at the different epochs of our observations. The data for HD 179949 seem to suggest that the additional Ca II emission is smaller and the range of phase spanned by the emission is larger when the average (or minimal) K emission is larger. Presumably this has something to do with the intrinsic stellar activity and therefore the stellar field geometry. The observed phase lead may be caused by spiral stellar fields loaded with stellar winds. When a star is in its quiet phase and therefore the average Ca II emission is very low, no enhancement happens probably because $V_{\text{wind}} \lesssim V_A$ for a hot Jupiter located far out from its parent star and therefore being outside the Alfvén radius, as may be the case for the 2001 August observations of $\upsilon$ And. As the star shifts to its more active phase, the average Ca II emission is at the moderate level and $V_{\text{wind}}$ is not much smaller than $V_A$ at the hot Jupiter. At this time, the configuration of the field lines on the surface of the star may be characterized by the open fields from the coronal holes covering a large area of the star, as well as the closed fields distributed only near the magnetic equator. Consequently, the footpoints of the open stellar field lines pointing to the planet are located at lower latitudes, as indicated by the 2001 and 2002 data for HD 179949 fitted by a truncated sine curve (Shkolnik et al. 2003; also shown in Fig. 8). While a great number of closed fields form at low magnetic latitudes during this time, the coronal holes shrink to the magnetic polar regions. The bright spot at a high latitude implied from the observation for HD 179949 in 2003 September might be caused by the scenario that the hot Jupiter perturbs the open field lines emanating from the shrinking coronal holes near the polar regions, leading to a longer phase duration of the additional Ca II flux and perhaps reducing the additional emission due to the smaller projection along the line of sight at higher latitudes. Note that at the time close to the stellar maximum activity, the stellar field lines might be occasionally stretched out like solar streamers emanating from the low latitudes of the star where closed loops of stellar magnetic fields aggregate, possibly giving rise to the planet-induced heating at low latitudes of the stellar surface as well.

The picture that we have sketched thus far assumes that most of the energy flux released from the vicinity of the hot Jupiter is transported along the field lines by Alfvén waves and deposited at the footpoints of the magnetic lines. Since the field lines inside the Alfvén radius are dominated by the poloidal component, detailed calculations for stellar wind models are needed to study how the integration of small pitch angles of the field line can lead to the moderate to large phase angles, 60° for HD 179949 and 180° for $\upsilon$ And. The phase difference is also determined by the Alfvén speed travel time along the stellar

9 The characteristic frequency of the cyclotron radiation is $eB_p/2\pi mc$, where $c$ is the speed of light and $e$ and $m_e$ are the electron charge and mass, respectively. The radiation can reach $\approx 30$–60 MHz if $B_p \approx 10$–20 G.
field line. If $V_A \gg V_{\text{wind}}$, the Alfven disturbance $aV_A$ takes roughly a few hours to propagate from the hot Jupiter to the star with $V_A \approx 10^8 \text{ cm s}^{-1}$ at 0.04 AU. This means that the azimuthal angle that the planet has already traveled over the Alfven speed travel time is not small. Since the hot Jupiter of $v$ And is located farther out ($a = 0.06$ AU) from its star than HD 179949b ($a = 0.045$ AU), the large phase angle of 180° for $v$ And might actually represent a phase lag caused by the small inward group velocity of the Alfven waves $V_A - V_{r,\text{wind}}$ that takes considerable amount of time to travel along the field lines right after the waves are generated from the planet. Alternatively, a large phase difference between the location of the heating spot in the chromosphere and the position of the hot Jupiter might be caused by the entangled or rotationally spiraled magnetic fields connecting directly between the hot Jupiter and the star (Rubenstein & Schaefer 2000; Saar et al. 2003; Ip et al. 2004).

Besides considering the energy transported along the field lines and field geometry, understanding how the energy is dissipated is important to construct a complete picture for the Ca ii emission in the planet-induced scenario. In our own solar system, a bow shock of the solar wind generally hinders this because Alfven waves cannot propagate toward the star from the region outside the Alfven radius. The inward Poynting energy of Alfven waves $r^2B^2\rho^{1/2}$ is roughly conserved if the wind velocity $V_{r,\text{wind}}$ is much smaller than the Alfven speed $V_A$. Here $r$ is the distance away from the star, $\rho$ is the magnetic disturbance of the wave, and $\rho$ is the mass density of the stellar wind. At first glance, the transition region characterized by a steep decrease of the Alfven speed with depth seems to provide a possible radial stratification for the inward-propagating Alfven waves to pile up the magnetic energy density, leading to the nonlinear dissipation of the growing waves and therefore the heating on the top of the chromosphere. However, the extremely narrow transition region corresponding to sharp gradient in density and Alfven speed should act as a wave barrier to reflect the Alfven waves. In this case, the wavelength is comparable to the size of the magnetopause of the hot Jupiter (Wright 1987) unless the high-frequency modes are largely excited at the reconnection site. The energy carried by the planet-induced Alfven waves along the open fields might be finally transmitted to coronal loops and therefore might be dissipated via reconnection absorption, a damping mechanism in contradiction to the observations of the solar corona and the coronae of cool stars (Schrijver & Aschwanden 2002; Dé moulin et al. 2003). The heating due to accelerated particles by Alfven waves (Crary 1997) is not important either because, unlike the interplanetary space, the dense corona eliminates the kinetic effect of plasmas inside 0.04 AU. Despite the difficulties, the energy deposit on the surface of the star from the planet-induced Alfven disturbances may be achieved by interacting nonlinearly with stellar winds. The stellar wind consists of charged particles, stellar fields, and probably Alfven waves. Nonlinear interaction between planet-induced incoming and stellar intrinsic outgoing waves is one route of heating the surface of the star.

The scenario of magnetic interaction implies the orbital decay of hot Jupiters since the ultimate source of energy comes from the orbital energy. Theoretically the orbital decay of hot Jupiters on the timescale of a few billion years can result from the tidal dissipation in the host star driven by the hot Jupiter so long as the tidal dissipation in the solar-type stars is efficient (Rasio et al. 1996; Witte & Savonije 2002; Pätzold & Rauer 2002; Jiang et al. 2003). In the magnetic interaction scenario for Ca ii emission, the timescale of orbital decay is roughly equal to the ratio of the orbital energy of the hot Jupiter (∼10^{44} ergs) to 10^{-7} ergs s^{-1}. This gives a timescale as short as several billion years, imposing a nonnegligible constraint on modeling the orbital evolution of hot Jupiters.

In the case of $\tau$ Boo, the F-type star might be almost tidally locked to its hot Jupiter. Therefore, there is less free energy available from the planet’s orbit. According to equation (1), the azimuthal relative motion between the stellar and the planetary magnetospheres is smaller than that for the HD 179949 system by a factor of 0.2 if 3.2 days is indeed the rotation period of $\tau$ Boo. The mean chromospheric emission (K') from $\tau$ Boo is weaker than that from HD 179949 roughly by a factor of 0.9. Assuming that the mean stellar field of $\tau$ Boo is smaller than that of HD 179949 by 0.9$^2$ $(K' \propto B_0^2)$, one can estimate that the input energy to $\tau$ Boo is less than that to HD 179949 roughly by a factor of 0.15. If the corresponding Ca ii emissions are dimmed by this same factor, this effect should have been detected. However, unlike the other two F-type stars HD 179949 and $v$ And, the variability of Ca ii emissions from $\tau$ Boo did not show any consistent phase relation with the planet’s orbit. Note that the radial movement of spiral stellar fields with the stellar winds might be important in providing energy in this case because $V_{r,\text{wind}} \approx V_{\text{orb}}$ at 0.04 AU in the solar system. However, in the case of small pitch angles of the field lines inside the Alfven radius, the Alfven modes driven solely by the radial impact of the stellar winds might not be as efficient since the stellar fields sweep across the hot Jupiter owing to the slow relative azimuthal motion.

The transiting system HD 209458 did not show synchronized Ca ii enhancement, perhaps because G stars have $V_{r,\text{wind}} > V_A$ at the distance of the hot Jupiter owing to weaker stellar fields. The nonsynchronized Ca ii enhancement of $\tau$ Boo and HD 209458 (as well as the flaring on HD 73256 and $\kappa^1$ Cet, discussed in § 3.4) might still be attributed to direct interactions with their planets but through more chaotic means as a result of the variability of the stellar winds at the locations of these hot Jupiters relative to the nearby Alfven radius. Monitoring these stars continuously through several orbital and rotational periods should pinpoint down the cause (intrinsic owing to fast rotation or induced by a hot Jupiter) of the strong night-to-night variabilities detected in these systems.

5. SUMMARY AND FUTURE

Of the sample of stars observed from the CFHT, those with planets (with the exception of 51 Peg) show significant night-to-night variations in their Ca ii H and K reversals. The Sun and $\tau$ Cet, which have no close planets, remained very steady throughout each of the four observing runs. HD 179949 and $v$ And exhibited repeated orbital phase-dependent activity with enhanced emission leading the subplanetary point by 0.17 and 0.47 in orbital phase, respectively. Both systems are consistent with a magnetic heating scenario and may be the first glimpse at the magnetospheres of extrasolar planets. The phase lead or lag of the peak emission relative to the subplanetary longitude can provide information on the field geometries and the nature of the effect such as tidal friction, magnetic drag, or reconnection with off-center magnetic fields, including a Parker spiral–type scenario.
HD 209458 and τ Boo also exhibited night-to-night variations that could not exclusively be due to stellar rotation. If τ Boo is indeed tidally locked by its hot Jupiter, there is no orbital energy available to generate the Alfvén modes efficiently as the stellar fields sweep across the planet owing to the slow relative azimuthal motion. We measured the excess absolute flux released in the enhanced chromospheric emission of HD 179949 to be the same order of magnitude as a typical solar flare, $\sim 10^{27}$ ergs $s^{-1}$ or $1.5 \times 10^{27}$ ergs $s^{-1} cm^{-2}$. This implies that flareslike activity triggered by the interaction of a star with its hot Jupiter may be an important energy source in the stellar outer atmosphere. This offers a mechanism for short-term chromospheric activity.

The H and K emission of κI Cet, an active star with no confirmed planet, was clearly modulated by the star’s 9.3 day rotation. Similarly, HD 73256 displayed rotational modulation with its 14 day period. In these two cases, the chromospheric emission increases by $\geq 6\%$ (relative to the normalization level at $\frac{1}{2}$ of the continuum). Any planet-induced heating at the level of $1\%-2\%$ could have been diluted by the dominating hot spot on the stellar surface. Neither the ΔRVs nor the Ca ii periodicity exclude the possibility of a substellar companion in a tight orbit around κI Cet.

Apart from the cyclical component for four of the stars, short-term chromospheric activity appears weakly dependent on the mean K line reversal intensities for the sample of 13 stars. In addition, a suggestive correlation exists with $M_p \sin i$ and thus with the hot Jupiter’s magnetic field strength. Because of their small separation ($\leq 0.1$ AU), many of the hot Jupiters lie within the Alfvén radius of their host stars, which allows a direct magnetic interaction with the stellar surface.

Additional Ca ii observations are crucial to confirm the stability of the magnetic interaction, as well as to establish better phase coverage. Observations on timescales of a few years will begin to characterize the long-term activity of our program stars and allow us to see correlations between intrinsic Ca ii emission and night-to-night activity more clearly. This work opens up the possibility of characterizing planet-star interactions with implications for extrasolar planet magnetic fields and the energy contribution to stellar atmospheres.

A next step in understanding planet-star interactions is to map the activity as a function of stellar atmospheric height. Above the chromosphere lies the thin transition region (TR), where the temperature increases steeply as density and pressure drop, and the corona, which can extend out to several stellar radii. Furthermore, since the magnetic field drops off as $r^{-p}$ (where $2 \leq p \leq 3$), these layers facilitate a stronger interaction with the planet. Their far-ultraviolet and X-ray emissions will be extremely important diagnostics. One indication that the heating is from the outside in is if the increase in emission occurs slightly earlier in phase than in Ca ii. Moreover, the relative strengths of the different emission lines will tell us where most of the energy is dissipated. The energy sum will point out if there are any discrepancies with the theorized energy budget. Orbital phase-dependent variability at these heights will constrain further the nature, form, and strength of the interaction, as well as specify nonthermal radiative processes in these hot layers of gas.

We are grateful to Marek Wolf and Petr Harmanec for their photometric observations of HD 179949 made at the South African Astronomical Observatory (SAAO). We thank Geoff Bryden, Peng-Fei Chen, Gary Glatzmaier, Gordon I. Ogilvie, and Ethan T. Vishniac for useful communications regarding § 4. Research funding from the Canadian Natural Sciences and Engineering Research Council (G. A. H. W. and E. S.) and the National Research Council of Canada (D. A. B.) is gratefully acknowledged. We are indebted to the CFHT staff for their care in setting up the CAFE fiber feed and the Gecko spectrograph, as well as to the staff at ESO’s VLT for their telescope and instrument support and the real-time data reduction pipeline. We also appreciate the helpful comments and suggestions from the referee, Steve Saar.

REFERENCES

Arge, C. N., Mullan, D. J., & Dolphinov, A. Z. 1995, ApJ, 443, 795
Baliunas, S. L., et al. 1995, ApJ, 438, 269
Bastian, T. S., Dulk, G. A., & Leblanc, Y. 2000, ApJ, 545, 1058
Baudrand, J., & Vitry, R. 2000, Proc. SPIE, 4008, 182
Bartel, R. P., Marcy, G. W., Fischer, D. A., Brown, T. M., Contos, A. R., Korzennik, S. G., Nisenson, P., & Noyes, R. W. 1999, ApJ, 526, 916
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Catalano, S., Rodonò, M., Frasca, A., & Cutispoto, C. 1996, in IAU Symp. 176, Stellar Surface Structure, ed. K. G. Strassmeier & J. L. Linsky (Dordrecht: Kluwer), 403
Charbonneau, D. 2003, in IAU Symp. 219, Stars as Suns: Activity, Evolution, and Planets, ed. A. O. Benz & A. K. Dupree (Dordrecht: Kluwer), 140
Charbonneau, D., Brown, T., Latham, D., & Mayor, M. 2000, ApJ, 529, L45
Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ, 568, 377
Cr{\`y}, F. J. 1997, J. Geophys. Res., 102, 37
Cumming, A., Marcy, G. W., & Butler, R. P. 1999, ApJ, 526, 890
Cuntz, M., Saar, S. H., & Musielak, Z. E. 2000, ApJ, 533, L115
D{\`e}moulin, P., van Driel-Gesztelyi, L., Mandrini, C. H., Klimchuk, J. A., & Harra, L. 2003, ApJ, 586, 592
Donahue, R. A. 1993, Ph.D. thesis, New Mexico State Univ.
Donati, J.-F., Henry, G. W., & Hall, D. S. 1995, ApJ, 443, 293, 107
Dorren, J. D., & Guinan, E. F. 1994, ApJ, 428, 805
Farrell, W. M., Desch, M. D., Lazio, T. J., Bastian, T., & Zarka, P. 2003, in ASP Conf. Ser. 294, Scientific Frontiers in Research on Extrasolar Planets, ed. A. O. Benz & A. K. Dupree (Dordrecht: Kluwer), 140
Francesco, P., Spite, M., Gillet, D., Gonzalez, J.-F., & Spite, F. 1996, A&A, 310, L13
Glebocki, R., Bielcz, E., Pastuszka, Z., & Sikorski, J. 1986, Acta Astron., 36, 369
Gray, D. F. 1982, ApJ, 255, 200
G{"u}del, M., Guinan, E. F., & Skinner, S. L. 1997, ApJ, 483, 947
Halbwachs, J. L., Mayor, M., Udry, S., & Arenou, F. 2003, A&A, 397, 159
Hartmann, L., Soderblom, D. R., Noyes, R. W., Burnham, N., & Vaughan, A. H. 1984, ApJ, 276, 254
Henry, G. W., Baliunas, S. L., Donahue, R. A., Fekel, F. C., & Soon, W. 2000, ApJ, 531, 415
Henry, G. W., Donahue, R. A., & Baliunas, S. L. 2002, ApJ, 577, L111
H{"u}nsch, M., Schmitt, J. H. M. M., & Voges, W. 1998, A&A, 132, 155
Ip, W.-H., Kopp, A., & Hu, J.-H. 2004, ApJ, 602, L53
Jiang, I.-G., Ip, W.-H., & Yeh, L. C. 2003, ApJ, 582, 449
Lotova, N. A., Blums, D. F., & Vladimirskii, K. V. 1985, A&A, 150, 266
Marcy, G. W., Butler, R. P., & Vogt, S. 2000, ApJ, 536, L43
Marcy, G. W., Butler, R. P., Williams, E., Bingsten, L., Graham, J. R., Ghez, A. M., & Jernigan, J. G. 1997, ApJ, 481, 926
Mayor, M., Udry, S., Naef, D., Pepe, F., Queloz, D., Santos, N., & Burnet, M. 2004, A&A, 415, 391
Mazeh, T., et al. 2000, ApJ, 532, L55
Messina, S., & Guinan, E. F. 2002, A&A, 393, 225
Montes, D., Fernandez-Figueroa, J. M., de Castro, E., & Comide, M. 1994, A&A, 285, 609
Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Pasquini, L., de Medeiros, J. R., & Girardi, L. 2000, A&A, 361, 1011
Pätzold, M., & Rauer, H. 2002, ApJ, 568, L117
Radick, R. R., Lockwood, G. W., Skiff, B. A., & Baliunas, S. L. 1998, ApJS, 118, 239
Rasio, F. A., Tout, C. A., Lubow, S. H., & Livio, M. 1996, ApJ, 470, 1187
Robinson, C. R., & Bopp, B. W. 1987, in Cool Stars, Stellar Systems, and the Sun, ed J. L. Linsky & R. E. Stencel (Berlin: Springer), 509
Rubenstein, E. P., & Schaefer, B. E. 2000, ApJ, 529, 1031
Rucinski, S. M., et al. 2004, PASP, 116, 1093
Ryabov, V. B., Zarka, P., & Ryabov, B. P. 2003, AGU Fall Meeting, Abstract SM31C-1131
Saar, S. H., Shkolnik, E., & Cuntz, M. 2003, in IAU Symp. 219, Stars as Suns: Activity, Evolution, and Planets, ed. A. O. Benz & A. K. Dupree (Dordrecht: Kluwer), 119
Sánchez-Laveaga, A. 2004, ApJ, 609, L87
Sanford, R. F., & Wilson, O. C. 1939, ApJ, 90, 235
Santos, N. C., Mayor, M., Nael, D., Pepe, F., Queloz, D., Udry, S., Burnet, M., & Revaz, Y. 2000, A&A, 356, 599
Santos, N. C., et al. 2003, A&A, 406, 373
Schaefer, B. E., King, J. R., & Deliyannis, C. P. 2000, ApJ, 529, 1026
Schneider, J. 2004, Extrasolar Planets Catalog (Paris: Observatoire de Paris), http://www.obspm.fr/encycl/catalog.html
Schrijver, C. J., & Aschwanden, M. J. 2002, ApJ, 566, 1147
Schrijver, C. J., Cote, J., Zwaan, C., & Saar, S. H. 1998, ApJ, 337, 964
Schrijver, C. J., Dobson, A. K., & Radick, R. R. 1992, A&A, 258, 432
Shkolnik, E. 2004, Ph.D. thesis, Univ. British Columbia
Shkolnik, E., Walker, G. A. H., & Bohlender, D. A. 2003, ApJ, 597, 1092
Tinney, C., Butler, P., Marcy, G., Jones, H., Penny, A., McCarthy, C., Carter, B., & Bond, I. 2003, ApJ, 587, 423
Tinney, C., Butler, P., Marcy, G., Jones, H., Penny, A., Vogt, S., Apps, K., & Henry, C. 2001, ApJ, 551, 507
Udry, S., et al. 2000, A&A, 356, 590
———. 2003, A&A, 407, 679
Vidal-Madjar, A., Lecavelier des Étangs, A., Désert, J.-M., Ballester, G., Ferlet, R., Hébrard, G., & Mayor, M. 2003, Nature, 422, 143
Vrsnak, B., Magdalenic, J., Aurass, H., & Mann, G. 2002, A&A, 396, 673
Walker, E. C. 1944, JRASC, 38, 249
Walker, G. A. H., Shkolnik, E., Bohlender, D. A., & Yang, S. 2003a, PASP, 115, 700
Walker, G. A. H., Walker, A. R., Irwin, A. W., Larson, A. M., Yang, S. L. S., & Richardson, D. C. 1995, Icarus, 116, 359
Walker, G. A. H., et al. 2003b, PASP, 115, 1023
Weber, E., & Davis, L. 1967, ApJ, 148, 217
Witte, M. G., & Savonije, G. J. 2002, A&A, 386, 222
Wolf, M., & Harmannec, P. 2004, Inf. Bull. Variable Stars, 5575, 1
Wright, A. N. 1987, J. Geophys. Res., 92, 9963
Wright, J., Marcry, G., Butler, R., & Vogt, S. 2004, ApJS, 152, 261
Yokoyama, T., & Shibata, K. 2001, ApJ, 549, 1160
Zarka, P., Treumann, R. A., Ryabov, B. P., & Ryabov, V. B. 2001, Ap&SS, 277, 293