Stars as Suns: Activity, Evolution, and Planets
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Stellar Activity Enhancement by Planets: Theory and Observations

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Abstract. Many of the newly discovered exoplanets are gas giants in close proximity to their parent stars. Therefore, they raise tides on their host stars, and (if similar to Jupiter) will likely have substantial magnetospheres which can interact with stellar magnetic field. Both tidal and magnetospheric interactions can enhance stellar activity levels. An initial search for such planet-induced activity using the Ca II IR triplet found no clear signal, but recently a more sensitive study using the Ca II H and K lines has uncovered evidence for planet-enhanced emission on HD 179949, and hints of it in other systems. The phase dependence of the enhanced emission for HD 179949 suggests a magnetospheric interaction. We discuss a simple model of this interaction, the implications of this possible detection for diagnosing exoplanetary magnetospheres, and future observations.

1. Introduction

Extra-solar planets have been identified around more than 100 solar-type stars mostly by the cyclic Doppler shift of stellar photospheric spectral lines. For recent reviews on the status of observations and the most pivotal findings on extra-solar planets see, e.g., Marcy et al. (2003) and Fischer & Valenti (2003). A particular interesting group of planet stars are those that possess close-in giant planets with star-planet distances of $d \lesssim 0.1$ AU, also called "Hot Jupiters" or 51 Peg-type planets. These planets can be as close as 10% of the Sun-Mercury distance, i.e., only seven stellar radii above the photosphere (e.g., HD 83443b; Butler et al. 2002).

Stars with close-in giant planets are interesting for a variety of reasons, including the inherent problems of the formation of those planets (Boss 1995; Kuchner & Lecar 2002), questions of orbital stability, including resonances with other planets (Noble, Musielak, & Cuntz 2003; Novak, Lai, & Lin 2003), metallicity distribution (Santos et al. 2003), and the possibility of stellar activity enhancements by those planets. The latter is the focus of this review.

All close-in extrasolar giant planets (CEGPs) are known to orbit solar-type stars. Since those stars also have chromospheres, transition regions, and coronae, and since those layers are most tenuous and closest to the giant planets, they are expected to be most affected by either type of interaction. Observationally, it is well-known that stellar chromospheric and coronal activity can strongly increase when two (or more) stars interact with each other. But aside from the obvious case of rotational synchronization (where tidally-driven rapid rotation leads to enhanced dynamo activity), there are other effects as well — enhanced activity even without synchronization and at specific rotational phases (see e.g., Schrijver & Zwaan 1991; Holzwarth & Schüssler 2003). The RS CVn systems are also well-known for their spectacular flare activity (e.g., White et al. 1990; Fox et al. 1994), which may even occur *between* the two stars (e.g., Graffagnino, Wonnacott, & Schaeidt 1995). Non-flare activity between the stars is also present (e.g., Siarkowski 1996).

By analogy, effects of *tidal interaction* and *magnetic interaction* are also expected to occur in stars with CEGPs, whether or not they are rotationally synchronized, largely dependent on the distance of the planets to their host stars. Rotational synchronization occurs only if the synchronization time-scale $t_{\rm syn}$ is smaller than the stellar age $t_{\rm \ ge}$; tidal forces are present throughout. Both processes are expected to significantly increase chromospheric, transition region and coronal activity, although detailed model calculations are not yet available. For example, "superflare" activity has been identified on 9 single dwarfs (Schaefer, King, & Deliyannis 2000), which according to the authors may be caused by the interaction between magnetic fields of these stars with nearby (as yet undetected) EGPs (Rubenstein & Schaefer 2000).

2. Initial Theoretical Efforts

Possible interactions between stars and planets can be broadly divided into gravitational (tidal) and magnetic catagories. A discussion of those effects has been given by Cuntz et al. (2000; hereafter CSM); we summarize this below. Tidal interactions arise from the gravitational acceleration caused by the CEGP and vary in strength and direction over the host star's surface. Tidal interaction will affect both the motions in the stellar convective zone and the flow field in the outer atmospheric layers. If the orbital and rotational periods are not equal (i.e., $P_{\rm orb} \neq P_{\rm rot}$), the resulting stellar tidal bulges should rise and subside fairly quickly due to the rapid response time of the low density gas to any changes in the tidal forces.

Turbulent (v_t) and flow (v_f) velocities will be enhanced in the lower density tidal bulges. Since the generation of acoustic and magnetic wave energy depends on v_t^8 (e.g., Musielak et al. 1994) and v_t^6 (e.g., Musielak, Rosner, & Ulmschneider 1989; Ulmschneider & Musielak 1998), respectively, even small increases in the local v_t by CEGPs will result in significantly higher production of nonradiative energy, leading to enhanced heating and activity. Tidal interaction will also amplify existing velocity patterns and waves in the outer atmosphere. Amplified shocks (both acoustic and magnetic) will directly increase the energy dissipation in these layers, which will also increase non-radiative emission. A further possible tidal effect arises if the increased turbulence produces a locally enhanced subsurface α-effect due to increased helicity (e.g., Dikpati & Charbonneau 1999), which should also result in additional magnetic field generation and heating.

In the absence of detailed calculations of acoustic energy generation resulting from star-planet tidal interaction, CSM estimated the relative strength of those effects by evaluating the gravitational perturbation by the planet $\Delta g_*/g_*$ as well as the height of the tidal bulge $h_{\rm tide}$ relative to the stellar photospheric pressure scale height H_p. The height of the tidal bulge is given by

$$h_{\rm tide} \propto (\Delta g_*/g_*)R_* \propto (M_{\rm P}/M_*)R_*^4 d^{-3} \quad , \tag{1}$$

where $M_{\rm P}$ is the planet mass, M_* and R_* are the stellar mass and radius, and d the star-planet distance. Clearly, $\Delta g_*/g_*$ and $h_{\rm tide}$ strongly decrease with increasing distance between the star and planet.

The second star–planet interaction is magnetic, i.e. between stellar magnetic fields and the CEGP. By analogy with Jupiter, one might generally expect large, active magnetospheres around CEGPs. Interaction with the stellar magnetic field could then produce reconnection and heating. Rubenstein & Schaefer (2000) proposed that magnetospheric interaction may lead to *superflares* on solar-type stars, which would also have a large impact on the planets (e.g., intense aurorae). Their study describes stellar flares detected on nine ordinary F and G dwarfs with 10^2 – 10^7 times more energy than the largest solar flare (Schaefer et al. 2000). As none of those stars is a very rapid rotator or very young, an alternative flaring mechanism seems to be required. Rubenstein & Schaefer (2000) claimed reconnection of stellar fields with planetary magnetospheres could explain the energies, durations, and spectra of superflares, and also explain why the Sun does not have such events. Support for this concept seems a bit sketchy, though, in part because no planets around those stars have yet been found. CSM estimated the release of energy due to magnetic interaction relative to the standard case of 51 Peg. They found that to zeroth order, the released energy flux is given as

$$F_{\rm int} \propto B_*^{4/3}(B_{\rm P}/B_*)^{1/3} v_{\rm rel} d^{-2} \quad , \tag{2}$$

where B_* and $B_{\rm P}$ are the stellar and planetary magnetic fields, and $v_{\rm rel}$ is the relative velocity between them. The d^{-2} dependence arises because of the radial dependence of B_* in the "Parker spiral" of the stellar field in the star's wind (e.g., Schatten et al. 1969). Also note that Eqs. (1) and (2) need to be modified if R_* is not negligible compared to d.

In summary, CSM found that tidal and magnetic interaction should exist for all close-in giant planets. Tidal and magnetic interactions were found to differ concerning the number of maxima of the expected activity enhancement (i.e., two versus one) and distance dependence of the strength of the interaction (i.e., d^{-3} versus d^{-2}).

3. Previous Observational Results

Three different attempts have been made to identify planet-induced chromospheric or coronal emission from CEGPs, which includes efforts by Bastian et al. (2000), Saar & Cuntz (2001) and Shkolnik et al. (2001, 2003). Bastian et al. used the VLA to search for cyclotron maser emission at the planet itself at decimeter and 74, 333, and/or 1465 MHz frequencies. Their search considered four systems with the planet (or brown dwarf) closer than $d \lesssim 0.1$ AU, which are: 51 Peg, υ And, HD 98230, and ρ^1 Cnc. No detections were made, however. The authors list various possible reasons, either physical or instrumental in nature, for this finding, including (1) mismatches of the observed frequencies to the sources, (2) insensitivity of the observations (e.g., a too low $B_{\rm P}$; Jupiter would have been undetected at stellar distances), (3) lack of keV electrons from the sources, and (4) misses of the flaring events because of bad timing or mismatches to the direction of emission.

The fact that planet-induced radio emission should nevertheless exist was pointed out by Zarka et al. (2001), who evaluated the generation of planetary radio emission using formalisms originally developed for solar system conditions. By estimating magnetospheric planetary radii and height-dependent kinetic and magnetic pressures of solar-type stellar winds, they concluded that Jupiter-type planets as close as 0.047 AU to their host stars should release radio power 10^4 times higher than found at Jupiter's orbit. Consequently, auroral radio emission from magnetized hot Jupiters should be detectable above galactic background fluctuations with the largest available telescopes up to a distance of 15-20 pc.

Saar & Cuntz (2001) followed up their theoretical musings (CSM) with a study of variations in the Ca II IR triplet, as observed in the Lick planet search database (resolution $\sim$ 50,000; typical continuum S/N $\sim$ 100). The target list included seven planet stars, including four stars (τ Boo, 51 Peg, υ And, and ρ^1 Cnc) with giant planets as close as $d < 0.1$ AU. Saar & Cuntz searched for periodicities at both $P_{\rm orb}$and $P_{\rm orb}/2$, as well as statistical enhancements in flux at phases centered at the sub-planet point (due to a possibly sporadic, flare-like magnetic interaction with $P = P_{\rm orb}$) in some stars with CEGPs. No identifications were made, however. This result came as no surprise considering the poor temporal spacing of the data, which are completely unrelated to any planet research after all. Nevertheless, the Saar & Cuntz were able to deduce upper limits for potential planet-induced chromospheric enhancements, which if existent would be consistent with the data. For the phase-dependent activity enhancements, the results for the IR analogue of the $S_{\rm HK}$ Mount Wilson index are 3.1% (τ Boo), 4.1% (51 Peg), 6.4% (υ And), and 9.5% (ρ^1 Cnc) (2σ limits).

4. Ca II Observations by Shkolnik et al.

More recently, Shkolnik et al. (2003) reinvestigated planet-induced activity using high resolution ($\sim 10^5$) optical spectra. They focused on observations of Ca II HK (somewhat more sensitive than the Ca II IR triplet to chromospheric variations), obtaining very high S/N data ($\sim$ 500 in the continuum and $\sim$ 150 in the core). Multiple spectra of four CEGP stars were obtained, together with two comparison stars (the Sun and τ Ceti, an inactive G8 dwarf). They characterize

HK emission variations in the form of a mean absolute deviation (MAD): if F_i are the individual HK spectra, MAD $= \langle |(F_i - \langle F_i \rangle)_{S21}| \rangle$, where $S21$ indicates a boxcar smooth over 21 pixels (Fig. 1). All stars showed a non-zero MAD spectrum in the H and K cores (Fig. 2), except τ Ceti (as expected, since it is a "flat activity" star; e.g., Baliunas et al. 1995), although in 51 Peg the enhancement was quite weak.

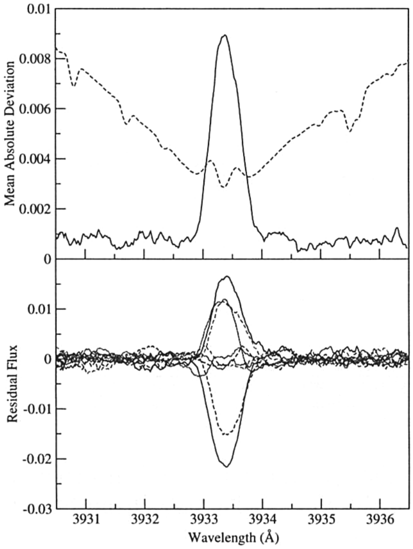

Figure 1. Top: Mean absolute deviation as a fraction of the normalized intensity (=MAD; solid) of variations in the Ca II K line core (dashed, on a different vertical scale). Bottom: Smoothed residuals from the mean K line core at different orbital phases used to construct the MAD profile above (from Shkolnik et al. 2003).

These MAD spectra include variations of all kinds, both due to intrinsic stellar activity and (potentially) due to a CEGP. Qualitatively, the MAD amplitudes increased with increasing mean Ca II HK emission, but this is not inconsistent with the variations being due to stellar activity changes (e.g., $\sigma_{\rm HK} \propto R'_{\rm HK}$; Radick et al. 1998). To test for possible planet-induced activity, Shkolnik et al. explored the phase dependence of the variations. One star showed a clear periodicity in its variations, with $P \approx P_{\rm orb}$: HD 179949 (Fig. 3). Unfortunately, since $P_{\rm orb}$ (=3.092 d) is almost exactly 3 d, phase coverage over a single observing run is rather poor. Repeat observations separated by about one year show very consistent results, however. The emission excess is centered at a phase shift of $\Delta\phi \approx 0.17$ *ahead* of the sub-planet point on the star. A simple geometric model with optically thick emission and no limb darkening/brightening fits the data reasonably well (Fig. 3); the best fits have a low latitude emission enhancement ($\theta \approx 30°$) on a high-inclination star ($i \approx 85°$). The implied peak flux enhancement is $\approx$ 5%, the integrated enhancement $\approx$3.5%. Clearly more

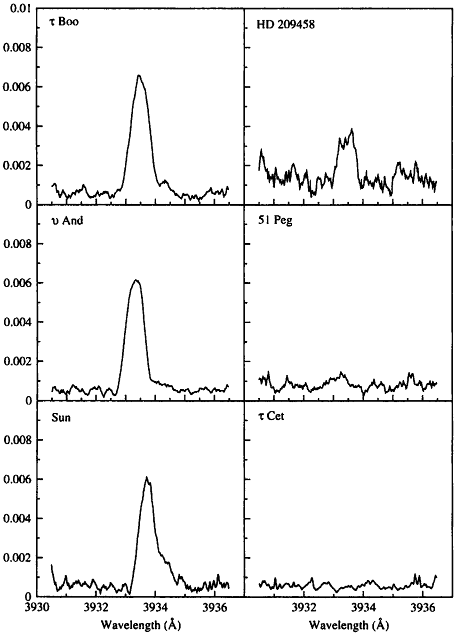

Figure 2. MAD profiles (K line core) for four other stars with CEGPs plus two comparisons, the Sun and τ Cet (from Shkolnik et al. 2003).

data with better phase coverage are needed to confirm these tentative results (further observations are scheduled for fall 2003). The data in hand, however, support a long-lived emission enhancement ($\gtrsim$ 1 year) synchronous with the planet's orbital period.

Still, one could argue that the observed enhancement was due to the chance positioning of an active longitude on the star. Active longitudes are known on the Sun (Berdyugina & Usoskin 2003) and other stars (Jetsu 1996), and can exist for years. It is more difficult to explain, however, that the *level* of enhanced activity is also effectively unchanged. Repeat observations at several phases ($\phi \approx 0.65, 0.95$; see Fig. 3) show on time scales on the order of one year that the enhancements are very similar. Active longitudes on stars are rarely of equal "intensity" for long durations.

Perhaps the strongest piece of evidence that the activity enhancement is planet-induced would be if $P_{\rm rot} \neq P_{\rm orb}$, as it would be very hard to explain emission on the star that essentially "followed" the CEGP without a planet-related cause. Unfortunately, HD 179949 does not have a measured $P_{\rm rot}$. A number of arguments can be made, though, in support for $P_{\rm rot} \neq P_{\rm orb}$, in particular, for $P_{\rm rot} \sim 9$ days. First, the strength of the Ca II HK emission can be used to estimate a $P_{\rm rot}$ based on the $R'_{\rm HK}$ – Rossby number relation of Noyes et al. (1984). Tinney et al. (2001) find log $R'_{\rm HK}$ = -4.72; using their adopted $B-V$ and the Noyes et al. relation, we find $P_{\rm rot} \approx 8.7$ days. Using the mean Mount

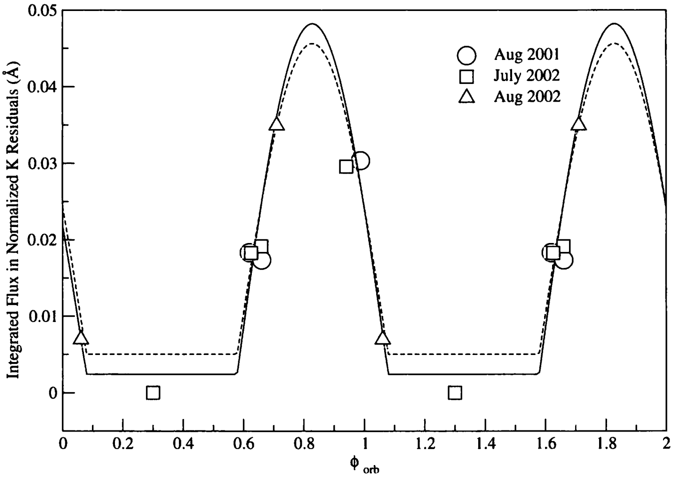

Figure 3. Integrated flux in the K line residuals plus an offset setting the minimum flux =0; errors are equal to the symbol size. Best fit "bright spot" models for latitude $\theta = 30°$ and $i = 87°$ (solid) or $i = 83°$ (dashed) are shown (from Shkolnik et al. 2003). Repeat observations show excellent agreement, and there is a clear phase offset.

Wilson index $\langle S \rangle = 0.210$ from Rutten (1987), we find $P_{\rm rot} \approx 5.6$ days with $B - V = 0.503$ (SIMBAD value) or 8.1 days with $B - V = 0.54$ (Rutten 1987). With $v \sin i = 6.3$ km s^{-1} (Tinney et al. 2001) and $R/R_\odot \approx 1.2$ (Gray 1992), we estimate $P_{\rm rot}/\sin i = 2\pi R/(v \sin i) \approx 9.7$ days, or $P_{\rm rot} = 7.6$ d for an average $\langle \sin i \rangle = \pi/4$. The models of the emission (see above), however, suggest $\sin i \sim 1$. Finally, using the tidal synchronization theory of Zahn (1977), which seems to better fit the observations of $P_{\rm rot}$ and $P_{\rm orb}$ in CEGP systems (e.g., Drake et al. 1998), we find $t_{\rm syn} \sim 70$ Gyr for HD 179949, and therefore $P_{\rm rot} = P_{\rm orb}$ is unlikely. Thus, evidence points to 6 d $\lesssim P_{\rm rot} \lesssim 10$ d, and therefore $P_{\rm rot} \neq P_{\rm orb}$.

5. Theoretical Implications and Future Modeling

If the observations of Shkolnik et al. (2003) are confirmed by further data, there are several major implications:

(a) An interaction periodicity $P = P_{\rm orb}$ (and not $P_{\rm orb}/2$) implies a magnetic, rather than a tidal interaction. Lack of a clear enhancement at $\phi \approx 0.5$ at the given noise level suggests tidal effect for this system must be $\gtrsim 5$ times weaker than the magnetic effect in HK emission. *This result may indicate the first detection of an CEGP magnetosphere.* On the other hand (in a scenario not studied by CSM), the planet may be non-magnetic, and act as a passive unipolar inductor (like Io around Jupiter; e.g., Zarka et al. 2001). The CEGPs are in most cases likely *rotationally* locked to the stellar $P_{\rm rot}$ even if $P_{\rm orb} \neq P_{\rm rot}$.

Hence, $P_{\rm rot}$(CEGP) > $P_{\rm rot}$(Jupiter), and their dynamos are consequently less effective, making $B_{\rm P} \sim 0$ plausible. See, however, (b) and (c) below.

(b) Optically thick emission suggests a source near the stellar surface (high density) rather than far off the surface (e.g., at the planet or between the star and planet, both in much lower density environments). Since interaction is likely magnetic (see above), chromospheric evaporation (or some other form of heating) at the base of stellar flux tubes might be a possible origin. This argues against a unipolar inductor model, where emission near the CEGP is predicted (Zarka et al. 2001).

(c) A *positive* emission phase shift $\Delta\phi$ also is hard to explain in the unipolar induction model, since emission in the vicinity of the planet would yield $\Delta\phi \approx 0$. One possible scenario for a positive $\Delta\phi$ would be that the magnetic field of the planet moving at a significant relative velocity through the star's magnetic field (see Table 1) interacts with the stellar field, which is swept back in a so-called "Parker spiral" due to freezing into the stellar wind. High energy particles from the interaction/reconnection region (likely near the planet) then travel forward along the spiral and impact the upper stellar atmosphere, generating the observed emission. Viability of this idea depends on whether the star's "Parker spiral" is actually extant at $d \sim 0.05$ AU. This in turn depends on properties of the stellar magnetic field and wind.

5.1. Why HD 179949? Some Tweaks to the Theory

If planet-induced activity has indeed been detected on HD 179949, why was it first detected there? What is special about HD 179949? To explore this a little, we compare the enhancement seen in HD 179949 and the upper limits seen in the CEGP stars in Shkolnik et al. (2003) with some simple magnetic interaction theories. We also show the results for tidal interaction (CSM) for comparison.

CSM developed their magnetic interaction theory using the empirical stellar wind relations of Wood & Linsky (1998). This law (wind pressure $P_{\rm W} \propto F_{\rm X}^{-0.5}$) has since been significantly modified to $P_{\rm W} \propto F_{\rm X}^{1.15}$ (Wood et al. 2002). In view of the somewhat fluid situation involving the dependence of $P_{\rm W}$, we have developed a modified theory less dependent on the precise relationship.

The most likely magnetic interaction involves reconnection between stellar and planetary magnetic fields. In this case, following the flare theory of Parker (1988), the strength of magnetic interaction $F_{\rm mag}$ proportional to

$$F_{\rm mag} \sim B_{\rm P}(r_{\rm int}) B_*(r_{\rm int}) v_{\rm rel}(r_{\rm int}) \quad , \tag{3}$$

where $r_{\rm int}$ is the radius at which the interaction takes place. If the magnetospheres of the planets are relatively weak because planetary rotation is slowed by tidal synchronization (see above), we can take $r_{\rm int} \approx d$. We also have $v_{\rm rel} = [(2\pi d/P_{\rm orb} - 2\pi d/P_{\rm rot})^2 + (v_{\rm mac} d/R_*)^2/2]^{0.5}$, where $v_{\rm mac}$ is the stellar macroturbulent velocity and R_* is the stellar radius, and $B_{\rm P}(r_{\rm int}) = B_{\rm P}$. Finally, we may write $B_*(r_{\rm int}) = B_*(R_*)(R_*/R_{\rm ss})^3(R_{\rm ss}/d)^2$ (if $d > R_{\rm ss}$), or $B_*(r_{\rm int}) = B_*(R_*)(R_*/d)^3$ (if $d \leq R_{\rm ss}$), where $R_{\rm ss}$ is the "source surface" radius beyond which the overall stellar dipole transitions into the radial "Parker spiral" (e.g., Zhao & Hoeksema 1995). Using relations from Schrijver et al. (2003), we find $R_{\rm ss} = 2.5 R_\odot (v_A(*)/v_A(\odot))^{-0.5} (B_*/B_\odot)^{0.88}$, where v_A is the Alfvén velocity of the stellar wind.

We compare this $F_{\mathrm{m\ g}}$ with that predicted by the unipolar inductor model of Zarka et al. (2001). In their model, $B_{\mathrm{P}} \sim 0$ and the interaction is mediated by the stellar wind. They find

$$F_{\mathrm{uni}} \sim 2/(1+M_A^{-2})^{0.5} B_*^2(d) R_{\mathrm{P}}^2 v_{\mathrm{flow}} \quad , \tag{4}$$

where $v_{\mathrm{flow}} \approx [v_W^2 + v_{\mathrm{rel}}^2]^{0.5}$ is the net flow velocity of the wind impinging on the planet (v_W is the wind velocity), and M_A is the Alfvénic Mach number of the flow at the planet (i.e., $M_A = v_{\mathrm{flow}}/v_A$) Following Wood et al. (2002), we take $v_W = v_W(\odot) = v_\infty(\odot) \sim 400$ km s^{-1}, and we further assume $v_W \sim v_A$ (Schrijver et al. 2003). For simplicity, we use the empirical relation $F_{\mathrm{X}} = B_*(R_*)^{0.9}$ (Saar 1996, 2001), and thus $B_*(R_*) \propto F_{\mathrm{X}}^{1.1}$.

Table 1 compares the expected $F_{\mathrm{m\ g}}/B_{\mathrm{P}}$, F_{uni}, and h_{tide}/H_p (a proxy for the tidal interaction) with the integrated flux of the enhancement (E_{HK}) seen in HD 179949, and the integrated (maximum-minimum) flux for the other Shkolnik et al. (2003) targets (which gives an approximate upper limit on the possible planet-star interaction). All model values are normalized to the observed E_{HK} value for HD 179949. Parameter values not otherwise given above or in Table 1 are taken from CSM; for HD 179949 we use $P_{\mathrm{rot}} \approx 9$ d, $M_*/M_\odot = 1.24$, $v_{\mathrm{m\ c}} = 4.2$ km s^{-1} (Saar & Osten 1997), $T_{\mathrm{eff}} = 6050$ K, and $F_{\mathrm{X}} = 5 \times 10^5$ ergs cm^{-2} s^{-1} (Hünsch et al. 1999). We adopt $\langle L_{\mathrm{X}}(\odot)\rangle \approx 4.3 \times 10^{27}$ ergs s^{-1} (from Judge et al. 2003), and hence $\langle F_{\mathrm{X}}(\odot)\rangle \approx 7 \times 10^4$ ergs cm^{-2} s^{-1}. We assume $R_{\mathrm{P}} \approx$ constant.

Table 1. Planet Properties and Star-Planet Interactions

star	d [AU]	P_{orb} [d]	$M_{\mathrm{P}} \sin i$ [M_{Jupiter}]	$\sin i$	h_{tide}/H_p [*]	F_{uni} [*]	$F_{\mathrm{mag}}/B_{\mathrm{P}}$ [*]	E_{HK} [%]
HD 179949	0.045	3.092	0.93	0.94	3.5	3.5	3.5	3.51
HD 209458	0.045	3.525	0.63	0.97	1.9	0.9	1.1	<0.65
τ Boo	0.046	3.313	3.66	0.67	31.7	5.3	1.4	<1.64
51 Peg	0.05	4.229	0.44	0.90	1.2	0.6	0.7	<0.2
υ And	0.059	4.617	0.69	0.80	2.2	1.7	1.9	<1.46

[*] : normalized to the observed E_{HK} value for HD 179949

Clearly, the tidal and unipolar inductor models overestimate the strength of the interaction for the case of τ Boo. Only the magnetic interaction model predicts the interaction for HD 179949 will be the strongest (assuming $B_{\mathrm{P}} \approx$ constant for these CEGPs). This, combined with the prediction of a single emission peak per P_{orb}, and a positive $\Delta\phi$, lead us to claim the magnetic interaction ($B_{\mathrm{P}} \neq 0$) model is the one currently most favored by the observations.

6. Conclusions and Future Work

We discussed whether close-in giant planets ("Hot Jupiters") are able to increase chromospheric and coronal emission of ordinary solar-type stars. The current status of observational and theoretical research can be summarized as follows:

1. The potential interactions between stars and CEGPs include both tidal and magnetic interactions. These will be largest at the smallest separations,

d. Tidal and magnetic interactions differ with respect to the number of expected activity maxima (i.e., two versus one) and radial dependence of the strength of the interaction (i.e., d^{-3} versus d^{-2} beyond a certain radius). The magnetic interaction may manifest itself in flare-like events, while tidal interactions will likely yield more steady heating.

2. Tentative observational support for planet-induced enhancements of stellar activity has been found by Shkolnik et al. (2001, 2003). They found modulations in the Ca II HK flux of $\sim 5\%$, phased with the planet's orbital period $P_{\rm orb}$. All evidence suggests that $P_{\rm orb} \neq P_{\rm rot}$, thus clearly identifying the enhancement as generated by the planet. There appears to be is a small phase shift of the enhancement relative to the sub-planet point on the star.

3. These preliminary results by Shkolnik et al. (2001, 2003) suggest that the star-planet interactions, if confirmed, are magnetic (rather than tidal) in nature, and further, that the planetary magnetic field is non-zero. *If confirmed, this would indicate the existence of exosolar planetary magnetospheres and dynamo activity for the first time.*

Further observations (and better phase coverage) are needed to confirm and extend these results. UV and X-ray data would be extremely helpful to substantiate and quantify planet-induced activity since the anticipated effects (flare heating) should be easier to detect in those regimes. We are pursuing observations at these wavelengths to compliment the ground-based data.

The model is rudimentary and needs further development. It does not, for example, consider "pile-up" of B_* field lines as the planet plows through the stellar "Parker spiral". This would effectively increase the B_* available for the interaction. Also, $F_{\rm X}$(HD 179949) $\approx 7F_{\rm X}(\odot)$, and $R_{\rm ss} \approx 17R_\odot$ (if $v_A = v_A(\odot)$!), while $d \approx 10R_\odot$. Thus, $R_{\rm ss} > d$, which suggests there is no significant "Parker spiral" yet at the distance of HD 179949's CEGP, and rules out a large $\Delta\phi$. The observed $\Delta\phi$, while not large, is apparently non-zero. Given the many approximations, it is unclear whether this discrepancy is significant.

Clearly, more work is needed to understand these intriguing observations. If the observations are confirmed and our simple model is correct, at least in an approximate sense, this kind of study offers a unique opportunity to explore both CEGP magnetic field strengths (by modeling the enhancement amplitude $E_{\rm HK}$) and the close-in wind zone of late-type stars (by modeling $\Delta\phi$).

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