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ON STELLAR ACTIVITY ENHANCEMENT DUE TO INTERACTIONS WITH EXTRASOLAR GIANT PLANETS

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ABSTRACT

We present a first attempt to identify and quantify possible interactions between recently discovered extrasolar giant planets (and brown dwarfs) and their host stars, resulting in activity enhancement in the stellar outer atmospheres. Many extrasolar planets have masses comparable to or larger than Jupiter and are within a distance of 0.5 AU, suggesting the possibility of their significant influence on stellar winds, coronae, and even chromospheres. Beyond the well-known rotational synchronization, the interactions include tidal effects (in which enhanced flows and turbulence in the tidal bulge lead to increased magnetoacoustic heating and dynamo action) and direct magnetic interaction between the stellar and planetary magnetic fields. We discuss relevant parameters for selected systems and give preliminary estimates of the relative interaction strengths.

Subject headings: binaries: general — planetary systems — stars: activity — stars: chromospheres — stars: coronae — stars: late-type

1. INTRODUCTION

The existence of planets around several solar-type stars has been demonstrated by the cyclic Doppler shift of their photospheric spectral lines. Since the Doppler technique favors massive planets with small orbits, most detected extrasolar planets are giant (Jupiter-like) planets (or brown dwarfs if $M > 13\ M_J$) with orbits close to their host stars (i.e., $d < 2$ AU). The discovery of the first extrasolar planetary system (υ And) has now also been reported (Butler et al. 1999; Lissauer 1999). The discovery of extrasolar giant planets (EGPs) has profound implications, including for both planet formation theories and the dynamical stability of their orbits (e.g., Marcy & Butler 1998). With the exception of the association between giant planets and enhanced metallicity (Gonzalez 1997, 1998), the astrophysical effects of close-by EGPs, including their influence on the outermost atmospheric layers of the stars, have barely been investigated. Since all solar-type stars also have chromospheres, transition regions, and coronae and since those layers are most tenuous and closest to the giant planets (or brown dwarfs), they are expected to be most affected.

Observationally, it is well known that stellar chromospheric and coronal activity can strongly increase when two (or more) stars interact with each other. A prominent example is the RS CVn binary systems, in which the observed level of the chromospheric and coronal activity can be orders of magnitude higher than in single stars with the same spectral class (e.g., Ayres & Linsky 1980). Much of this effect is caused by *rotational synchronization* in the binary system, leading to more rapid rotation and enhanced dynamo activity. There is, however, evidence for a purely tidal effect as well—enhanced activity at the subbinary point. For example, RS CVns with complete light curves in Catalano et al. (1996) show almost as many spots and plages (9) within ±45° of the subbinary point ($\phi = 0$) as on the rest of the stellar surfaces combined (10). The RS CVn systems are also well known for their spectacular flare activity (e.g., White et al. 1990), which may even occur *between* the two stars (e.g., Graffagnino, Wonnacott, & Schaeidt 1995). Nonflare activity between the stars is also present (e.g., Siarkowski 1996; Kővári et al. 2000).

By analogy, effects of *tidal interaction* and *magnetic interaction* are also expected to occur in stars with nearby EGPs, whether or not they are rotationally synchronized (see Fig. 1), largely dependent on the distance of the planets or brown dwarfs (BDs) to their host stars. Rotational synchronization occurs only if the synchronization timescale $t_{\rm syn}$ is smaller than the stellar age $t_{\rm age}$; 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, similar "superflare" activity has been recently identified on nine single dwarfs (Rubenstein & Schaefer 2000), which according to the authors may be caused by the interaction between magnetic fields of these stars with nearby (as-yet-undetected) EGPs. We explore such planet-star interactions in this Letter. In § 2, we discuss the tidal and magnetic interactions, including their dependence on the stellar and planetary parameters. Our conclusions are given § 3.

2. PLANET-STAR INTERACTIONS

2.1. *Tidal Interaction*

Tidal interaction is a direct consequence of gravitational acceleration, which is caused by nearby planets (or BDs) and varies in strength and direction over the surface of the host stars. The tidal interaction will affect both the motions in stellar convective zones and the flow fields 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 because the low-density gases respond quickly to any changes in the tidal forces. The resulting ex-

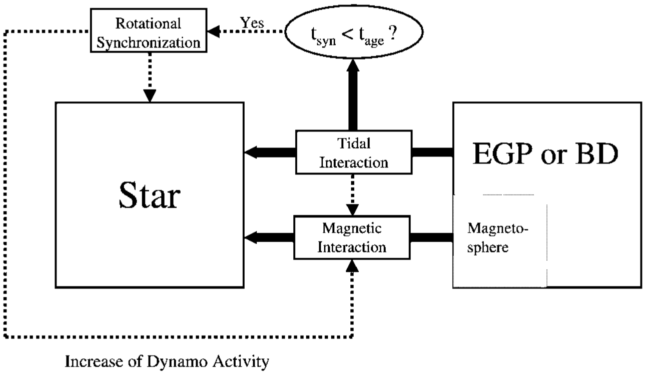

FIG. 1.—Flow diagram of interactions of an extrasolar giant planet (EGP) or brown dwarf (BD) with its host star.

pansion and contraction of the outer layers will also drive flows and waves. Turbulent and flow velocities will be enhanced in the lower density tidal bulges (and to a lesser degree also in deeper photospheric layers). Since the generation of acoustic and magnetic wave energy depends on the *eighth* (Lighthill 1952; Stein 1967; Musielak et al. 1994) and *sixth* (Musielak, Rosner, & Ulmschneider 1989; Ulmschneider & Musielak 1998) powers of the local turbulent velocity, respectively, even small increases of this velocity caused by nearby planets (or BDs) will result in significantly higher production of nonradiative energy. This will lead to enhanced heating and a higher level of stellar activity. Another effect due to tidal interaction is the amplification of velocity patterns and waves themselves, which occurs in the chromosphere, transition region, and corona rather than in the convection zone. Amplified shocks (both acoustic and magnetic) will directly increase the energy dissipation in these layers, which will also increase the UV emission. A further possible tidal effect arises if the increased turbulence produces a locally enhanced subsurface α-effect due to increased helicity (e.g., Krause & Rädler 1980; Dikpati & Charbonneau 1999). This enhanced α could then either drive a local turbulent dynamo (see Durney, de Young, & Roxburgh 1993) or be drawn down to the convective zone bottom to interact with toroidal field there and amplify an interface dynamo (e.g., Schmitt, Schüssler, & Ferriz-Mas 1996). In either case, the planet-induced α-enhancement should yield additional magnetic field generation and heating, although detailed models are still unavailable.

Although detailed calculations of nonradiative energy generation resulting from tidal interaction have not yet been performed, we can nonetheless put constraints on the tidal interaction and the generation of tidal bulges. Table 1 summarizes the parameters of the host stars, whereas Table 2 gives information on relevant quantities of tidal interaction, i.e., the gravitational perturbation by the planet (or BD) $\Delta g_*/g_*$ and the height of the tidal bulge $h_{\rm tide}$ relative to the photospheric pressure scale height H_p. We find

$$\frac{\Delta g_*}{g_*} = \frac{M_P}{M_*} \frac{2R_*^3}{(d - R_*)^3} \tag{1}$$

and

$$h_{\rm tide} = \frac{\Delta g_*}{2g_*} R_*, \tag{2}$$

where M_* is the stellar mass, R_* is the stellar radius, M_P is the planet mass, and d is the distance between the star and planet. We find that $\Delta g_*/g_*$ and $h_{\rm tide}/H_p$ strongly decrease with increasing distance d between the star and the planet (or BD), as expected.

2.2. *Magnetic Interaction*

The second main star-planet interaction is magnetic, i.e., between stellar active regions and the EGP or BD magnetosphere. By analogy with Jupiter, one might in general expect large, active magnetospheres around EGPs. It is very likely that this magnetic interaction will have the strongest effects on

TABLE 1

PARAMETERS OF PLANET HOST STARS

	SPECTRAL TYPE		$P_{\rm rot}$		M_*		R_*		$v \sin i$		K		$v_{\rm mac}$		$-\log R'_{\rm HK}$		$F_{\rm X}$	
STAR	Value	Ref.	Value (days)	Ref.	Value ($M_\odot$)	Ref.	Value ($R_\odot$)	Ref.	Value (km s^{-1})	Ref.	Value (km s^{-1})	Ref.	Value (km s^{-1})	Ref.	Value	Ref.	Value[a]	Ref.
HD 283750	K5 V	1	1.797	1	0.68	2	0.68	2	7.4	3	955[b]	...	1.8	4	4.0	5	2.9E7	6
HD 187123	G3 V	7	~23	8	~1.0	2	1.14	9	<2	7	83	7	3.2	4	4.93	7	9.0E4:[c]	...
HD 209458	G0 V	10	~17	8	~1.1	10	1.1	10	3	11	81	10	4.0	4	~4.9	11	1.3E5:[c]	...
HD 75289	G0 V	12	~17	8	1.05	12	1.31	12	4.4:	12	54	12	3.8	4	5.0	12	6.0E4:[c]	...
τ Boo	F7 V	13	3.2	13	1.36	13	1.41	13	14.9 ± 0.5	13	468	13	4.7	4	4.733	13	7.4E5	6
51 Peg	G2–3 V	13	21.9:	13	1.05	13	1.15	13	2.1 ± 0.4	13	56	13	3.1	4	5.068	13	1.1E4	14
υ And	F8 V	13	14:	13	1.31	13	1.60	13	9.0 ± 0.4	13	72	13	4.2	4	4.927	13	8.5E4	6
HD 98230	G5 V	1	3.98	1	0.98	2	0.96	2	2.8 ± 0.7	1	635[b]	...	3.8	4	4.3	15	1.1E7	6
HD 217107	G8 IV	16	~36	8	0.96	16	1.6	9	?	...	140	16	3.6	2	5.0	16	5.0E4:[c]	...
HD 130322	K0 V	12	?	...	0.79	12	0.83	9	1.9:	12	115	12	2.1	4	?	...	...	...
ρ^1 Cnc	G8 V	13	39	13	~1.0	13	0.96	13	1.7 ± 0.5	17	76	13	2.3	4	4.949	13	6.0E4:[c]	...
HD 13445	K1 V	18	~30	8	0.79	18	0.76	18	<0.7	19	379	18	1.9	4	4.74	20	1.2E5	6

NOTE.—Colons indicate highly uncertain values.

[a] In units of ergs $\rm cm^{-2}\ s^{-1}$.

[b] Estimated from $P_{\rm orb} = P_{\rm rot}$.

[c] Estimated from $R'_{\rm HK}$ (see text).

REFERENCES.—(1) Strassmeier et al. 1993; (2) Gray 1992; (3) Vogt, Soderblom, & Penrod 1983; (4) estimated using Saar & Osten 1997; (5) Bopp et al. 1983; (6) calculated from $L_{\rm X}$ (Hünsch et al. 1999) and R_*; (7) Butler et al. 1998; (8) estimated from $R'_{\rm HK}$ using Noyes et al. 1984; (9) calculated from L and $T_{\rm eff}$ in Gonzalez, Wallerstein, & Saar 1999; (10) Charbonneau et al. 2000; (11) Henry et al. 2000b; (12) Udry et al. 2000 (or calculated from data therein); (13) Henry et al. 2000a; (14) calculated from $L_{\rm X}$ (Pravdo et al. 1996) and R_*; (15) Rutten 1987; (16) Fischer et al. 1999; (17) S. H. Saar, unpublished; (18) Queloz et al. 2000 (or calculated from data therein); (19) Saar & Osten 1997; (20) Henry et al. 1996.

TABLE 2

PARAMETERS OF EXTRASOLAR PLANETS/BROWN DWARFS

Star	d[a] (AU)	$P_{\rm orb}$[b] (days)	$M_P \sin i$[b] ($M_{\rm J}$)	$\sin i$[c]	M_P ($M_{\rm J}$)	$\Delta g_*/g_*$	$h_{\rm tide}/H_p$	$F_{\rm int}$ [$F_{\rm int}$(51 Peg)]
HD 283750	0.04	1.797[d]	50	0.38	132	2.3E−4	7.0E−1	16
HD 187123	0.042	3.097	0.57	<0.8	>0.71	>4.1E−6	>1.1E−2	0.9
HD 209458	0.045	3.5247	0.63	0.97	0.63	2.3E−6	6.9E−3	1.6
HD 75289	0.046	3.51	0.42	1.0:	0.42	2.7E−6	6.5E−3	2.3
τ Boo	0.0462	3.3128[d]	3.66	0.67[e]	5.5	3.5E−5	1.0E−1	22
51 Peg	0.05	4.2293	0.44	0.90	0.49	1.5E−6	4.2E−3	1.0
υ And	0.059	4.6170	0.69	0.80	0.86	3.8E−6	9.2E−3	4.4
HD 98230	0.06	3.98[d]	37	0.23	162	1.6E−4	5.0E−1	4.6
HD 217107	0.07	7.11	1.28	0.79[f]	1.63	5.5E−6	9.8E−3	0.34
HD 130322	0.088	10.724	1.08	0.79[f]	1.38	3.2E−7	9.2E−4	…
ρ^1 Cnc	0.11	14.648	0.85	0.45[e]	1.89	2.7E−7	8.5E−4	0.08
HD 13445	0.11	15.78	3.60	<0.54	>6.6	>5.8E−7	>1.8E−3	0.08

NOTE.—Colons indicate highly uncertain values.

[a] From Perryman 1997.

[b] From the 1999 December 8 version of the online Extrasolar Planets Encyclopedia (J. Schneider).

[c] Estimated from $v \sin i$, R_*, and $P_{\rm rot}$ except HD 209458 (Charbonneau et al. 2000), 51 Peg and υ And (Gonzales 1998), and ρ^1 Cnc (Trilling & Brown 1998).

[d] Tidally synchronized.

[e] Alternative values: $\sin i \simeq 1.0$ and $M_P \simeq 0.85\ M_{\rm J}$ (ρ^1 Cnc), $\sin i \simeq 0.48$ and $M_P \simeq 7.5\ M_{\rm J}$ (τ Boo; Collier-Cameron et al. 2000); values of $\Delta g_*/g_*$, $h_{\rm tide}/H_p$, and $F_{\rm int}$ are accordingly altered.

[f] Assumed: $\sin i = \langle \sin i \rangle = \pi/4$; values of M_P, $\Delta g_*/g_*$, $h_{\rm tide}/H_p$, and $F_{\rm int}$ are thus uncertain.

the heating of the stellar corona and transition region, since these regions are closest to the region in which the star and planet fields meet and interact. The magnitude of magnetic interaction will be determined by MHD effects such as coronal reconnection (e.g., Narain & Ulmschneider 1996). Rubenstein & Schaefer (2000) propose that magnetospheric interaction may lead to *superflares* on solar-type stars, which likewise 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, King, & Deliyannis 2000). Since none of those stars is a very rapid rotator or is very young, an alternative flare-forming mechanism is required. By invoking known planetary properties and reconnection scenarios, Rubenstein & Schaefer (2000) claim to be able to explain the energies, durations, and spectra of superflares and to also explain why the Sun does not have such events.

Based on general assumptions, we can provide preliminary estimates of the magnetic interaction between extrasolar planets and stars. Obviously, without detailed knowledge of planetary magnetospheres, this cannot be done in absolute terms, but we can at least gauge the relative values of magnetic energy release $\mathcal{E}$ in various considered systems. It can be assumed that $\mathcal{E}$ should be proportional to the magnetic energy of the system given by $\mathcal{E} \propto B_* B_P$ (i.e., proportional to the magnetic energy density), with B_* and B_P being the mean magnetic field strengths averaged over the surface of the star and planet, respectively. Both values need to be scaled by the distance to the interaction point: $d_{\rm mag}$ (the magnetospheric radius) for B_P and $(d - d_{\rm mag})$ for B_*. For $d_{\rm mag}$, we find (e.g., Kivelson & Bagenal 1999)

$$d_{\rm mag} \propto R_P \left(\frac{B_P^2}{\rho_w v_w^2} \right)^{1/6} , \tag{3}$$

where ρ_w and v_w are the stellar wind density and velocity, respectively. Although our knowledge about the winds of late-type stars is limited, we can use the empirical relationship of Wood & Linsky (1998), who found that the wind pressure at the heliopause follows $p_w \propto \rho_w v_w^2 \propto F_{\rm X}^{-1/2}$ with $F_{\rm X}$ as the X-ray flux at the surface of the star. Assuming that this relationship holds generally, we find $d_{\rm mag} \propto R_P B_P^{1/3} F_{\rm X}^{1/12}$. Now, we can use the obtained magnetospheric radius to scale the energy density $\mathcal{E}$. Considering radially symmetric magnetic fields, we get

$$\mathcal{E} \propto \frac{B_* B_P}{(d - d_{\rm mag})^2 d_{\rm mag}^2} . \tag{4}$$

Note that there will be a "steady state" amount of reconnection even in the case of tidal locking. This will be caused by random motion of the stellar surface magnetic elements due to photospheric motions and subsequent field tangling, reconnection, and energy release (following Parker's 1988 flare concept). These motions will be related to the mean rms granular convective velocity at the stellar surface, observationally seen as rms macroturbulence, $v_{\rm mac}/\sqrt{2}$. However, there will be an additional effect if $P_{\rm rot} \neq P_{\rm orb}$ because of the relative velocity $v_{\rm rel}$ and shearing between field lines connecting the star and planet. We therefore introduce a combined velocity $v_c = \left(v_{\rm mac}^2/2 + v_{\rm rel}^2\right)^{1/2}$, where $v_{\rm rel} = K(R_*/d) - v_{\rm rot}$, with K the orbital velocity and $v_{\rm rot}$ the equatorial rotational velocity, $v \sin i/ \sin i$. Now we assume that magnetic interaction releases a fraction ϵ of the total available magnetic energy per unit time. Thus, to zeroth order, the energy flux due to the magnetic interaction is given as $F_{\rm int} \propto (\epsilon B_* B_P v_c)/(d^2 d_{\rm mag}^2)$ considering that we can expect $d \gg d_{\rm mag}$. Substituting for $d_{\rm mag}$ yields

$$F_{\rm int} \propto \frac{\epsilon B_* B_P^{1/3} v_c}{d^2 R_P^2 F_{\rm X}^{1/6}} . \tag{5}$$

B_* can be estimated from stellar magnetic field measurements since $B_* = f B_{\rm phot}$, where f is the surface area filling factor of magnetic regions and $B_{\rm phot}$ is the field strength in those regions. Saar (1996) finds $B_* = f B_{\rm phot} \propto P_{\rm rot}^{-1.7}$. It is more difficult, however, to estimate B_P. As an initial guess, we take $B_P = B_{\rm J} \approx$ constant, $\epsilon =$ constant, and $R_P = 1.5\ R_{\rm J}$ (viz., HD 209458; Mazeh et al. 2000) $\approx$ constant (Guillot et al. 1996). Since less than half of our stars have published X-ray measurements, we use the relation for normalized Mg II *h, k* flux $L_{\rm X}/L_{\rm bol} = F_{\rm X}/F_{\rm bol} \propto (F_{hk}/F_{\rm bol})^{2.9}$ (where $F_{\rm bol} = \sigma T_{\rm eff}^4$; Ayres et al. 1995) and assume the normalized Ca II H + K flux $R'_{\rm HK} =$

$F'_{\rm HK}/F_{\rm bol} \propto F_{hk}/F_{\rm bol}$. In the case of HD 98230, we doubled the Hünsch et al. (1999) $L_{\rm X}$ value because less than 5% of X-ray flux should arise from the inactive, unresolved G0 V companion (HD 98231). Table 1 gives estimated values of the magnetic interaction flux $F_{\rm int}$ relative to 51 Peg.

3. CONCLUSIONS

We now can compare the relative strength of planet-star interactions for selected systems. Since both tidal and magnetic interaction strongly decrease with distance d between the star and planet (see eqs. [1] and [5]), we restrict this study to systems with $d \lesssim 0.1$ AU, which results in a total of 12 systems (see Tables 1 and 2). The most effective tidal interaction is found for HD 283750, which is rotationally synchronized, i.e., $P_{\rm rot} \simeq P_{\rm orb} = 1.797$ days. The strongest magnetic interaction is found for τ Boo (also likely synchronized) because although B_* is smaller and d is larger than for HD 283750, these are compensated by larger v_c and smaller $F_{\rm X}$ values. HD 98230 is also rotationally synchronized and also has strong tidal and magnetic interactions. To clearly distinguish the planet-induced activity from synchronization effects, we need to consider the systems in which $P_{\rm orb} \neq P_{\rm rot}$. Of these (in descending order), HD 187123, HD 217107, υ And, and HD 209458 have the strongest tidal interaction and υ And, HD 75289, and HD 209458 have the strongest magnetic interaction. Our study suggests several new directions for the future research. These include (1) computing the magnetic/acoustic energy generation in stars with nearby giant planets (or BDs), (2) modeling of the height-dependent magnetic/acoustic heating and line formation, (3) studying the dynamo action under the planetary influence, and (4) searching for these effects in observational data. We are actively pursuing several of these topics.

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