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Tenth anniversary of 51 Peg-b : Status of and prospects for hot Jupiter studies
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The potential of exoplanetary radio emissions as an observation method

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Abstract. Similarly to the magnetized planets of the solar system, giant exoplanets are expected to be strong nonthermal radio emitters. This is especially true for Hot Jupiters, where the interaction of the planet with the stellar wind is believed to be much stronger than for planets at larger orbital distances. Also, radio detection would yield additional information about the emitting planet, turning the search for radio emission of extrasolar planets into a useful additional observation method. In this work, the method is explored. The key parameters for the estimation of the radio flux resulting from the stellar wind–magnetosphere interaction are reviewed and discussed. It is shown that the radio flux anticipated for certain planets is strong enough to allow ground-based detection in the near future.

1. Introduction

In the solar system, we known that all strongly magnetized planets are intense nonthermal radio emitters. At frequencies typical for planetary radio emissions, for example, the planetary radio flux of Jupiter exceeds the radio flux of the quiet sun by several orders of magnitude [Grießmeier et al., 2005a]. However, because of the large distances to other planetary systems, it would still be difficult to detect such an emitter from another planetary system. Because of their location close to the host star, Hot Jupiters are expected to be much stronger radio sources than the planets of the solar system [Zarka et al., 1997; Farrell et al., 1999; Zarka et al., 2001; Lazio et al., 2004; Farrell et al., 2004; Stevens, 2005; Grießmeier et al., 2005a; Grießmeier et al., 2005b], so that for some exoplanets radio detection seems possible, at least in principle.

Such a detection would increase our knowledge of Hot Jupiters by providing the following information:

(a) The maximum frequency of the radio emission ("cutoff frequency") contains information on the planetary magnetic field. With measurements at different frequencies, the planetary magnetic field (and thus its magnetic moment) could be estimated. (b) The radio signal should contain a periodic modulation with the period of the planetary rotation. In first order approximation, Hot Jupiters can be assumed to be tidally locked, so that the rotation period is equal to the orbital period. Thermal atmospheric tides, however, are expected to lead to a deviation from perfect tidal locking (Showman & Guillot, 2002). The influence of this effect could be estimated using the periodicity of a planetary radio signal. (c) The orbital inclination of the planet could be constrained with studies of planetary radio emission (Stevens, 2005). (d) Finally, with sensitive enough instruments, the measurement of planetary radio emissions could be used as an additional method for the detection and confirmation of new exoplanets.

This paper is organized as follows: Section 2. reviews under what circumstances an exoplanet is expected to be a strong radio emitter. In Section 3., past attempts to observe exoplanetary radio emissions are presented. In Section 4., these observational campaigns are compared to the radio flux densities and emission frequencies obtained from theoretical models, explaining why, so far, none of the observations resulted in a detection. Section 5. closes with a few concluding remarks.

2. Conditions favorable for observation

A Hot Jupiter can be expected to be a relatively strong source of non-thermal radio emissions when it fulfills the following criteria:

- Proximity to the solar system. The flux density of a radio signal emitted to space decreases quadratically with distance. For this reason, observation attempts should concentrate on nearby planets.

- Large enough mass. Due to the Earth's ionosphere, frequencies below $\sim 5 - 10$ MHz (Zarka et al., 1997) are not accessible to ground-based observations. The maximum emission frequency of a planet is determined by the cyclotron frequency close to the polar cloud top:

$$f_c^{\max} = \frac{e\mu_0\mathcal{M}}{4\pi^2 m R^3}, \tag{1}$$

where e and m are the electron's charge and mass, respectively. R is the planetary radius, and $\mathcal{M}$ is the planet's magnetic moment. Farrell et al. (1999) and Grießmeier et al. (2004) show that $\mathcal{M}$ is increasing with increasing planetary mass. For this reason, a large enough planetary mass is required for the planet to generate radio emissions with frequencies above the ionospheric cutoff.

- Proximity to the host star. Usually, the emitted radio power is assumed to be (roughly) proportional to the energy transported into the planetary magnetosphere by the stellar wind. A Hot Jupiter experiences a denser stellar wind than a planet at larger distances, so that a larger amount of energy is available for the generation of radio emissions.

- For similar reasons, planets around young star are favorable. The stellar wind velocity and density are much higher for young stars than for stars of solar age (Grießmeier et al., 2004). The higher kinetic energy flux into the planetary magnetosphere leads to a strongly increased radio emission (Grießmeier et al., 2005a).

- Stellar activity. Coronal mass ejections (CMEs) can further enhance the plasma density and velocity in the vicinity of the planet. This leads to stronger planetary radio emission for planets around star with frequent CMEs (Grießmeier et al., 2005b).

3. Observational attempts

Already before the discovery of the first extrasolar planets, different attempts were made to discover radio emissions from extrasolar planets. In recent years, when targeted radio observations became possible due to the knowledge of the position of extrasolar planets, new efforts were undertaken to search for radio emission from known extrasolar planets. So far, however, all such efforts have been unsuccessful. This includes:

- Early observations by Yantis et al. (1977), where 22 nearby stars (i.e. within 5 parsec) were observed using the Clark Lake radio telescope at a frequency of 26.3 MHz.

- The observation of 6 nearby stars (i.e. within 5 parsec) by Winglee et al. (1986) using the VLA. Frequencies of 330 MHz and 1460

MHz were used, and the typical observation time was 3.5 h. One star was additionally observed for 1 hour at 4.9 GHz.

- Observations made between 1994 and 1996 by the Ukrainian radio array UTR-2 in the decametric wavelength range (Zarka et al., 1997). 4 stars were observed for approximately 45 minutes each.
- VLA observations of 10 stars made from 1996 to 1998. The planet-hosting target stars had distances between 2.5 and 41 pc (Bastian et al., 2000). Observations were performed at 74 MHz, 333 MHz and 1465 MHz, with an observation time of $\lesssim$ 6 hours per star.
- Targeted observations of τ Bootes (1999 and 2002), using the VLA (Farrell et al., 2003). Time per measurement: $\lesssim$ 6 hours.
- The analysis of the VLA Low-frequency Sky Survey (VLSS), an ongoing effort to survey the northern sky at 74 MHz (Lazio et al., 2004). While not as sensitive as targeted observations, a much larger number of stars will be observed eventually.
- A search for decametric radio bursts using the UTR-2 radio array (Ryabov et al., 2004). From 1999 to 2002, 19 stars were observed, with an observation time of typically several hours per star. For τ Bootes, the sensitivity reached 160 mJy.
- An observation of HD 209458 using the Effelsberg 100 m radio telescope. On March 31, 2004, the system was observed for 1 hour out of transit (Guenther, private comm.).
- Observations made with the 10 m Mizusawa telescope and 11 m Tokai university telescope since 1996 (Shiratori & Kameya, 2005). 4 stars were observed at a frequency of 8.6 GHz with a sensitivity of approximately 1 Jy. More than 100 hours of observations were made per target.
- The observation of two targets with the Giant Meterwave Radiotelescope (GMRT) in India (Majid et al., 2005). The data of these observations are still under examination.

Many reasons were proposed why these searches for radio emission from Hot Jupiters have not yet proven successful (see, e.g. Bastian et al. 2000; Ryabov et al., 2004). The most fundamental problem of these observations probably is the lack of sensitivity in the appropriate frequency range. This becomes clear when the frequencies and sensitivities of the observation attempts (compiled in Table 1) are compared to the values expected for exoplanetary radio emissions. This comparison is performed in Section 4.

Table 1. *Past observational attempts*

Telescope	Frequency	Sensitivity	Reference
Clark Lake	26.3 MHz	1 Jy	Yantis et al. (1977)
VLA	330 MHz	30 mJy	Winglee et al. (1986)
	1460 MHz	0.3 mJy	
	4900 MHz	0.15 mJy	
UTR-2	7-35 MHz	2-4 Jy	Zarka et al. (1997)
VLA	74 MHz	50 mJy	Bastian et al. (2000)
	333 MHz	1-10 mJy	
	1465 MHz	0.02-0.07 mJy	
VLA	74 MHz	120 mJy	Farrell et al. (2003)
VLA	74 MHz	300 mJy	Lazio et al. (2004)
UTR-2	18-32 MHz	100-1600 mJy	Ryabov et al. (2004)
Effelsberg	4850 MHz	0.8 mJy	Guenther (private comm.)
Mizusawa	8600 MHz	1 Jy	Shiratori et al. (2005)
GMRT	153 MHz	2 mJy	Majid et al. (2005)

4. Estimated radio flux

One of the best candidates for exoplanetary radio emissions is the planet τ Bootes b. For this planet, the conditions of Section 2. are satisfied:

- With a distance of 15.6 pc, it is reasonably close to the observer.
- The planetary mass is not known precisely, but the minimum mass obtained from radial velocity measurements is 4.4 Jupiter masses. Grießmeier et al. (2005a) estimate a magnetic moment of between 0.5 and 2.7 times the magnetic moment of Jupiter.
- The planet is located at only 0.0489 AU from its host star. Thus, the planet is a “Hot Jupiter”, and experiences extreme stellar wind conditions.
- The age of the stellar system is estimated to be around 1 Gyr (Fuhrmann et al., 1998). For such a young system, the stellar wind velocity and density are much larger than for the sun.
- The CME activity of τ Bootes is presently not known. However, at the young age of the star, the CME activity of the star can be expected to be at least that of the sun.

Considering these points, the radio flux of τ Bootes b was estimated by Grießmeier et al. (2005a, 2005b). The results of the calculation are given in Table 2. The different values are: the stellar wind velocity v and density n at the planetary orbit, the total emitted radio power P_{rad}, the flux densities Φ_{AU} (normalised to 1 AU) and Φ_s (for a detector at a distance of $s = 15.6$ parsec), and the maximum emission frequency $f_c^{\max}$. The radio flux expected from τ Bootes b, together with the radio flux from Jupiter and the sensitivities reached by the different observation attempts from Table 1 are shown in Figure 1.

τ Bootes b	1.0 Gyr
v (stellar wind velocity) [km/s]	731
n (stellar wind density) [m^{-3}]	$4.0 \cdot 10^{10}$
P_{rad} (emitted radio power) [W]	$1.3 \cdot 10^{15} \ldots 3.8 \cdot 10^{15}$
Φ_{AU} (flux density at 1 AU) [Jy]	$7.4 \cdot 10^{11} \ldots 1.8 \cdot 10^{12}$
Φ_s (flux density at distance s) [Jy]	$0.071 \ldots 0.17$
$f_c^{\max}$ (maximum frequency) [MHz]	$6.7 \ldots 19$

Table 2. *Estimated quantities for the planet around τ Bootes (from Grießmeier et al., 2005a).*

Concerning the current non-detection of radio emission from τ Bootes b, we suggest that the main problem is the relatively low maximum frequency of 19 MHz of the emission as compared to the majority of measurements which took place at frequencies $f \geq 74$ MHz (see Table 1 and Figure 1). The observations of Zarka et al. (1997) and Ryabov et al. (2004) are in a more promising frequency range (between 7 and 35 MHz), but the sensitivity reached by Zarka et al. (1997) was not sufficient. The observations by Ryabov et al. (2004) barely reach the parameter range where radio emission from τ Bootes are thought possible. For this reason, future UTR-2 observations are either likely to lead to a positive detection or impose constraints on the planetary magnetic moment. The radio flux Φ_s from Table 2 can also be compared to the detection limit of the planned LOw Frequency ARray (LOFAR, described by Kassim et al. 2004). However, according to the modified instrument design plans, LOFAR will only include frequencies above 30 MHz, with a sensitivity of approximately 2 mJy (Zaroubi & Silk, 2005; `http://www.lofar.org`). For this reason, the detection of planetary radio emissions by this instrument is uncertain.

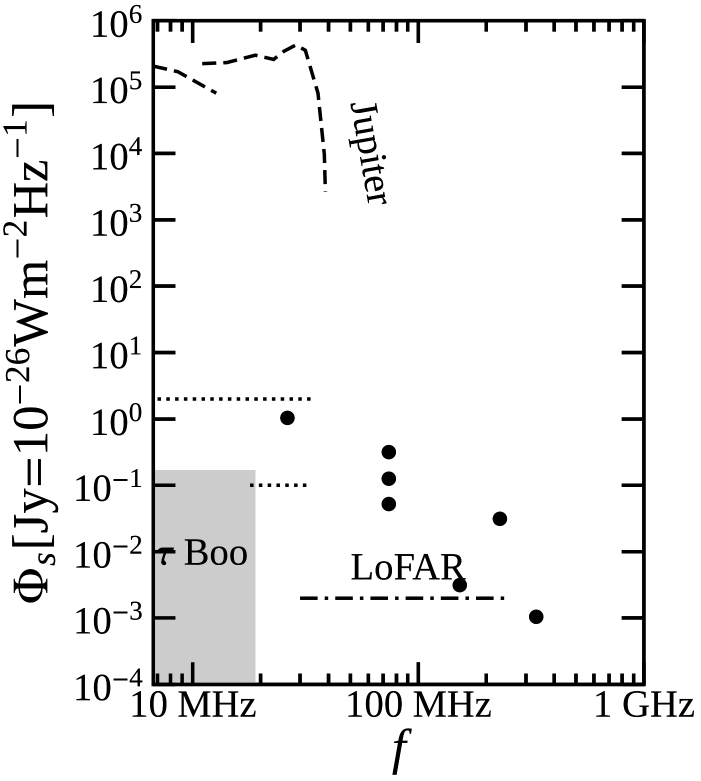

Figure 1. *Comparison of detection limits to the radio flux expected from τ Bootes b. Bullets, dotted lines: Past observational attempts. (see Table 1). Dash-dotted line: prospected detection limit of LOFAR.*

5. Conclusions

In this work, the detection of radio emissions from extrasolar planets was discussed. The radio flux expected from the τ Bootes system was compared to the sensitivity of past and future observation campaigns, showing that past observations like those of Zarka et al. (1997) and Bastian et al. (2000) were either not sensitive enough or were limited to higher frequencies. However, the anticipated radio flux can be strong enough to allow ground-based detection in the near future.

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Precise photometry of 51 Peg systems with MOST

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Abstract. Four 51 Peg systems have been monitored with the MOST (Microvariability & Oscillations of STars) photometric satellite. τ Boo, HD179949 and 51 Peg each show strong evidence of activity or brightness increases induced on the hemisphere facing their respective planets. HD209458 shows no significant variations phased to its planetary orbit but we set a 1 σ limit of 0.053 mmag to the depth of the secondary eclipse corresponding to a geometrical albedo of 0.25 which is significantly lower than for Jupiter.

1. MOST

The MOST (Microvariability & Oscillations of STars) photometric satellite, launched in 2003 June, circulates in the twilight zone in a 101.4 minute polar Sun-synchronous orbit at an altitude of 820 km (Walker et al 2003, Matthews et al 2004). It can stare for weeks at targets within an equatorial band some 54° wide. For stars brighter than V=6.5 the 15 cm telescope feeds a Fabry image onto the Science CCD through a broadband filter (350 – 700 nm). Fainter, defocussed star images are recorded in a Direct Imaging field where photometric precision is not as high.

The satellite was designed to achieve a precision of a few parts per million ($\sim \mu$mag) at frequencies > 1mHz in the Fourier domain and does not rely on comparison stars or flat-fielding for stability. Tracking jitter was dramatically reduced early in 2004 to ~1 arcsec.

Apart from a basic interest in any p-modes excited in the primaries, MOST offers a unique opportunity to detect subtle photometric variations such as those associated with stellar rotation or planetary revolution. Table 1 summarises the 51 Peg systems observed so far. Only in the case of τ Boo was there much chance of detecting the signature of rotation.

MOST suffers from parasitic light at certain orbital phases, with the amount and phase depending on stellar coordinates. In consequence, a certain amount of data is excluded in each orbit but duty cycles are always >60%.

Table 1. *51 Peg systems Observed by MOST in 2004 and 2005*

			vsin$i$	P_{rot}	P_{orb}	$M_p$sin$i$	MOST(d)	
star	V	spect	km/s	days	days	M_J	'04	'05
τ Boo	4.5	F7IV	14.8	~3.2	3.313	3.87	11	18
HD179949	6.3	F8V	6.3	<9	3.092	0.98		12[a]
HD209458	7.7	G0V	4.2	~16	3.525	0.69	14	(44)[b]
51 Peg	5.5	G2IV	2.4	~22	4.231	0.47	29	

[a] *outside CVZ*

[b] *in progress at time of meeting*

2. Light Curves and Phase Plots

2.1 HD 209458

The analysis reported here is by Jason Rowe, Jaymie Matthews, Sara Seager and Rainer Kuschnig and will appear shortly with full details of the reduction and analysis (Rowe et al. 2005). The 14 day light curve of HD209458 acquired in 2004 is shown in Fig 1 and includes 4 transits and 4 secondary eclipses. Photometry was in the Direct Imaging mode because HD209458 is too faint for Fabry imaging. The lightcurve of a control star, HD209346, of similar brightness is shown in B. Panel C shows the HD 209458 observations phased to the 3.525 d planetary revolution and heavily binned in the final panel. The dashed lines in the last two panels indicate the duration of secondary eclipse. Unfortunately, the orbital period of MOST is almost an exact harmonic (50.049) of the revolution of HD209458b so that over 2 weeks the satellite orbital period roughly synchronised with the exoplanet causing the gaps in the original data due to high parasitic light to reappear in the phased plots.

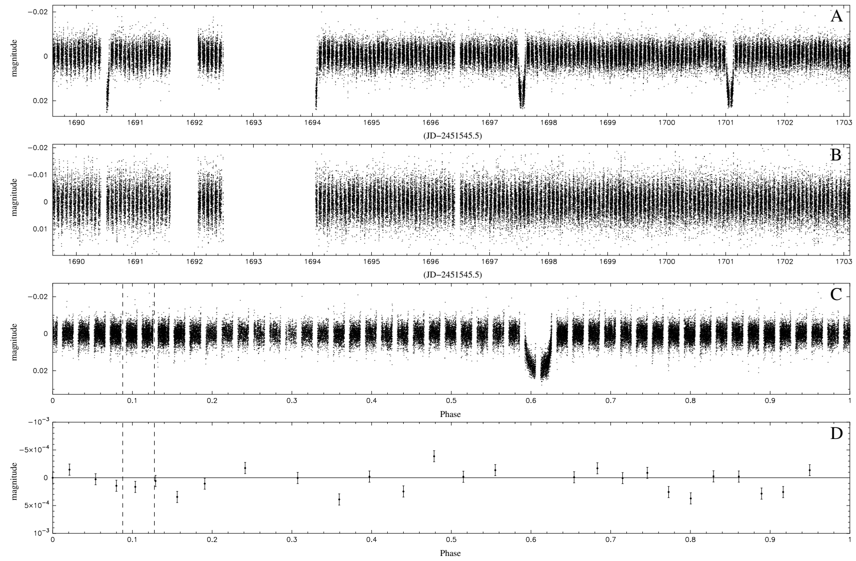

Figure 1. *A: MOST light curve for HD209458, B: HD209346, C: HD209458 data phased with planet orbital period, and D: data heavily binned and phased with the planet orbital period. The dashed lines in C and D mark the predicted duration of the secondary eclipse. Adapted from Rowe et al (2005).*

No secondary eclipse was detected to a 1σ limit of 0.053 mmag. This corresponds to an upper limit of 0.25 for the geometric albedo in the MOST bandpass implying HD209458b is only half as bright as Jupiter. The low value of the albedo is an important constraint for theoretical models of the HD209458b atmosphere, in particular, ruling out the presence of reflective clouds. The 2005 MOST campaign on HD209458 of 44 days which was underway during the conference is expected to be sensitive to an exoplanet albedo as low as 0.13 (1σ).

2.2 τ Boo, HD179949 & 51 Peg

Figures 2 and 3 display the MOST light curves and phased (0.05 phase bins) to the orbital periods of their respective planets. In the case of τ Boo the 2004 and 2005 data are shown separately in the phased plot. Error bars in Fig 3 are $\sim \pm$ 0.0004 in each case.

3. MAD Plots

A plot of the mean absolute deviation (MAD) shows up cycle to cycle variability at high contrast in phased plots where:

$$MAD = n^{-1}\Sigma|data_i - mean|$$

and n is the total number of points within a bin and varies between 900 and 5000 depending on the star. The MAD plots for all four stars (with only the 2005 data for τ Boo) are shown in Figure 4. Errors in the individual MAD values go as $MAD/n^{0.5}$ making them smaller than the points in all cases. These plots are essentially differential since the MAD DC levels are ignored.

4. Planet Induced Activity

For τ Boo, whose rotation is probably synchronised to its planet's revolution, there is an active 'spot' seen in Fig 3 near $\phi = 0.8$ ($\phi = 0$ is the sub-planetary point) which shows a clear synchronism between 2004 and 2005 meaning that it has persisted for >100 orbits. The variability of this spot also shows up in high contrast at $\phi = 0.8$ in Fig 4. It is interesting that the wide range of activity of this spot from cycle to cycle - sometimes dark, sometimes bright - mimics the cycle to cycle changes in the Ca II H & K activity reported by Shkolnik et al (2005).

From Fig 3, HD179949 reaches a maximum brightness close to $\phi = 0.75$ which agrees with the longitude of Ca II H & K enhancement seen by Shkolnik et al (2005) which has persisted for ~600 orbits. HD179949, the most active of the stars, also shows a peak activity in Fig 4 near

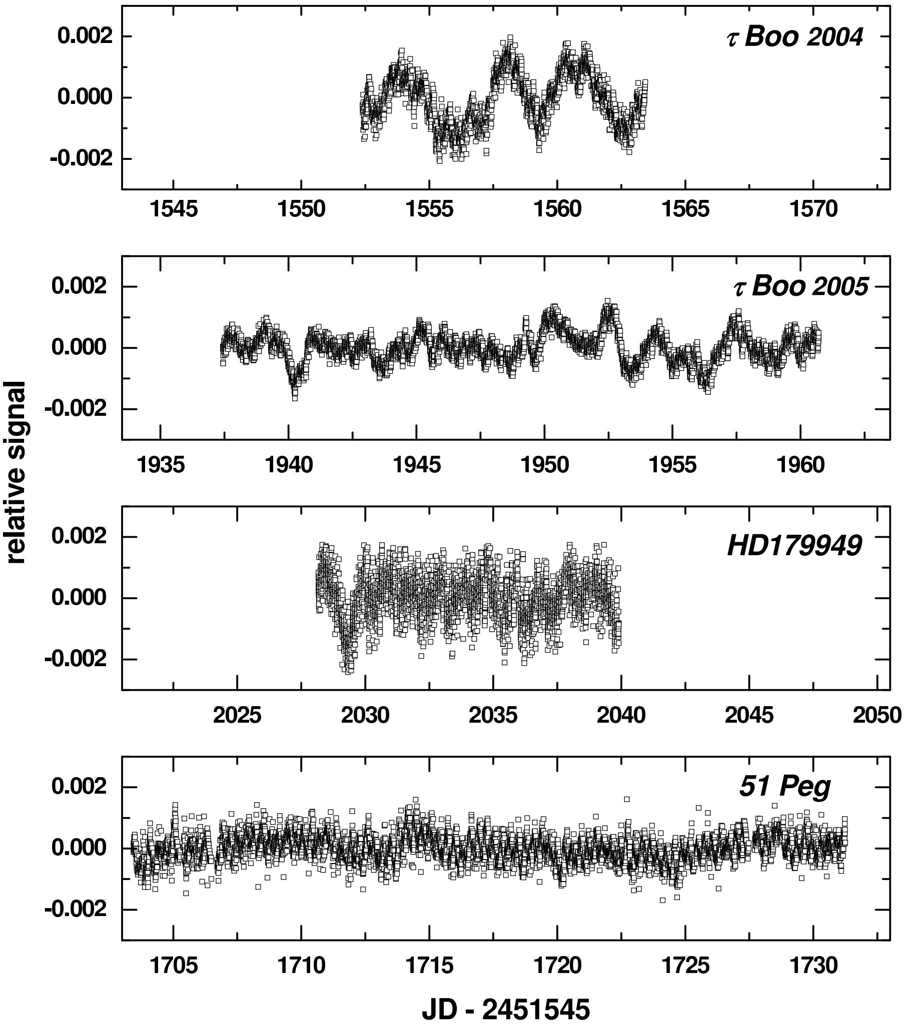

Figure 2. *The MOST light curves for τ Boo, HD179949 and 51 Peg.*

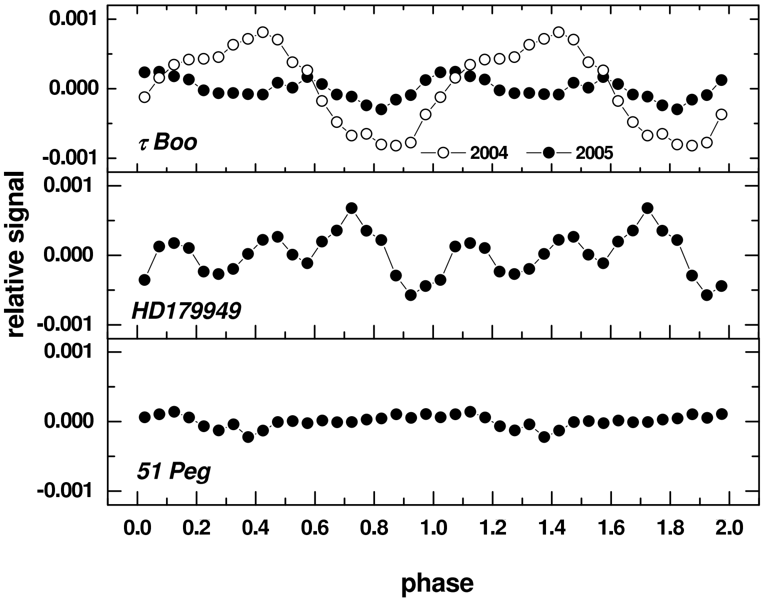

Figure 3. *The data for the three stars in Figure 2 phased to their respective planetary orbital periods.* $\phi = 0$ *corresponds to the sub-planetary point. Error bars are* $\sim \pm 0.0004$ *in each case.*

$\phi = 0.9$. 51 Peg shows a small excess of activity in Figure 4, and marginal brightening in Figure 3, near $\phi = 0.1$. For HD209458 there is no significant activity in Figure 4 - it remains to be seen what the more extensive data from the present run will show.

From these results one can say that for τ Boo, HD179949 and 51 Peg, the greatest cycle to cycle activity is on the hemisphere exposed to the planet. Although the data strings are too short to detect any stellar rotational signature for HD179949 and 51 Peg, it is clear that their active regions track their respective planets and not their rotation.

We plan to continue monitoring 51 Peg systems.

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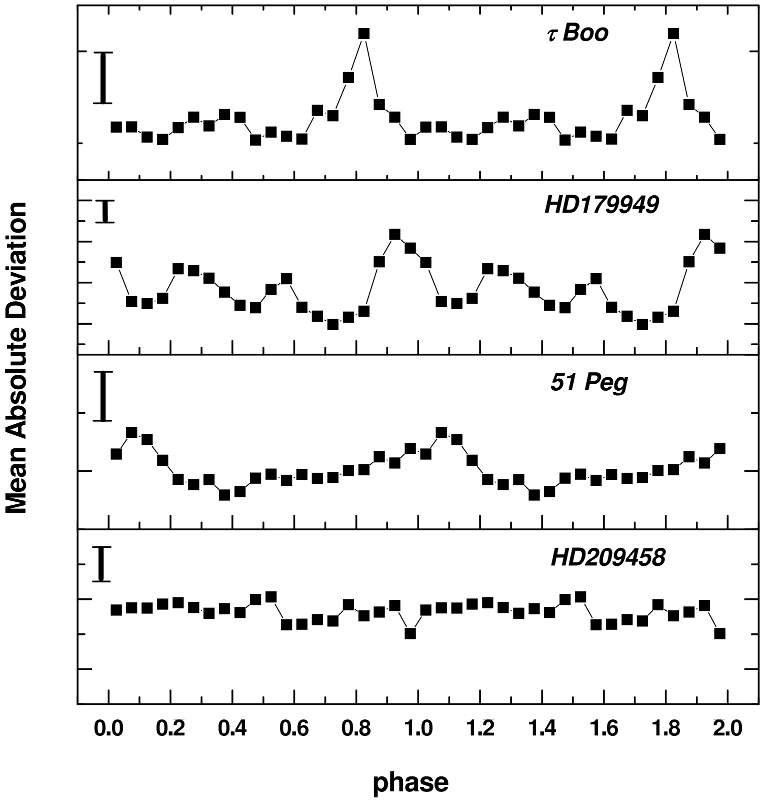

Figure 4. *The mean absolute deviation (see text) of the data for all four stars phased to their respective planetary orbital periods. The bar in each plot corresponds to* 2×10^{-4}. *Error bars are smaller than the points in all cases.*

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Magnetic communication scenarii for close-in extrasolar planets

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Abstract. Close-in extrasolar planetary systems are often considered to be scaled up versions of Jupiter and its satellite, Io, which exhibit a strong electromagnetic interaction. Still, this scenario lacks detailed modeling to show its feasibility. We try to fill this gap by studying the magnetic interaction of close-in extrasolar planes and their stars on the basis of realistic stellar wind models and numerical simulations in the frame of resistive magneto-hydrodynamics. We find that a current system between the planet and its star may be established. Contrary to Io and Jupiter it seems to be unlikely that the flux tubes connecting the planet and the star are the source region for radio emissions due to a cyclotron maser instability. Therefore, we suggest that the energy contained in the current system may be dissipated in the chromosphere of the star. This is indicated by observations of an enhanced chromospheric activity on HD 179949.

1. Introduction

A striking feature of the observed extrasolar planetary systems is the close vicinity of many planets to their central stars. This fact is expected to have a large influence on the interaction between star and planet or stellar wind and planet. Up to now, many interaction scenarios have been proposed. The most prominent among them are radio emissions due to a stellar wind-planetary magnetosphere interaction as is e.g. discussed by Farrell et al. (1999), Zarka et al. (2001), Griessmeier et al. (2005) and Stevens (2005). The radio emissions are expected to be strong and distinguishable from a stellar signal, so that they would complement today's observational methods. As a different interaction scenario, Cuntz et al. (2000) predict a magnetic activity enhancement on the star due to the existence of a close-in extrasolar planet with a strong magnetic field. This is expected to result in heating processes. In this context Shkolnik et al. (2003) interpret their observations of an enhanced chromospheric emission on HD 179949.

The different scenarios have in common that they lack a detailed and realistic model of the plasma environments of the planets. This was first presented by Preusse et al. (2005). In the context of the strong magnetic interaction of Jupiter and his satellite, Io, we now use these results to study the applicability of this scenario to close-in extrasolar planets. In this paper, we show that an Io-Jupiter like current system linking close-in extrasolar planets and their stars can be established. We perform this on the basis of realistic stellar wind models, which are described in Section 2. Here, we also pin-point the idea leading to our study. We then describe the Io-Jupiter scenario and its consequences for our model in Section 3 and conclude in Section 4.

2. The stellar wind model

The magnetic interactions of close-in extrasolar planets and their stars strongly depend on the local state of the plasma environment of the planets, i.e the stellar wind. As we are interested in an interaction involving the magnetic fields of the stellar wind, we use the stellar wind model of Weber & Davis (1967) as described in Preusse et al. (2005). This model uses a single-fluid description of the plasma in a magnetohydrodynamic approach where in particular the rotation of the star is taken into account.

For our stellar wind model we need the stellar parameters radius, mass, particle flux, magnetic field and (isothermal) temperature at the base of the corona, located at one stellar radius here. Due to the stellar rotation, the stellar wind velocity and the magnetic field have radial and azimuthal components depending only on the distance from the star. The expanding stellar wind carries the stellar magnetic field into the interplanetary space similar to the Parker spiral. If the wind is disturbed by a planet, Alfvén waves will transport the disturbance through the plasma. For the solar system planets, the Alfvén waves will be carried away into the interplanetary space as their velocity is slower than the expansion speed of the solar corona. Hence, no information about the planet can be carried back to the Sun.

The situation for close-in extrasolar planets may look different. Preusse et al. (2005) show that they may be located within a sub-Alfvénic stellar wind as the Alfvén wave velocity is larger than the stellar wind velocity. A disturbance in the magnetic field may thus be carried back to star by Alfvén waves. Hence, the star may get to "know" about the existence of the planet. This is, what we like to call the magnetic communication scenario.

3. The Io - Jupiter scenario

The strong magnetic interaction between Jupiter and its satellite, Io, in the sub-Alfvénic parameter regime of the Jovian magnetosphere can be regarded as a prototype for extra-solar planetary systems. It manifests itself through strong decametric radio emissions and aurora along the current system between the ionospheres of satellite and planet.

3.1 Modeling the current system

Neubauer (1980) showed that the current system between Io and Jupiter may be set up by Alfvén waves which travel along the Alfvén characteristics which are given by the geometric location of the wave front. If $\vec{B}$ is the magnetic field, μ_0 the magnetic field constant and ρ the density of the plasma, the Alfvén velocity is given by $\vec{v}_\mathrm{A} = \pm\vec{B}/\sqrt{\mu_0\rho}$ with $\vec{v}$ being the flow velocity of the plasma. The Alfvén characteristics are given by $\vec{c}_\mathrm{A}^{\pm} = \vec{v} + \vec{v}_\mathrm{A}$.

We now transfer the roles of Io and Jupiter to an extra-solar planet and its host star, respectively. Figure 1 shows for HD 179949 the characteristics in the equatorial plane of the Weber & Davis stellar wind solution, starting at the location of the planet. Both axes show the distance from the star in AU. The big circle located around the origin of the coordinate system is the star, the small circle to the right represents the planet. For all stellar wind solutions the stellar radius was taken to be 1.17 $R_\odot$, the mass 1.14 $M_\odot$ and the magnetic field $0.9 \cdot 10^{-4}$ T. For the particle flux we use the particle flux of today's Sun of $6.3 \cdot 10^{34}$ s^{-1}, scaled with the ratio of the surfaces of HD 179949 and the sun. The different lines show the solution for different rotation periods of the star, which were varied from 3 (black) to 9 days (light grey). If we connect the centres of star and planet with a straight line, the intersection of it with the stellar surface yields the sub-planetary point. We define the angle between the intersection of a characteristic with the stellar surface and the sub-planetary point as the phase angle. For the stellar wind models as described above the phase angles lie between 30 and 80°. For

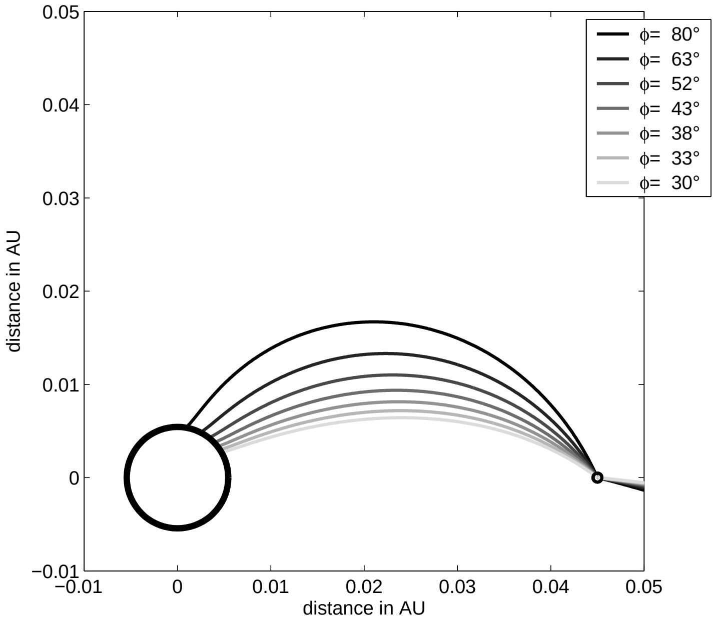

Figure 1. *Field lines of the Alfvén characteristics for HD 179949. The stellar wind model uses a particle flux of* $8.6 \cdot 10^{34}$ *s^{-1}, a coronal temperature of* $0.8132 \cdot 10^{6}$ *K, a magnetic field strength of* $0.9 \cdot 10^{-4}$ *T and varying rotation periods from 3 (black) to 9 days (light grey). The characteristics* $\vec{c}_{\mathrm{A}}^{\,-}$ *lead away from the planet (small circle) to the star (large circle), the characteristics* $\vec{c}_{\mathrm{A}}^{\,+}$ *are carried away by the stellar wind.*

a rotation period of 4 days, we obtain a phase angle of 63°, which is in good agreement with the 60° observed by Shkolnik et al. (2005).

We estimate the maximum power contained in the current system according to Neubauer (1980) where in particular the Alvfén Mach number and the orientation of the stellar wind magnetic field with respect to the stellar wind velocity enter. We can use this as a lower limit for estimating the power contained in the current system between planet and star. For the example of HD 179949, in which a rather low value for the magnetic field in combination with the rotation period was used, we obtain 10^{14} to 10^{15} W. If we compare HD 179949 with the sun and consider the relationship between rotation period and magnetic field, we can assume a stronger magnetic field. This in turn will lead to a higher temperature of the corona and an enhanced particle flux. Thus we can easily achieve 10^{17} to 10^{18} W. Shkolnik et al. (2005) estimate

10^{20} W from their observations of the enhanced chromospheric activity of HD 179949. This is an integrated value over the entire disk of the star and may thus be regarded as an upper limit.

The observations give two constraints to the model: the phase angle and the power of the emission. We find that the phase angle is strongly influenced by the rotation of the star and the distance of the planet. It becomes larger the closer the planet is located to the Alfvén radius.

We find that large phase angles can also be obtained for an appropriate combination of strong magnetic fields, hot temperatures of the coronae and high mass fluxes. With these parameters the power contained in the system will increase. Furthermore, this opens up the possibility that this model will also work for young systems.

We also use the Weber & Davis stellar wind model as a starting model for numerical simulations on a three-dimensional cartesian grid in the frame of resistive magnetohydrodynamics. For the planet we add a dipolar magnetic field, which axis is oriented perpendicular to the ecliptic. We then integrate the equations until a steady-state is reached. The left contour plot of Figure 2 shows the field aligned current density in the plane perpendicular to the equatorial plane for a planet with a magnetic moment of 0.05 $\mathcal{M}_\mathrm{j}$ ($\mathcal{M}_\mathrm{j}$ =$1.55 \cdot 10^{27}$ Am^2 magnetic

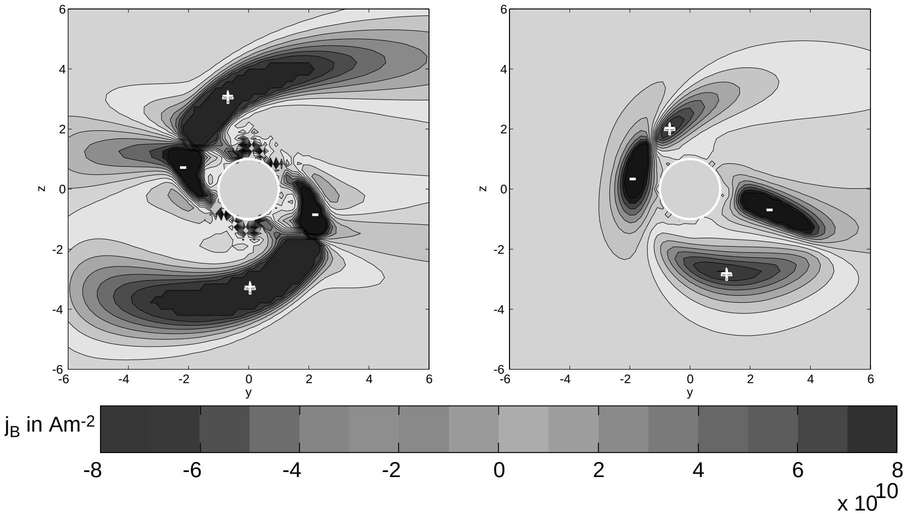

Figure 2. *Field-aligned current densities for a planet located at 0.025 AU (left) and at 0.15 AU (right) in the plane perpendicular to the ecliptic. The axes are normalised to Jupiter radii. The star is to the left hand side outside of the simulation box at* −94 *Jupiter radii (*−0.045 *AU). The Alfvén radius is located at 0.0856 AU.*

moment of Jupiter) located in a today's solar wind at 0.025 AU. This distance is equivalent to an Alfvén Mach number of 0.2. The distances are given in Jupiter radii. The star is located to the left of the figure outside of the simulation box at -94 Jupiter radii (-0.045 AU). The structure of the current system suggests currents running along the field lines that connect the planet and the star. The right plot of Figure 2 shows the field aligned current system for the same planet but in a different distance from the star, which is equivalent to a different plasma environment. The Mach number is 1.9. The structure of the current system is now bent into the direction of the stellar wind flow away from the star.

3.2 Radio emissions

For Io and Jupiter the connecting magnetic flux are the source regions for the strong decametric radio emission. On the basis of the Weber & Davis model we can investigate in how far the magnetic flux tubes of the stellar wind connecting planet and star provide a suitable environment for radio emissions to occur. The radio emissions in the Io-Jupiter system can be explained with the cyclotron maser instability (for a detailed discussion see Zarka 1998). A necessary condition for this to occur is the existence of strong magnetic fields. This means that the cyclotron frequency of the electrons $\Omega_{\rm ce} = e\vec{B}/m_e$ has to be large compared to the plasma frequency $\omega_{\rm pe} = \sqrt{n_e e^2/m_e \varepsilon_0}$, i.e. $\Omega_{ce}/\omega_{pe} >> 1$. This criterion can be easily investigated with the stellar wind models.

We find that the particle flux has the largest influence on the frequency ratio. This is shown Figure 3 for different stellar wind models. For all models the stars have one solar mass and radius and the same magnetic field strength of $1.5 \cdot 10^{-3}$ T at the base of the corona. The different lines show the results for different temperatures. The horizontal dashed line is plotted at a frequency ratio of unity. The vertical line shows the today's particle flux of the Sun. Figure 3 shows that large frequency ratios require a small mass loss of the star and a hot corona. In combination with the necessary strong magnetic fields, which is not shown here, extremely small Mach numbers are required.

We can translate our findings into the characteristic features the star should have, so that the prerequesite for the cyclotron maser instability to occur is fulfilled: The ideal star should have a strong magnetic field at the base of the corona, a high coronal temperature and a small particle flux. If we have a close look to the observed characteristics of stars on the main sequence, we find: If main sequence stars have strong magnetic fields, they will have a hot corona and a large particle flux. Hence, we expect the frequency ratios for main sequence stars to be rather small. If such a star and its planet are connected by a current

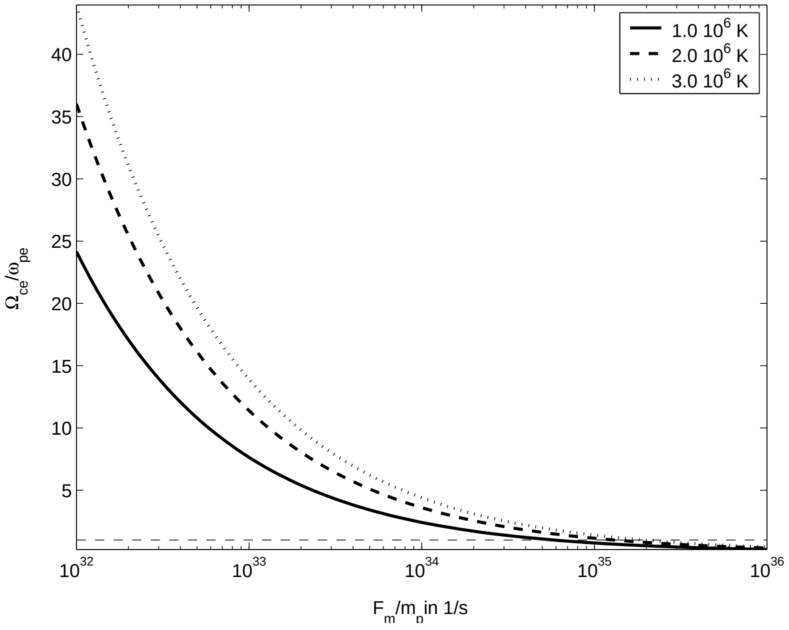

Figure 3. *Ratio of cyclotron to plasma frequency at 0.0225 AU in dependence on particle flux and coronal temperature. The magnetic field of* $1.5 \cdot 10^{-3}$ *T and the rotation period* 3 *d as well as the stellar radius and mass of one solar radius and one solar mass are kept constant. The horizontal line marks a frequency ratio of one, the vertical the today's particle flux of the sun*

system, we expect it to be unlikely that the stellar wind will be a source region for radio emissions.

4. Conclusions

We have adopted the model by Neubauer (1980) for the current system between Io and Jupiter to the situation of close-in extrasolar planets and their stars. In this model, Alfvén waves running along the Alfvén characteristics set up a current system that which links both interacting components of the system. On the basis of realistic stellar wind models we show that indeed Alfvén waves may establish a current system between close-in extrasolar planets and their stars. The results of our numerical simulations of the interaction support the existence of such a current system.

We find that stellar winds of the considered main-sequence stars do not meet the prerequesite for the cyclotron maser instability to develop within flux tubes connecting the planet and its star. Thus, strong radio emissions with source regions in the stellar wind seem to be unlikely. Still, the current system may exhibit features like the bright footpoints observed in the aurora of Jupiter. In this context, such a current system may be a possible scenario for the chromospheric activity enhancement observed on HD 179949, which Shkolnik et al. (2005) suggest to be the result of magnetic interaction between the HD 179949 b an its central star. The phase angle that can easily be reproduced by our model may support this suggestion. Nevertheless, this model does not need the planet to have a magnetic field. We therefore suggest that the observations do not indicate the existence of a planetary magnetic field as Shkolnik et al. (2003) conclude.

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Tenth anniversary of 51 Peg-b : Status of and prospects for hot Jupiter studies
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Magnetized exoplanets

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Abstract. We monitored the chromospheric activity in the Ca II H and K lines of 10 stars with hot Jupiters - 5 for three years at the CFHT and 5 in a single run at the VLT. There is an intriguing, still tentative, correlation between short-term (night-to-night) stellar activity and the $M_p \sin i$ of the hot Jupiter. This is akin to the linear mass-magnetic moment relationship for the magnetised planets in the Solar System. Both HD 179949 and υ And have shown chromospheric activity synchronised to the orbital period of their hot Jupiters which implies magnetic, rather than tidal, interaction. Because of their small separation (<0.1 AU), many of the hot Jupiters lie within the Alfvén radius of their host stars, allowing 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 the probable reason why a relatively weak effect was seen for the prime candidate, τ Boo.

1. Introduction

The presence of a giant planet influences its parent star beyond the dynamical perturbations measured by the Precise Radial Velocity method. Cuntz et al. (2000) suggested an observable, periodic interaction (P_{int}) between a parent star and its hot Jupiter in the form of enhanced stellar activity of the star's outer atmosphere, which can take the form of tidal (where $P_{int} = P_{orb}/2$) and/or magnetic heating (where $P_{int} = P_{orb}$) of the plasma with a distance dependence of $1/r^3$ and $1/r^2$, respectively. There exists ample observational evidence of such tidal and magnetic interactions in the amplified case of RS CVn stars. Our own Ca II H & K observations of ER Vul, an RS CVn system with two G V dwarfs orbiting each other with $P_{orb} = 0.69$ d, exhibit clear enhancements near the sub-binary longitudes (Shkolnik et al. 2005a). 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.

We searched for periodic chromospheric heating by monitoring the Ca II H & K emission in stars having giant planets within a few stellar radii.

2. The Spectra and Planet-Induced Activity

Our program stars have orbital periods between 2.5 and 4.6 days, eccentricities ≈ 0 and semi-major axes < 0.06 AU. We observed τ Boo, HD 179949, HD 209458, 51 Peg and υ And from the Canada-France-Hawaii Telescope (CFHT) with the Gecko échellette spectrograph (R=110,000). Differential radial velocities were measured to better than 7 m s^{-1} producing updated ephemerids (Walker et al. 2003). We also observed five southern targets, HD 46357, HD 73256, HD 75289, HD 76700, and HD 83443, at the Very Large Telescope (VLT) with UVES (R=75,000). The system parameters for the program stars as well as the details of the data reduction can be found in Shkolnik et al. (2005b). The final spectra were of high S/N reaching ≈ 500 per pixel (or 4300 Å^{-1}) in the continuum and 150 (or 1290 Å^{-1}) in the H & K cores. A specimen, flat-fielded spectrum of υ And is shown in Figure 1 (left).

The spectra were grouped by date and a nightly mean was computed for the H and K lines. The residuals of the normalised spectra were used to compute the mean absolute deviation (MAD $= N^{-1}\Sigma|data_i - mean|$ for N spectra). As an example, the nightly residuals used to generate the MAD plot for υ And are displayed in Fig 1

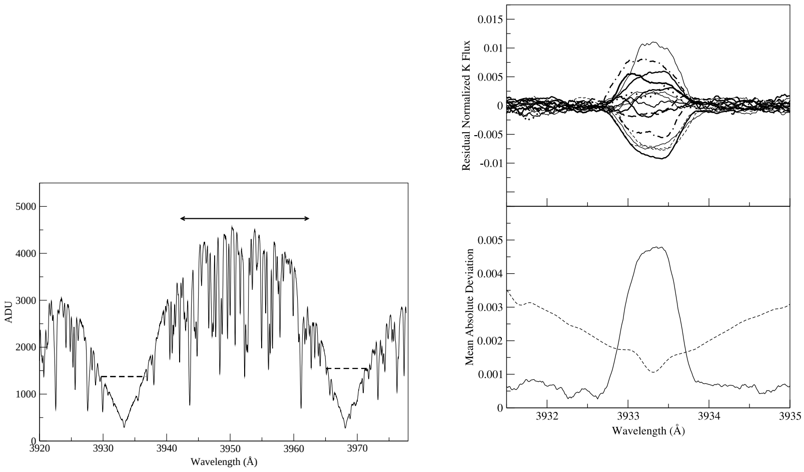

Figure 1. *Left: A single spectrum of υ And. The arrow defines the 3942 – 3963 Å region used to measure the differential radial velocities. The dashed lines show the levels of normalization used to isolate the Ca II H and K cores in order to minimize continuum errors. Right, top: The residuals (smoothed by 21 pixels) from the normalized mean spectrum of the Ca II K core of υ And. Right, bottom: The mean absolute deviation (MAD). 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) showing that the activity on υ And is confined to the K reversal.*

(right, top). Below it, the MAD plot with the corresponding K-core superimposed is shown. The identical analysis was performed on the Ca II H line of all target stars (Shkolnik 2004).

τ Boo has the largest $v\sin i$ (= 14.8 m s^{-1}) and is believed to be in synchronous rotation (tidally locked) with its tightly-orbiting planet. Therefore, the planet-star interaction may be minimal due to the fact that there is near zero relative velocity. The integrated residuals from the mean normalised K core are plotted against orbital phase in Figure 2 (left). A coherence with P_{orb} appears to be emerging in the last two observing runs. 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 Figure 2 (right).

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

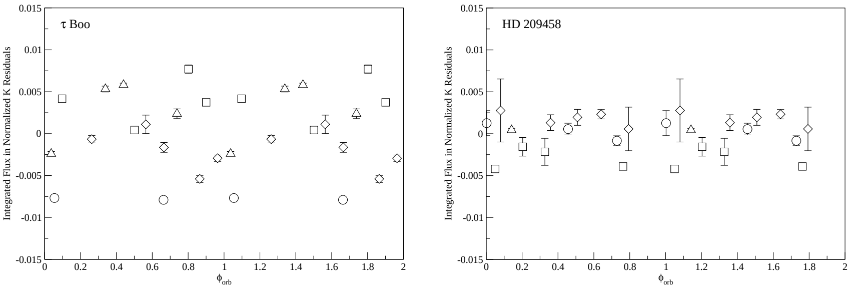

Figure 2. *Integrated flux of the K-line residuals from a normalised mean spectrum of τ Boo and HD 209458 as a function of orbital phase. The symbols distinguish data from different observing runs: circles – 2001 August, squares – 2002 July, triangles – 2002 August, diamonds – 2003 September. Units of the integrated flux are in equivalent Angstroms relative to the normalisation level which is approximately 1/3 of the stellar continuum. The error bars in residual flux are ± 1 σ as measured from the intra-night variations. The size of the phase error is within the size of the points.*

a truncated, best-fit sine curve with $P = P_{orb} = 3.092$ d corresponding to the change in projected area of a bright spot on the stellar surface before being occulted by the stellar limb. The spot model peaks at $\phi = 0.83$. Figure 3 (left) updates the integrated K residuals to include the 2003 September data. Clearly, the average K emission is higher during the latest run with a much smaller level of variability. It is interesting to note that the 2003 data still peak between $\phi = 0.80 - 0.95$, consistent with the previous results. The second convincing case of magnetic interaction is between υ And and its innermost giant planet. In Figure 3 (right), the 2002 and 2003 runs show good agreement in phase-dependent activity with an enhancement at $\phi = 0.53$. 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_{orb} and peaks near $\phi = 0.5$.

For these two cases, the peak of the emission does not coincide with the sub-planetary point, $\phi = 0$. For HD 179949, it leads the planet by 60° in phase and for υ And, the Ca II emission is 169° out of phase with the sub-planetary point. The phase offset of a star-spot or group of star-spots 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).

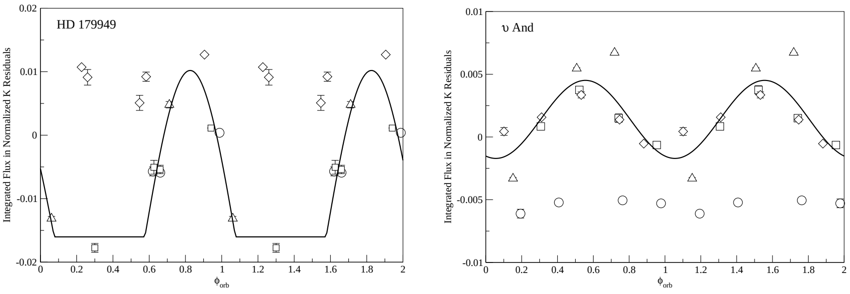

Figure 3. *Integrated flux of the K-line residuals from a normalised mean spectrum of HD 179949 and υ And as a function of orbital phase. The solid lines are best-fit spot models. For HD 179949, we used a truncated sine curve fitted to the 2001 and 2002 data and for υ And, we fitted the curve to the 2002 and 2003 data.*

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 υ And, the time spans 88 orbits or approximately 29 rotations.

One consistent result for the 'active' stars (τ Boo, HD 179949, HD 209458 and υ And) is their night-to-night modulation of H & K emission. Also, unlike the case for HD 73256, the night-to-night variations of these stars do not increase or decrease monotonically throughout an observing run, implying the variability cannot be explained exclusively with star-spots 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 τ Boo, the timescale of activity is short compared to the stellar rotation period. This interpretation is supported by the recent photometric observations by the MOST space telescope (Walker et al. 2005).

3. A Physical Mechanism

The location of the hot Jupiter relative to the Alfvén radius (the distance from the star at which the radial velocity of the wind $V_{r,\mathrm{wind}}$ equals the local Alfvén velocity V_A plays a significant role in transporting energy toward the star against the stellar winds. 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). Since the Alfvén radius of the Sun is about 10 to 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 might resemble the Io-Jupiter interactions or the RS CVn binaries.

The picture that we have sketched thus far assumes that most of energy flux released from the vicinity of the hot Jupiter is transported along the field lines by Alfvén waves and deposited at the foot-points 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 υ And (Shkolnik et al. 2005b, Preusse et al. 2005.)

We estimated 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, $\sim 10^{27}$ erg s^{-1} or 1.5×10^{5} ergs cm^{-2} s^{-1}. This implies that flare-like activity triggered by the interaction of a star with its hot Jupiter may be an important energy source in the stellar outer atmosphere.

The scenario of magnetic interaction implies the orbital decay of hot Jupiters. For Ca II emission, the time scale of orbital decay is roughly equal to the ratio of the orbital energy of the hot Jupiter ($\sim 10^{44}$ ergs) to 10^{27} erg/s. This gives a timescale as short as several billion years, imposing a non-negligible constraint on modeling the orbital evolution of hot Jupiters.

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 (Sánchez-Lavega 2004). This is observed in our own Solar System for the magnetised 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 the average integrated MAD per observing run ($\langle$MADK$\rangle$) in Fig 4 where we still see an intriguing correlation. The $\langle$MADK$\rangle$ values for HD 179949 and υ And were corrected for the orbital (geometric) modulation. Of our sample, τ Boo has the most massive planet and yet falls well below the correlation. As mentioned earlier, if the star and planet are tidally locked, then there is little or no free energy left from the orbit and we would expect weak, if any, magnetic coupling. We require observations of new systems with a range of planetary masses in order to confirm this $M_p \sin i$-⟨MADK⟩ correlation and potentially begin to use short-term stellar activity as a proxy for planetary magnetic field strength.

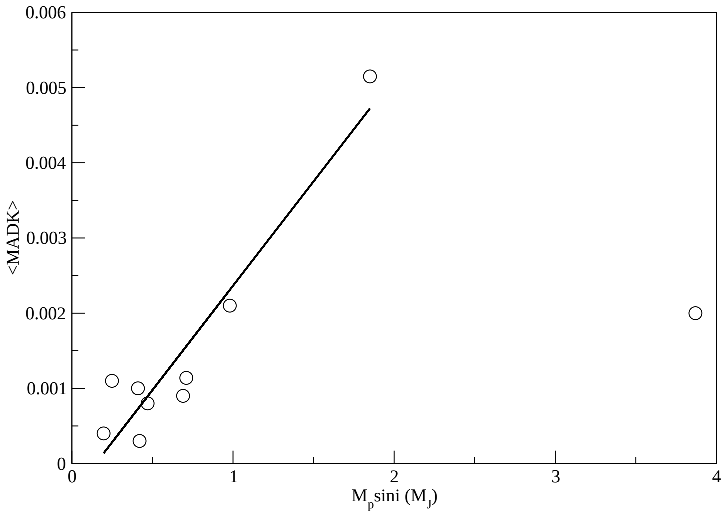

Figure 4. *The minimum planetary mass (in Jupiter masses) plotted against the average MAD of the K-line per observing run.*

We have begun a new program to observe both old and new targets with high-resolution échelle spectroscopy spanning the entire optical wavelength range. We are able to observe the various stellar activity indicators to map the activity as a function of stellar atmospheric height. 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, while the energy sum will point out if there are any discrepancies with the theorized energy budget.

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Tenth anniversary of 51 Peg-b : Status of and prospects for hot Jupiter studies
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Ten years of quests for radio bursts from extrasolar planets

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Abstract. We searched for radio bursts towards 51 Peg, τ Boo, ν And and 55 Cancri, which were found to have "hot Jupiter" companions. The star 51 Peg has a planet with 0.5 M_{Jup} (lower limit) and 4.23 day period. The star τ Boo has a planet of 3.7 M_{Jup} and 3.31 day period. Such planets are called "Hot Jupiter". We made a non-thermal radio emission model of magneto-electric environment between the stars and their planets. Since a detection of signals is expected, we made observations at 8.6 GHz with Mizusawa 10-m telescope. From 1996 to 2000, we observed with a detection limit of 10 Jy using a position-switching method. Since 2001, we changed to beam-switching method, and achieved a detection limit of 1 Jy. No radio burst signals were detected.

1. Introduction

During the last 15 years, a increasing number of groups have initiated long term Doppler searches for planets orbiting solar-type stars. These groups have attained precision of few m/s, and have surveyed more than 3000 stars for 2 to 12 years. After the spectacular detection of the first planetary companion by Mayor & Queloz (1995), additional 160 planet-like companions have been found towards solar-type stars thanks to precise Doppler monitoring (e.g. Butler et al. 1997; Marcy et al. 2005; Vogt et al. 2005). These companions have Msini between 0.5 and 7 M_{Jup}, suggesting that the actual masses reside within a range associated with extrasolar giant planets, whatever their origin. All these planets were detected by spectroscopy in a visible wavelength region. We thought that these planets can be observed in radio wavelength region. We made a model for radio emission and tried to search a radio burst from these planetary systems.

2. Radio Burst Model

Our model is based on magnetic loops with arch-like configuration, which is elongating from stellar surface (Hori et al. 1997). When a planet goes across an elongated magnetic loops, which is generated from stellar spots of central star, the planet creates a disturbance of magnetic wave near the main star. When the disturbance of magnetic waves crosses these tubes, radio bursts occur. Stellar companions magnetic fields are unfortunately unknown. We apply Busse's law to calculate a magnetic moment M of the planets (Warwick 1976; Busse 1976; Dolgirov 1977; Jacobs 1979):

$$M = \rho_c^{1/2}\,\omega\,R_c^4, \tag{1}$$

with ρ_c the fluid density in the planet core, ω the angular rotation velocity of the planet, and R_c the core radius.

When this law is applied to Jupiter-like planets, we obtain 0.4 Gauss for 51 Peg companion planet, which is 10 % less than Jupiter.

3. Selected sources and Observations

The extrasolar planets exhibit a variety of characteristics (e.g. Udry et al. 2003). We selected "51 Peg-type" planets (51 Peg, 55 cancri, τ Boo, and ν And) which are distinguished by an orbital distance less than 0.15 AU. The extra-solar planet 70 Vir b has a relatively large mass (Msini = 6.5 M_{Jup}) and a high eccentricity ($e = 0.4$), suggesting a less-dissipative formation theory. The planet around 16 Cyg B has a smaller mass than 70 Vir b (Msini = 1.7 M_{Jup}), but an even larger eccentricity. The companion around 47 UMa resides in an circular orbit of radius 2.1 AU and has a minimum mass of 2.4 M_{Jup}, thus most closely comparable to Jupiter in our Solar System. According to Rosner et al. (1985), stellar X-ray luminosity indicates good correlation with stellar rotational velocity. Furthermore Gudel (1994) shows that stars with higher luminosity of X-ray radiate strong radio. These radio luminosity comes from stellar flares. So we expect that stars with higher rotational velocity will radiate stronger and/or more frequently radio bursts. Among those extra-solar planets, τ Boo has fast rotational period (5.1 day: Baliunas et al. 1997). We chose this star and 51 Peg as priority targets for our first observations. We performed observations at 8.6 GHz with Mizusawa 10-m telescope (HPBW $12'$) from 1996 to 2005. The Schottkey diode mixer receiver was used. System noise temperature was 110-130 K at elevation of 20°including contribution from atmosphere. The calibration and pointing accuracy was checked using the star Cas A every starting time for each monitoring star. A chart recorder was used for a back end. From 1996 to 2000, we observed with a detection limit of 10 Jy using a position-switching method. Since 2001, we changed to beam-switching method, and achieved a 1 Jy detection limit. The total duration of each observed period is shown in Table 1. We observed for about one week every March. Up to day, we do not detect any radio burst signal.

Table 1. *Total duration of observations of exoplanet host stars.*

Exoplanet host star	Total duration [h] period 1996-2000	Total duration [h] period 2001-2005
51 Peg	236.0	220.0
τ Boo	230.5	200.5
ν And	40.7	35.0
55 Cancri	19.0	17.5

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