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A magnetic communication scenario for hot Jupiters

S. Preusse[1,⋆], A. Kopp[2], J. Büchner[1], and U. Motschmann[3]

[1] Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
e-mail: preusse@steinbeis-europa.de;buechner@mps.mpg.de
[2] Theoretische Physik IV, Ruhr-Universität Bochum, 44780 Bochum, Germany
e-mail: ak@tp4.rub.de
[3] Institut für Theoretische Physik, Technische Universität Braunschweig, Mendelssohnstrasse 3, 38106 Braunschweig, Germany
e-mail: u.motschmann@tu-bs.de

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ABSTRACT

The observations of enhanced chromospheric activity on HD 179949 as well as on υ And with the same periods as their close-in planets seem to indicate some kind of magnetic interaction between star and planet. A constraint to any possible model are the large phase angles of 60° and 169°, respectively. We present a simple model, which is based on the propagation of Alfvén waves within the stellar wind flow relative to the planet and which can meet this restriction. In the solar system such a model is successfully used to explain the current system between Io and Jupiter.

Key words. planets and satellites: general – stars: magnetic fields – stars: winds, outflows – stars: activity

1. Introduction

The extremely small semi-major axes of many extrasolar planets with masses considerably larger than the mass of Saturn led to these planets to be called hot Jupiters. In fact, hot Jupiters were unknown until the detection of 51 Peg b as they do not exist in the Solar system. With the Solar system in mind, however, the detection of hot Jupiters opens up a new horizon for the study of the interaction between stellar winds and planetary magnetospheres.

An intensively studied type of stellar wind - planetary magnetosphere interaction is the production of radio emissions. As this is not the focus of this paper, the reader is asked to refer to Farrell et al. (1999), Zarka et al. (2001), Grießmeier et al. (2005), or Stevens (2005).

Other types of magnetic interaction have been suggested. There is, e.g., the superflare model by Rubenstein & Schaefer (2000) in which the interaction of the magnetic fields of planet and star results in extremely energetic flares. Cuntz et al. (2000) and Cuntz & Shkolnik (2002) suggested that magnetic interaction between a hot Jupiter and its central star may lead to an activity enhancement of the stellar activity. This model was also used by Shkolnik et al. (2003) (cf. also Shkolnik et al. 2004) who observed a periodic activity enhancement on HD 179949, a star with a hot Jupiter orbiting the star at a distance of $a = 0.045$ AU with an orbital period of $P_{\rm orb} = 3.1$ d (Tinney et al. 2001). The period of the enhanced activity corresponds to the orbital period of the planet. A similar process was observed by Shkolnik et al. (2005) in the system υ And where $d = 0.057$ AU and $P_{\rm orb} = 4.6$ d (Butler et al. 1997). This is again interpreted as evidence for some kind of magnetic interaction. One motivation for this conclusion are early observations of Jupiter, where radio emissions could be shown to correlate with the orbital motion of Io by Bigg (1964). These decametric radio emissions are conclusively explained by a magnetic interaction between satellite and planet (e.g. Belcher 1987).

It should be noted here that we concentrate here and in the following merely on the question to find a mechanism that can explain the observed activity enhancements for both systems. The modelling of the energetics of the system is postponed to future studies. Estimates by Preusse (2005), however, show that the energy input from the stellar wind into the planetary magnetosphere lies in a reasonable range to generate a hot spot. Gu et al. (2005) interpret the generation as the release of intrinsic magnetic energy stored already on the stellar surface.

A comparison of the systems of known hot Jupiters and their stars to the known objects in the Solar system brings up the analogy of both being a giant version of Io and Jupiter, respectively. The latter, as well as Jupiter and Ganymede or Jupiter and Europa are connected through a current system with each other. This is established by Alfvén waves travelling back and forth, see e.g. Neubauer (1980), Goertz (1980), Herbert (1985), Kopp & Schröer (1998), and Neubauer (1998) (cf. also Neubauer 1999). These waves carry the perturbation along the Alfvén characteristics, which describe the geometric location of the wave front as defined below in Eq. (1). Zarka et al. (2001) suggested a similar scenario for extrasolar planets located within the Alfvén radius. This is the radius at which the stellar wind reaches the speed of the Alfvén waves. Shkolnik et al. (2005) pick up this idea for their interpretation of the enhanced chromospheric activity on both stars, HD 179949 and υ And. This may also be the case for many extrasolar planets as shown by Preusse et al. (2005). In their model, McIvor et al. (2006) assume reconnection of the planetary and stellar wind magnetic fields, resulting in accelerated electrons travelling along the field lines back to the star. Due to the almost vanishing travel time of the electrons, the model does not have to account for the planetary motion. It succeeds to explain the observed phase shift for HD 179949 by

⋆ *Now at*: Steinbeis-Europa-Zentrum, Innovation Relay Centre, c/o Haus der Wirtschaft, Erbprinzenstr. 4-12, 76133 Karlsruhe, Germany.

assuming the stellar magnetic dipole to be tilted, but fails to do so also for υ And. As pointed out by McIvor et al. (2006), the scenario is complicated when Alfvén waves are taken into account, as during their travel time to the star, the planet moves a non-negligible distance along its orbit.

In this paper we present a different approach by simply considering these two processes: the propagation of the planet-induced perturbation along the Alfvén characteristics and the orbital motion of the planet. It should be noted that, as in the case of Io, we only require the planet to be conductive, but an (intrinsic or induced) planetary magnetic field is not necessary, even though the model also works for a magnetised planet as shown by Kopp & Ip (2002) for Ganymede. For our approach we adopt the Alfvén wing model by Neubauer (1980) for hot Jupiters, but use the stellar wind models by Preusse et al. (2005) as a basis. The Alfvén wing model is described in detail in Sect. 2. In Sect. 3 we study for which stellar parameters we obtain the phase angle between the enhanced chromospheric activity and the planet as observed by Shkolnik et al. (2003) (60° for HD 179949) and by Shkolnik et al. (2005) (169° for υ And). We conclude the paper with a critical discussion in Sect. 4.

2. The Alfvén wing model

For modelling the current system between a hot Jupiter and its central star, we adopt the Alfvén wing model by Neubauer (1980) for Io, originally developed by Drell et al. (1965) for satellites in the Earth's ionosphere. In this model the current system is set up by Alfvén waves, which travel forth and back between Io and Jupiter. The situation of hot Jupiters is rather different from the plasma environment encountered by Io: Io is located in a dipole field with the motion of the plasma resulting from the relative motion between the corotating magnetospheric plasma and Io's orbital motion. Instead, the hot Jupiter is surrounded by the expanding corona of the star, i.e. the stellar wind. As a result of the stellar rotation, the magnetic field is shaped similar to an Archimedean spiral while it is being carried away by the stellar wind. We take this into account by using the magnetohydrodynamic stellar wind model by Weber & Davis (1967) to describe the plasma environment of the hot Jupiters. For details we refer to Preusse et al. (2005).

Io is a conducting sphere perturbing the magnetic field due to its relative motion with respect to the field (Drell et al. 1965). For simplicity we can assume the relative plasma flow $\boldsymbol{v}$ and the Jovian magnetic field $\boldsymbol{B}$ to be locally perpendicular. The resulting propagation of the perturbation is shown in Fig. 1, taken from Kopp & Schröer (1998): the arrows show the magnetic field in Io's rest frame in a cylindrical coordinate system where φ is the azimuthal direction along Io's orbit with $\varphi = 0$ at Io's position and z is the direction of Jupiters rotation axis. As Jupiter's dipole tilt was neglected in these simulations, the φ-z-plane shown is also the $\boldsymbol{v}$-$\boldsymbol{B}$-plane. r is the radial direction away from Jupiter, which is located 5.9 Jovian radii or, in this normalisation, 232 Io radii behind the plane. Initiated at Io, the perturbation propagates via Alfvén waves along the magnetic field. The superposition with the relative motion of the magnetospheric plasma results in the so-called Alfvén wings (Neubauer 1980), so that the perturbation in the magnetic field follows the Alfvén characteristics (cf. Herbert 1985):

$$\boldsymbol{c}_{\mathrm{A}}^{\pm} = \boldsymbol{v} \pm \boldsymbol{v}_{\mathrm{A}}, \tag{1}$$

where $\boldsymbol{v}_{\mathrm{A}} = \boldsymbol{B}/\sqrt{\mu_0 \rho}$ is the Alfvén velocity, with μ_0 being the magnetic permeability and ρ the mass density of the plasma. The minus sign, i.e. $\boldsymbol{c}_{\mathrm{A}}^{-}$, refers to a propagation into the upper hemisphere ($z > 0$), whereas the plus sign ($\boldsymbol{c}_{\mathrm{A}}^{+}$) refers to a propagation into the lower hemisphere ($z < 0$). Observable phenomena related to this interaction are the enhancement of the decametric radio emissions as well as the Io footprint in the Jovian aurora (e.g. Clarke et al. 1998). Though the hot Jupiters are quite different, the result will be similar to Fig. 1 as long as the hot Jupiter is located within a sub-Alfvénic stellar wind. To get a crude idea of the geometry for this case, imagine the star to be located far above Fig. 1, so that $\boldsymbol{c}_{\mathrm{A}}^{-}$, i.e. the region of perturbed arrows above the circle representing Io, is directed toward the star.

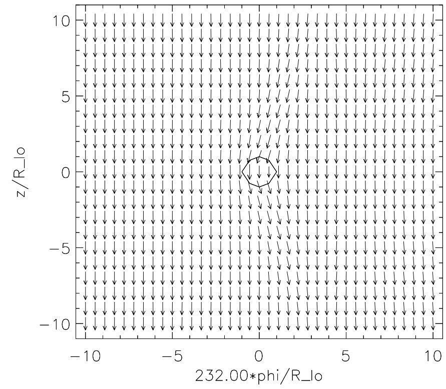

Fig. 1. Perturbed magnetic field in the $\boldsymbol{v}$-$\boldsymbol{B}$-(φ-z) plane in Io's (circle) rest frame along its orbit (Kopp & Schröer 1998). This figure illustrates the propagation of the perturbation along the Alfvén characteristics. The perturbation leaves the plane due to the radial component of Jupiter's dipole field. The length scale is in units of Io's radius.

For hot Jupiters we can calculate the characteristics using stellar wind models, which are described in detail in Preusse et al. (2005). For this we solve the stellar wind model by Weber & Davis (1967) for a given set of stellar parameters, i.e. the stellar mass, $M_\star$, and radius, $R_\star$, the stellar rotation period, $P_\star$, the mass flux, F_{m}, the magnetic flux density, $B_\star$, at the base of the corona and the temperature, $T_\star$, of the corona. The latter is assumed to be isothermal. This stellar wind model is one-dimensional and uses a spherical coordinate system (r, φ, ϑ). Due to the rotation of the star, the velocity $\boldsymbol{v}_{\mathrm{sw}}$ and the magnetic flux density $\boldsymbol{B}$ have both radial (subscript r) and azimuthal (subscript φ) components

$$\boldsymbol{v}_{\mathrm{sw}} = (v_r, 0, v_\varphi) \quad \text{and} \quad \boldsymbol{B} = (B_r, 0, B_\varphi). \tag{2}$$

All quantities depend on the distance r from the star only. The mass density ρ is obtained from the conservation of mass. We now use the rotational symmetry to construct the stellar wind solution in the equatorial plane. Transferring the rôles of Io and Jupiter to the hot Jupiter and its central star, respectively, we calculate the field lines for the characteristics $\boldsymbol{s}$ according to

$$\frac{\mathrm{d}\boldsymbol{s}}{\mathrm{d}\tau} = \boldsymbol{c}_{\mathrm{A}}^{\pm}(\tau) \tag{3}$$

in which τ may be taken as the travel time. We use the hot Jupiter as a starting point and follow both characteristics.

We would like to emphasise that direction and velocity of the propagation of the perturbation along the characteristics depend, according to Eq. (1) not only on the Alfvén velocity through the magnetic field and the plasma density, but to the same part on the relative velocity. This is especially important for the case of the hot Jupiters, in which the relative velocity $\boldsymbol{v}$ is given by the velocity of the stellar wind $\boldsymbol{v}_{\mathrm{sw}}$ and the velocity of the planet $\boldsymbol{v}_{\mathrm{p}}$. If $\boldsymbol{v} > \boldsymbol{v}_{\mathrm{A}}$ holds, both characteristics $\boldsymbol{c}_{\mathrm{A}}^{+}$ and $\boldsymbol{c}_{\mathrm{A}}^{-}$ will be carried

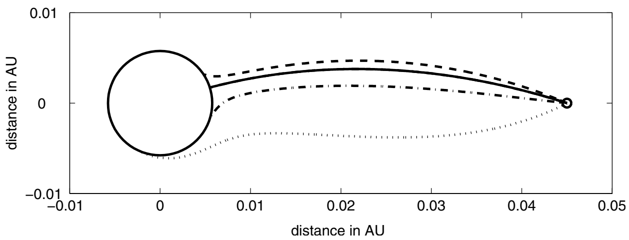

Fig. 2. Alfvén characteristics c_A^- in the equatorial plane for a star with a rotation period of 9 d and four different orbital periods P_{orb} of the planet in the same stellar wind, i.e. the fact that this corresponds to different star masses is ignored here in order to better illustrate the effect of the relative velocity. The solid line is a magnetic field line in the stellar wind. It is equivalent to c_A^- with $P_{\text{orb}} = 9$ d. The dashed line corresponds to $P_{\text{orb}} = 12$ d, the dash-dotted to $P_{\text{orb}} = 6$ d and the dotted to $P_{\text{orb}} = 3$ d.

away by the stellar wind. This is the case for the Solar system planets. If $\boldsymbol{v} < \boldsymbol{v}_A$, the characteristic c_A^+ will still be carried away by the stellar wind, but the perturbation travelling along c_A^- propagates in direction of the star. This can be the case for hot Jupiters, which may be located within a sub-Alfvénic stellar wind regime (Preusse et al. 2005). In this scenario $\boldsymbol{v}$ determines in how far the propagation of the perturbation differs from the propagation along the magnetic field. To demonstrate this, we show an somewhat unrealistic but illustrative example for HD 179949 in Fig. 2, where we change the orbital period of the planet, but leave all other quantities, in particular the stellar mass and, thus, the stellar wind, unchanged. The parameters are that of our best fit, which will be described in detail in Sect. 3. The figure shows the equatorial plane, the large circle represents the star, the small circle the planet. The lines connecting the planet and the star are different Alfvén characteristics c_A^-. All are based on the same stellar wind model, which assumes a rotation period of 9 d for the star. The solid line is one magnetic field line in the stellar wind, which is also equivalent to the characteristic if the orbital motion of the planet and the stellar rotation are tidally synchronised. For the dashed line we assumed the orbital period of the planet P_{orb} to be 12 d, for the dash-dotted it is 6 d and for the dotted 3 d. It should be noted, however, that the actual value of the rotation, $P_\star$, of HD 179949 is still somewhat uncertain. Gu et al. (2005) give a range of 7−10 days and refer to Shkolnik et al. (2005). The latter discuss observations by Wolf & Harmanec (2004), whose value of 7.07 d was obtained near the limit of detection, and give a (derived) value of ≈9 d. As this value was also used by McIvor et al. (2006) in their theoretical model, we use here a value of $P_\star = 9$ d.

In order to compare the theoretical results with observations we also have to take into account the orbital motion of the planet itself as well as the propagation time of the perturbation from the planet to the surface of the star. This is done in the following section.

3. Phase angles for HD 179949 and υ And

As pointed out in the previous section, we have to consider the relative motion between the stellar wind and the planet for the computation of the Alfvén characteristics. Therefore, we subtract the orbital motion from the φ-component of the stellar wind velocity. Hence, c_A^- is

$$c_A^- = \begin{pmatrix} v_{\text{sw},r} \\ 0 \\ v_{\text{sw},\varphi} - v_\text{p} \end{pmatrix} - \frac{1}{\sqrt{\mu_0 \rho}} \begin{pmatrix} B_r \\ 0 \\ B_\varphi \end{pmatrix}, \tag{4}$$

where we only consider the equatorial plane of the spherical coordinate system.

For a given set of stellar (mass $M_\star$, radius $R_\star$, mass flux F_m, rotation period $P_\star$) and planetary (semi-major axis a, orbital period P_{orb}) parameters, we vary the corona temperature, $T_\star$, and magnetic field, $B_\star$, and first compute the stellar wind solutions according to Preusse et al. (2005) for these parameters. In a second step, we integrate the Alfvén characteristic, c_A^-, by means of Eq. (3) with the planet as the starting point ($t = 0$) until the stellar surface is reached and obtain the travel time, τ_c, by integrating along the arc length s of the characteristic:

$$\tau_\text{c} = \int \frac{1}{|c_A^-|} \mathrm{d}s. \tag{5}$$

We now define ϕ_c as the angle between the starting point (position of the planet at $t = 0$) and the footpoint, where c_A^- hits the stellar surface. When the wave reaches the stellar surface, the planet has travelled an angle of

$$\phi_\text{p} = \tau_\text{c} \frac{360°}{P_{\text{orb}}} \tag{6}$$

since the wave was launched. Thus, the phase difference, $\Delta\phi$, which is equivalent to the observable phase angle, is

$$\Delta\phi = \phi_\text{c} - \phi_\text{p} = \phi_\text{c} - \tau_\text{c} \frac{360°}{P_{\text{orb}}}\cdot \tag{7}$$

The input parameters of our model are the stellar and planetary parameters listed above, of which only $T_\star$ and $B_\star$ are varied in order to fit the observations. The only output is the stellar wind solution, i.e. density, magnetic field and velocity as a function of the distance from the stellar surface, from which all other quantities are computed.

Whereas $M_\star$, $R_\star$, $P_\star$, a, and P_{orb} can be taken more or less from observations, the stellar mass flux, F_m, must be obtained from theoretical considerations. We constrain it here by scaling today's solar mass flux, $F_{\text{m},\odot} = 1.05 \times 10^8\ \text{kg s}^{-1}$ (Mann et al. 1999), by the ratio of the surfaces: $F_\text{m} = F_{\text{m},\odot}(R_\star/R_\odot)^2$. The influence of the spectral type – both stars under consideration are hotter and slightly younger than the Sun – was investigated by Collier Cameron & Jianke (1994), resulting in a similar formula, which also contains the ratio of the magnetic fields of the star, $B_\star$, and the Sun, $B_\odot$ due to coronal heating: $F_\text{m} = F_{\text{m},\odot}(R_\star/R_\odot)^2(B_\star/B_\odot)^b$. The exponent, b, lies in the range between 0 and 2. For slowly rotating stars b can be set to 1. Preusse (2005) obtains a value of $B_\odot = 1.435 \times 10^{-4}$ T for the model by Weber & Davis (1967). If this coronal heating is additionally taken into account, $B_\star$ and $T_\star$ are no longer independent and the parameter space is difficult to control. Thus, for our first approach we neglect the influence of the magnetic field. We set $b = 0$ so that $B_\star$ and $T_\star$ can be described independently. The error possibly committed through this simplification is not larger than the uncertainties of the other measured quantities, e.g. the rotation period of the star.

We obtain the best fits for the values for $B_\star$ and $T_\star$ that are listed together with the other (fixed) parameters in Table 1. They both appear to lie in the lower region of reasonable values, where we take the Solar values as an orientation. The parameter space leading to phase differences near the observed values, however, seems to be rather limited, so that already our simplified model can in principle explain the observations. Nevertheless it can be improved by including a more realistic magnetic field, in particular near the stellar surface, or the spectral type as described above. The solution for HD 179949 is shown in Fig. 3 and for

Table 1. Stellar parameters.

		HD 179949	υ And
$M_\star$	$[M_\odot]$	1.24^a	1.37^b
$R_\star$	$[R_\odot]$	1.24^a	1.45^b
$F_{\rm m}$	$[{\rm kg\,s^{-1}}]$	1.62×10^8	2.17×10^9
$P_\star$	[d]	$9^{a,e}$	14^d
a	[AU]	0.045^a	0.057^c
$P_{\rm orb}$	[d]	3.1^a	4.6^c
$T_\star$	[K]	0.557×10^6	0.51×10^6
$B_\star$	[T]	0.96×10^{-4}	1.5×10^{-4}
$\tau_{\rm c}$	$[d]$	1.60	1.54
$\Delta\phi$	[°]	62	171

References: [a] Tinney et al. (2001), [b] Allende Prieto & Lambert (1999), [c] Butler et al. (1997), [d] Henry et al. (2000), [e] Shkolnik et al. (2005).

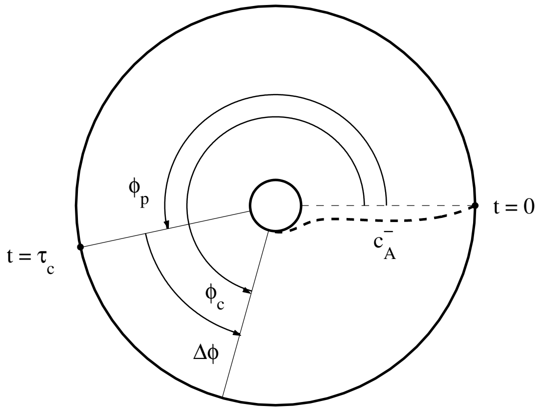

Fig. 3. Characteristic $\boldsymbol{c}_{\rm A}^-$ (thick dashed line) for HD 179949 resulting from a perturbation by the planet at $t = 0$ (thin dashed line). The perturbation reaches the stellar surface at $t = \tau_{\rm c}$. The angle between starting point and footpoint of the characteristic is $\phi_{\rm c}$. In the time period $\tau_{\rm c}$ the planet has travelled an angle of $\phi_{\rm p}$ resulting in a phase difference $\Delta\phi = 62°$.

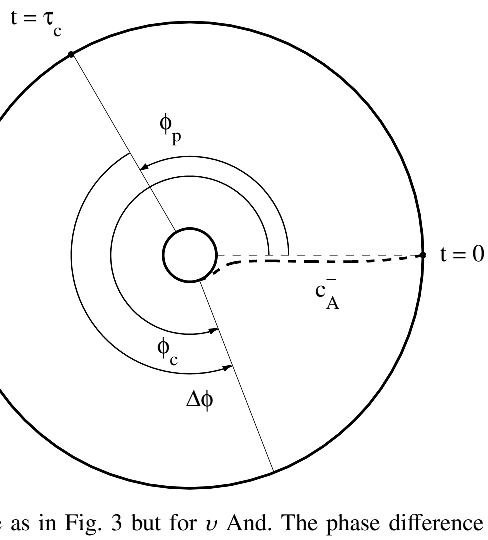

Fig. 4. Same as in Fig. 3 but for υ And. The phase difference for our best fit is here 171°.

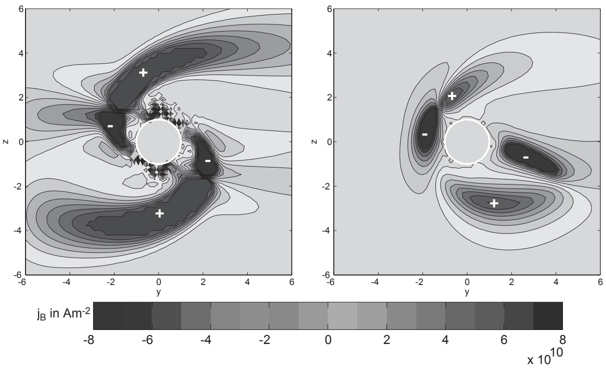

Fig. 5. Field-aligned current densities, $j_\parallel = (\boldsymbol{j} \cdot \boldsymbol{B})/B$, for planets in a distance of 0.025 AU (*left*) and 0.15 AU (*right*) in a today's solar wind as taken from Preusse et al. (2006). Shown is the y-z-plane (at $x = 0$), which is perpendicular to the ecliptic. The Sun is located far to the left. The slow magnetosonic point, the Alfvén point and the fast magnetosonic point are located at 0.033, 0.0856 and 0.0864 AU, respectively, i.e. between the panels. In the figures the distances are normalised to one Jupiter radius, i.e. 1 $R_{\rm pl} = 4.8 \times 10^{-4}$ AU.

υ And in Fig. 4. In both figures the characteristic $\boldsymbol{c}_{\rm A}^-$ (thick dashed line) results from a perturbation by the planet at $t = 0$ (thin dashed line). The perturbation reaches the stellar surface at $t = \tau_{\rm c}$. The angle between starting point and footpoint of the characteristic is $\phi_{\rm c}$. In the time period $\tau_{\rm c}$ the planet has travelled an angle of $\phi_{\rm p}$ resulting in the phase differences $\Delta\phi = 62°$ (HD 179949) and $\Delta\phi = 171°$ (υ And). Both agree well with the observations of increased stellar activity leading the subplanetary point by these angles.

As in the case of Jupiter and the Galilean satellites, the propagation of the perturbation is related to a field-aligned current system. As shown by Preusse et al. (2006), such a current system can only develop if the hot Jupiter is located within the Alfvén radius. The orbits for both planets under consideration lie within the Alfvén radius around their host stars: The semi-major axis for HD 179949 b is 0.045 AU, the Alfvén radius for the model by Weber & Davis (1967) is 0.0878 AU, for υ And b the radii are 0.057 AU and 0.1497 AU, respectively (see also Gu et al. 2005, and references therein).

In order to illustrate that field-aligned current systems do form for planets within the Alfvén radius, but do not so outside the Alfvén radius, Fig. 5 shows magnetohydrodynamic numerical simulation results for the more or less academic case of two hot Jupiters on two different orbits in today's solar wind. For details of these simulations confer to Preusse et al. (2006). In the solar wind the slow magnetosonic point, the Alfvén point, and the fast magnetosonic point are located at 0.033, 0.0856 and 0.0864 AU, respectively. The hot Jupiter shown in the left panel is located at 0.025 AU, i.e. within the Alfvén radius, the planet in the right panel has its orbit at 0.15 AU, i.e. beyond all three points. With other words: the Alfvén radius lies between the two panels. The Sun is located far to the left, outside of the figure. The distances are normalised to one planetary radius, taken as one Jupiter radius. The field-aligned current density, $j_\parallel = (\boldsymbol{j} \cdot \boldsymbol{B})/B$, is given in greyscale. For the planet located inside the Alfvén radius (left panel) one part of the current system is elongated towards the star. For the planet located outside of the Alfvén radius (right panel) the current system is directed downstream of the stellar wind and no connection to the star is possible. The first case, however, may indicate that the planet-induced perturbation is connected to a current system. As the two extrasolar planets considered in this paper both lie within the Alfvén radius, we can conclude that if such a current system is well-established between planet and star, this may be the source for the observable chromospheric activity as discussed e.g. by Gu et al. (2005).

4. Discussion

In this paper we present an interaction scenario between a hot Jupiter and its central star based on the propagation of Alfvén waves along the characteristics. Background for this research is the apparent similarity between hot Jupiters and their stars and Io and Jupiter in terms of the relative distance expressed in radii of the larger component of the systems. The similarity may even go further as the hot Jupiter may be located within a sub-Alfvénic stellar wind regime (Preusse et al. 2005) as are Io and the three other Galilean satellites in Jupiter's magnetosphere.

Io and Jupiter are linked by a current system, which is established by Alfvén waves (see e.g. Neubauer 1980). Connected to this are observable phenomena like radio emissions, which are produced in the flux tubes between them and a bright footpoint in the Jovian aurora. The latter can also be observed for the other Galilean satellites. Concerning hot Jupiters and their stars, observations by Shkolnik et al. (2003) and Shkolnik et al. (2005) indicate the existence of an area with enhanced chromospheric activity on the stars HD 179949 and υ And. Both stars possess hot Jupiters in distances of 0.045 AU and 0.0597 AU, respectively. Shkolnik et al. (2003) and Shkolnik et al. (2005) interpret these observations as evidence of some kind of magnetic interaction between the hot Jupiters and their central stars. This goes in hand with the theoretical predictions by Cuntz et al. (2000) and Cuntz & Shkolnik (2002).

In order to achieve a further step on the way to a better understanding of the interaction between the hot Jupiters and their central stars, we try to reproduce the observed phase angles between the chromospheric hot spots and the sub-planetary points of 60° for HD 179949 and 169° for υ And. Our model adopts the Alfvén wing model by Neubauer (1980). The planet is a conductor moving relatively to the stellar wind plasma and, thus, generates perturbations. These propagate towards the star where they can trigger the chromospheric hot spots (Gu et al. 2005).

The phase angle is a result of the propagation of the perturbation along the Alfvén characteristic, $\boldsymbol{c}_{\mathrm{A}}^{-}$, on the one hand and the orbital motion of the planet during this propagation on the other hand. Such a model is able to reproduce the observed phase angles both for HD 179949 and υ And. A crucial point is the fact that we consider the planet-induced perturbation to propagate along the Alfvén characteristic instead along the magnetic field (Herbert 1985) with which such large phase were impossible to reproduce. The direction of the characteristics, cf. Eq. (1), is also determined by the relative motion between the stellar wind and the orbital motion of the planet. This is particular important near the stellar surface, where the wind is slow, so that the azimuthal component of the relative velocity becomes important. We must, of course, admit that we benefit from the fact that the knowledge of the stellar parameters needed for our fit, in particular the magnetic field and the temperature of the corona, which could be somewhat underestimated, is very limited. Nevertheless, the results demonstrate that the basic idea indeed works.

Moreover, it should be noted that we used a simple stellar wind model, so that the phase shift in latitudinal direction (about 30° for HD 179949, cf. Shkolnik et al. 2003) cannot be reproduced. Here, more realistic models, which also take into account for a dipolar part of the stellar magnetic field (Banaszkiewicz et al. 1998; McIvor et al. 2006), should represent a next step. With a more elaborated model it might even be possible to use the observed phase shifts in order to estimate the coronal temperature and the magnetic field, which are very difficult to measure.

To obtain a better idea about the actual existence of such current systems, we supplemented our considerations by numerical MHD simulations of the stellar wind interaction with a planetary magnetosphere. For illustration we considered the today's solar wind in which wet put two hypothetical hot Jupiters: one of them is located inside the Alfvén radius, the other one outside the Alfvén radius. The simulation results show different structures of the field-aligned currents: For the planet located within the Alfvén radius one part of the current system appears to be connected to the star whereas for the planet outside the Alfvén radius the complete structure of the current system is bent into the direction of the stellar wind flow, so that no connection between planet and star can be established. Since both planets, HD 179949 b as well as υ And b, lie within the Alfvén radius, such a magnetic connection is possible.

The results summarised above support the idea of the similarity between Io and Jupiter and hot Jupiters and their stars. The latter may be connected by a current system, which is established by Alfvén waves, if the planet is located within the Alfvén radius. This is of course a necessary condition as otherwise Alfvén waves can not travel upstream towards the star without being carried away by the stellar wind. From this similarity between the rather different systems under consideration we may ask the question whether such a current system may be responsible for the enhanced chromospheric activity as observed by Shkolnik et al. (2003). This enhanced activity evolves around the star with the same period, but phase-shifted, as that of the hot Jupiter. This again puts in mind Io and Jupiter with the bright footpoint of Io's flux tube in the Jovian aurora. Indeed, we can create a stellar wind model such that the conditions set by the observed phase angles can be met. Let's assume this model as a possible explanation for the observations. Shkolnik et al. (2005) have a similar idea and interpret their observations as an indirect hint to a planetary magnetic field. Here, we would like to point out that the Alfvén wing model does not require the existence of an intrinsic magnetic field, but nevertheless also works if the planet possesses a dipole field. In fact, it is already sufficient that the planet is a conducting body, e.g. by a metallic (hydrogen for a hot Jupiter) core and/or a sub-surface ocean as for the Galilean satellites or even by a conducting atmosphere as in the case of Io. For the hot Jupiters the existence of a sub-surface ocean is unlikely. The few measurements allowing to derive a density indicate that they are gaseous bodies. Two sources of conductivity remain: an ionised atmosphere and a metallic hydrogen core. If the conductivity is due to an ionised atmosphere according to our results, the observed chromospheric enhancement cannot be necessarily interpreted as an indication for a planetary magnetic field as is done by Shkolnik et al. (2003). If the conductivity is due to a metallic hydrogen core its existence necessitates a rotating gas giant with an intrinsic planetary magnetic field. In this case the planetary magnetic field may not be directly causing the observed enhancement, but the necessary conductivity of the planet as predicted by the model does so. Hence, the observations together with the conductive model imply, though indirectly, a planetary field. We, thus, conclude that hot Jupiters triggering chromospheric activity enhancements will probably possess a dipole field, but this cannot be concluded from the observations alone.

What is the advantage of the Alfvén wing model? If we trace back the stellar wind magnetic field lines from the planet to the star, we will find quite small angles between their footpoints and the line connecting planet and star. In this case it is rather impossible to create a reasonable stellar wind model that leads to the observed phase angles of 60° for HD 179949 or even 169°

for υ And. In the Alfvén wing model the propagation of the Alfvén waves with respect to the relative motion between planet and stellar wind is taken into account instead, so that the perturbation actually propagates along the Alfvén characteristics (Herbert 1985). Only the latter provide angles large enough to reproduce the observed phase angles.

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