

Models of Star-Planet Magnetic Interaction

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Abstract Magnetic interactions between a planet and its environment are known to lead to phenomena such as aurorae and shocks in the solar system. The large number of close-in exoplanets that were discovered triggered a renewed interest in magnetic interactions in star-planet systems. Multiple other magnetic effects were then unveiled, such as planet inflation or heating, planet migration, planetary material escape, and even modification of the host star properties. We review here the recent efforts in modelling and understanding magnetic interactions between stars and planets in the context of compact systems. We first provide simple estimates of the effects of magnetic interactions and then detail analytical and numerical models for different representative scenarios. We finally lay out a series of future developments that are needed today to better understand and constrain these fascinating interactions.

Introduction

Stars and planet interact mainly through gravitation, magnetic fields and radiation. In this review we will focus on star-planet magnetic interaction (SPMI) for close-in planets around cool stars. By close-in planet we mean here planets that are sufficiently close to their star to orbit in a region where the wind of the star is in a sub-alfvénic regime (*i.e.* the local speed of the wind is smaller than the local Alfvén speed). Tidal and radiative interactions will be covered in other chapters of this book.

Numerous intriguing observations related to close-in systems have been reported with the advent of modern space telescopes and ground-based instruments

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(SPITZER, CoRoT, Kepler/K2, HARPS, HIRES, SPHERE, ...). To mention a few, these observations report anomalous chromospheric activity in close-in planet hosting stars (Shkolnik et al 2008; Poppenhaeger and Wolk 2014), a lack of X-ray emission in WASP-12 (Fossati et al 2013) and WASP-18 (Pillitteri et al 2014), possible bow shock absorption in the UV for HD 189733 (Llama et al 2013; Cauley et al 2015; Turner et al 2016b), a dearth of close-in planets around fast rotating stars (Pont 2009; McQuillan et al 2013; Lanza and Shkolnik 2014), and much more (*see, e.g.* Miller et al 2015; Figueira et al 2016; Staab et al 2017; Mengel et al 2016). Magnetic interactions are today a serious candidate to explain these fascinating phenomena.

We concentrate here on the effects of magnetic interactions and present the recent theoretical efforts for modelling them. We first review the main awaited effects of SPMIs and give an order of magnitude estimate for each of them. Then, we distinguish the cases of un-magnetized and magnetized planets and successively review analytical and numerical modelling efforts for each case. We conclude by listing the model improvements that are needed today for our understanding of SPMIs, and for helping the interpretation of future exoplanetary systems observations.

General characteristics of star-planet magnetic interactions

In this section we will describe the main possible impacts of star-planet magnetic interactions in distant exoplanetary systems, which are summarized in Figure 1. Detailed models of SPMI will be discussed in subsequent sections.

Main effects of star-planet magnetic interactions

Solar-type stars are thought to generate their large-scale magnetic field (Donati and Landstreet 2009) through dynamo processes in their convection zone (Brun et al 2015a,b). This magnetic field shapes the environment in which close-in planets orbit. Magnetic interactions then develop due to the orbital motion, as long as the planet is composed –at least in part– of ionized material. Multiple effects can occur due to the magnetic interaction, which we list hereafter. It is nevertheless important to realize that SPMIs are generally time-dependent and susceptible to intermittency, since close-in planets encounter inhomogeneous environments along their orbit.

1. Magneto-hydrodynamic shock The relative motion $\mathbf{v}_o = \mathbf{v}_K - \mathbf{v}_w$ between the ambient plasma (\mathbf{v}_w) and the orbiting planet (keplerian velocity \mathbf{v}_K) can be super-Alfvénic due to the proximity of the planet to its host. Under the assumption of a circularized orbit, the Keplerian velocity of the planet can be approximated by $v_K \simeq \sqrt{GM_\star/R_{\text{orb}}}$ (where R_{orb} is the orbital radius). Close to the star the wind speed in the orbital direction is likely to be rotationally constrained by the rotating host, and may be written $v_w \simeq R_{\text{orb}}\Omega_\star$ (Ω_\star is the stellar rotation rate). The coronal density can be

Main effects of star-planet magnetic interaction

1. MHD shock
2. Energy channeling
3. Planet migration
4. Planet heating
5. Planet emissions
6. Atmospheric escape

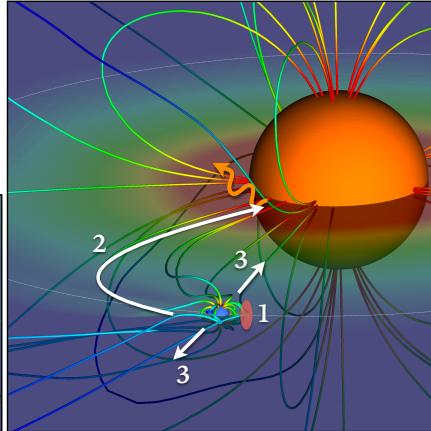
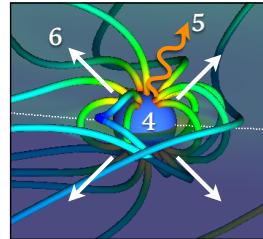


Fig. 1 Summary of the main effects of star-planet magnetic interactions discussed in this review. The illustrating image is based on a model published in Strugarek et al (2015) and shows a close-in planet (small blue sphere) around its host (orange sphere). The magnetic field lines are colored according to the magnetic field strength, and the transparent coloured plane shows the plasma density.

supposed to decrease with orbital distance as a power-law, *i.e.* $\rho \simeq \rho_*(R/R_*)^{-\alpha}$. The decrease of the coronal density is not well constrained by models or observations today, here to simplify the discussion we will crudely assume $\alpha = 8$, which is a fair approximation to density profiles obtained in standard 3D stellar wind models very close to the star. Assuming a dipolar field for the stellar magnetic field (for the sake of simplicity, defined by a stellar Alfvén speed v_{A*} at the base of its corona), the shock condition $v_o > v_A$ can be written as

$$R_{\text{orb}} < R_{\text{crit}} = R_* (f + v)^{-1/2}, \quad (1)$$

where R_{orb} is the orbital radius, $f = R_* \Omega_* (GM_*/R_*)^{-1/2}$ is the keplerian-normalized measure of the stellar rotation rate and $v = v_{A*} (GM_*/R_*)^{-1/2}$ a normalized measure of the stellar magnetic field. If the star rotates rapidly (large f) or possesses a strong magnetic field (large v), a close-in planet will likely not possess a bow-shock. For the particular case of the Sun, we expect $f_\odot \simeq 6 \times 10^{-4}$ and $v_\odot \simeq 0.1 - 10$, which gives a critical radius between 0.3 and 3 solar radii. Hence, only an extremely close-in planet ($R_{\text{orb}} < 3R_\odot$) could in principle develop a bow-shock in the sub-alfvénic region of a solar-like wind. As the orbital radius increases, the various approximations used to derive Equation 1 become invalid and the orbital radius eventually crosses the Alfvén surface of the stellar wind, where a shock will (almost) systematically develop.

One of the most interesting aspect of the development of a shock in close-in systems is the possibility (at least in theory) to actually observe its trace for transiting planets. This idea was recently put forward by Llama et al (2013); Cauley et al (2015) in the context of the HD 189733 system (see Figure 2). At the nose of the shock, material accumulation can cause a localized high density region. Prior to a transit, such a shock could in principle lead to an excess absorption of the stellar luminosity in several wavelengths (typically in the visible and near-UV spectra). They find that the shock position deduced from the pre-transit absorption suggests a planetary magnetic field strength of about 28 G (approximately 7 times larger than Jupiter's magnetic field). Even though many assumptions were made to deduce this value (see also Turner et al 2016a), pre-transit absorption observations remain a promising technique for the difficult task of constraining exoplanetary magnetic fields.

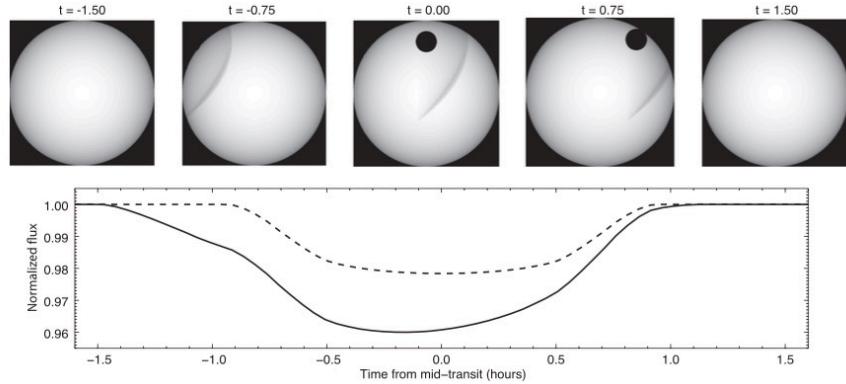


Fig. 2 Shock model during the transit of H189733b. The shock front affects the transit (bottom panel, solid line) compared to the case with no shock (dashed line). Figure adapted from Llama et al (2013).

2. Magnetic energy channeling A close-in planet can be viewed as a perturber orbiting in the likely non-axisymmetric inter-planetary medium. The perturbations will take the form of magneto-sonic waves, travelling away from the planet location in the $(\mathbf{v}_o, \mathbf{B}_w)$ plane (where \mathbf{B}_w is the interplanetary magnetic field). The degeneracy of the group velocity of the standard Alfvén waves (the group velocity is independant of the perturbation direction) allows for the focused propagation of waves packets along the Alfvén characteristics. This results in a net Poynting flux channeled away from the planet, along what is often referred to as *Alfvén wings*. One may do a back of the envelope calculation to estimate the travel time of Alfvén waves between the planet and the star. Alfvénic perturbations can travel back and forth the star and the planet if

$$\left| \frac{f - (R_{\text{orb}}/R_{\star})^{-3/2}}{(R_{\parallel}/R_{\star})(R_{\text{orb}}/R_{\star})^{-5}(v/2I_E)} \right| < 1, \quad (2)$$

where R_{\parallel} is the obstacle size along \mathbf{v}_0 , I_E is a geometric integral along the magnetic field lines, and we have assumed a classical alfvénic profile of a Weber and Davis-like solar wind (see previous paragraph). Using a solar-twin as an example, it appears that unless the magnetosphere of the planet is very large (typically of the order of the Sun itself), the perturbations triggered by the planet do not have time to travel back and forth between the planet and the star. This situation corresponds to the so-called *pure Alfvén wing* case (Neubauer 1998). Other scenarii can be realized, depending on the propagation time of these waves, the interested reader may find a detailed analytical description of them in Saur (2017). Nevertheless, in all cases the energy flux carried by the waves propagates in the $(\mathbf{v}_o, \mathbf{B}_w)$ plane in the form of two wings. Depending on \mathbf{v}_o and \mathbf{B}_w , both wings can connect onto host star; only one may while the other extends away from the star towards the interplanetary medium; or both may head away from the host star. As a result, the knowledge of the magnetic configuration in between the host star and the orbital path of the planet is mandatory to assess how much energy can actually be channeled (and where exactly) onto the host.

The idea of observable traces of this energy flux in exoplanetary systems traces back to early 2000's (*e.g.* Cuntz et al 2000; Rubenstein and Schaefer 2000) through the form of stellar activity enhancement at the impact point of the energy flux (see Figure 3). Since then a handful of detections of anomalous activity correlated with the planet orbital period were reported (see *e.g.* Shkolnik et al 2008). It is nonetheless important to realize that the impact point of the Poynting flux on the stellar chromosphere is determined by both \mathbf{v}_o **and** \mathbf{B}_w . If the stellar magnetic field is an inclined dipole, for instance, the impact point will at first order circulate around the magnetic pole of the star as the planet orbits around its host, and the enhanced emissions associated with the SPMI will be correlated with the stellar rotation rather than the orbital period. Conversely, if the stellar magnetic field is a dipole perfectly perpendicular to the orbital plane, the enhanced emissions will be correlated with the orbital period.

3. Planet migration and host star spin up/down The planet (with its magnetosphere, if any) can be viewed as an obstacle in a flow and consequently suffers a drag force from the ambient medium. The angular momentum lost by the planet will generally be exchanged with its host, spinning up/down the central star. Because the interplanetary medium is magnetized and the planet may possess a magnetosphere, the drag force felt by the planet depends as well on the magnetic topology of the interaction (these aspects will be detailed in the next sections). The direction of the angular momentum exchange can then be estimated by an order of magnitude calculation similar to Equation (1). The planet will migrate outwards only if

$$R_{\star}f^{-2/3} < R_{\text{orb}} < R_A, \quad (3)$$

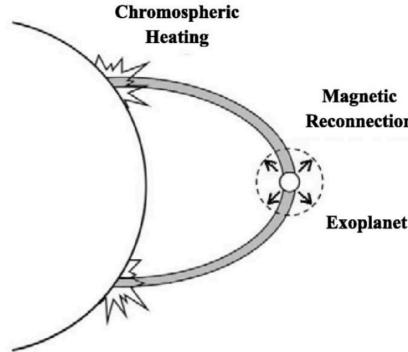


Fig. 3 Cartoon of the energy channeling due to the SPMI, from the pioneering modelling work of Ip et al (2004). Reproduced with the permission of AAS.

where R_A is the Alfvén radius on the orbital plane. Again using the Sun as an example, we find that the orbital radius has to be at the same time larger than 140 solar radii and smaller than $R_A \simeq 15R_\odot$, which of course cannot be realized. Hence, close-in planets orbiting solar twins will systematically lose their orbital angular momentum due to SPMI and inexorably fall onto their host if no other physical process sets in. Only planets around very fast rotators may experience outward migration due to SPMIs.

The strength of the magnetic torque \mathcal{T} felt by the planet is directly controlled by both the large-scale magnetic field of the star, and the size of the obstacle composed of the planet and its magnetosphere. It can be generically written as

$$\mathcal{T} = c_d R_{\text{orb}} A_{\text{eff}} P_t, \quad (4)$$

where c_d is a drag coefficient which represents the efficiency of the magnetic coupling, P_t is the total pressure of the ambient plasma impacting the planetary obstacle (generally, P_t will be dominated by the magnetic pressure in the stellar wind for close-in systems, see *e.g.* Strugarek 2016), A_{eff} the effective area of the planetary obstacle, and as a result $R_{\text{orb}} A_{\text{eff}} P_t$ is the amount of angular momentum that can be transferred to/from the planet orbital motion, with an efficiency parameter c_d . For T Tauri stars with typical magnetic fields of the order of 10^4 G, the migration time-scale associated with the torque \mathcal{T} can be of the order of 100 Myr (Strugarek et al 2015). As a result, magnetic torques have to be taken into account to explain the observed population of close-in planets with respect to the rotation period of their host (*e.g.* Pont 2009; McQuillan et al 2013; Lanza and Shkolnik 2014; Damiani and Lanza 2015, see Figure 4).

4. Planet heating In the case where the interplanetary field is able to permeate into at least a part of the planet, ohmic dissipation inside the planetary body may lead to a substantial heating (*e.g.* Laine et al 2008; Laine and Lin 2012). Such a dissipation could in theory lead to planet inflation, possibly result in a planetary mass loss due

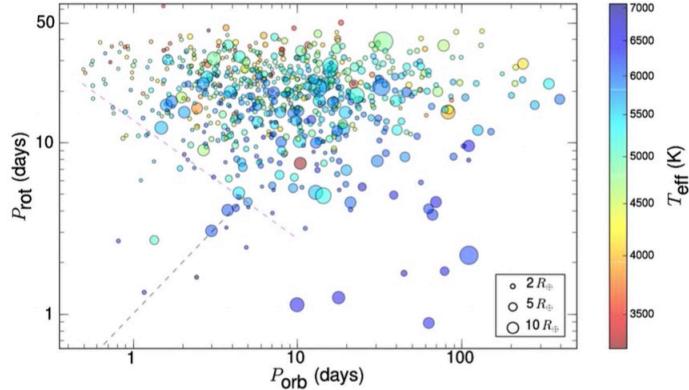


Fig. 4 Distribution of known exoplanets as a function of orbital period and rotation period of their host. The dearth of exoplanets nearby fast rotators clearly appears in the bottom left corner of the picture. Adapted from McQuillan et al (2013). Reproduced with the permission of AAS.

to Roche lobe overflow, or even molecular dissociation. This effect, though, directly depends on the resistivity profile inside the planet, which is very poorly constrained for close-in objects as of today.

5. Extreme events, aurorae and planetary emissions A by-product of the magnetic interaction is also the possibility of emissions inside the planetary magnetosphere, alike aurorae on Earth. These aurorae can be multi-wavelength signals, and are expected to be particularly intense in the radio domain (*e.g.* Zarka 2007; Grießmeier et al 2007). They can be sustained due to the continuous interaction of the planet with the ambient wind, or due to particular extreme eruptive events triggered in the stellar lower corona and impacting the exoplanet. It is fairly unlikely that we will be able anytime soon to capture the signature of the latter case, hence researchers have focused on characterizing the continuous radio emission expected from the SPMI (see Zarka 2017).

6. Atmospheric escape The stellar irradiation of the planet outer layers can lead to a substantial outflow (Tremblin and Chiang 2013; Matsakos et al 2015; Khodachenko et al 2015) and leave observable signatures for a distant observer. This phenomenon is not directly related to magnetic interactions, but magnetic fields can mediate and alter these outflows when the gas composing it is significantly ionized (Adams 2011). Hence, we simply mention this effect here and defer the reader to Barman (2017) for in-depth discussion of this phenomenon.

Stellar wind and star-planet magnetic interactions

We saw that most of the effects of the SPMIs heavily depend on the plasma conditions in the stellar wind at the orbital position as well as on the path in between the star and the planet. As a result, stellar wind models can be used on their own to infer valuable informations about SPMIs.

Early work on Alfvén wings in exoplanetary systems were carried out by Preusse et al (2005, 2006), where they used a Weber-Davis stellar wind model (Weber and Davis 1967) to estimate the amount of energy that could be channeled by the magnetic interaction for a planet-size obstacle. This estimation was recently revisited by Saur et al (2013) with many more exoplanets and a more sophisticated Alfvén wings model. Strong planet migration due to magnetic torques around T Tauri stars (Lovelace et al 2008) and proto-stars (Bouvier and Cébron 2015) were also assessed using similar stellar wind models. Observed stellar magnetic fields (see *e.g.* Donati and Landstreet 2009) allow to model more realistically stellar winds, and as a result provide more quantitative estimates of SPMIs (for more details see Vidotto 2017, Moutou et al 2017, Figure 5, and Vidotto et al 2014; Cohen et al 2014; Llama et al 2013; Strugarek et al 2014d; Alvarado-Gómez et al 2016a,b).

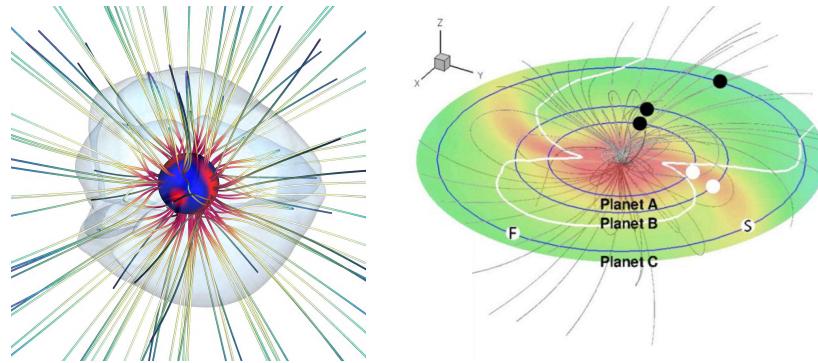


Fig. 5 Stellar wind models of HD 189733 (left, see Strugarek et al 2014d) and EV Lac (right, adapted from Cohen et al 2014) based on the spectropolarimetric reconstructions of their large scale magnetic field. Reproduced with the permission of AAs.

In all these studies, simplified models of the interaction with the planet are assumed (either analytical models, or localized simulations at particular orbital phases using the plasma conditions from the wind model as in Cohen et al 2014; Alvarado-Gómez et al 2016b). We will see in the following sections that ultimately, both a realistic stellar wind and a realistic model of the star-wind-planet coupling need to be considered to quantitatively model the effects of SPMIs.

Planet properties and star-planet magnetic interactions

The magnetic properties of the orbiting planet also change qualitatively the SPMI (as one would expect), and two families of interaction can be identified (following, *e.g.* Zarka 2007):

- **Unipolar interaction:** weakly/not magnetized planet in a magnetized wind
- **Dipolar interaction:** magnetized planet in a magnetized wind

One important distinction between the two families lies in the possibility of magnetic reconnections in the case of dipolar interaction, whereas in the case of unipolar interaction the stellar wind magnetic field generally permeates into some parts of the planet without necessarily reconnecting. Whether or not a close-in planet is able to sustain its own magnetosphere is out of the scope of this review (see Stanley and Glatzmaier 2010; Jones 2011). We will discuss various modelling efforts of the two interaction types in the next section, we now focus on giving a general overview of them.

Unipolar interaction The unipolar interaction occurs when the magnetic field of the planet can be neglected compared to the stellar wind magnetic field. Several cases of unipolar interaction need to be distinguished (upper panels in Figure 6), depending on the ionization and the resistivity of the planet material (Laine et al 2008; Laine and Lin 2012). If the planet material is not or weakly ionized, the magnetic field inside the planet is only subject to ohmic dissipation and two extreme cases are identified: if the resistivity inside the planet sufficiently high, the stellar wind magnetic field penetrates only on a small skin depth inside the planet, while in the opposite case the magnetic diffusivity is low and the wind magnetic field permeates into the whole planetary volume (Laine et al 2008). If the planet material is ionized, induction can occur inside the planet and the situation is slightly more complex: different regimes of the interaction occur depending on the ratio between the advection across the planetary obstacle and the ohmic dissipation time-scale inside the planet. In this latter case, the extreme situations are realized when the planet is able to completely drag the magnetic field lines along its orbital motion (similar to a *frozen-in* situation of ideal MHD, see also Laine and Lin 2012; Strugarek et al 2014c), and when the planet effectively screens the surrounding wind magnetic field, leaving a magnetic cavity in the planetary interior. It must be noted that in reality, more complicated situations occur with strong anisotropies in the conductive properties of the planet material, due to *e.g.* day-night asymmetries that are likely realized in tidally-locked states for close-in exoplanets.

Dipolar interaction In the dipolar case the interaction occurs between the stellar wind magnetic field and the planetary magnetosphere. Here the critical parameter of the interaction is the topology of the interaction (three topologies are illustrated in the lower panels of Figure 6) that determines the location of the reconnection sites between the two fields (we assume for the discussion here that there is no shock at the nose of the magnetosphere). If the planetary field is locally aligned with the stellar wind field, reconnections occur on the (magnetic) equatorial plane

and the polar field lines are directly connected to the stellar wind. This is the so-called *open magnetosphere* case, where only a small volume of closed planetary field lines exists around the equatorial plane. In the anti-aligned configuration, the *closed magnetosphere* case is realized and the reconnection sites are located near the polar caps of the planetary magnetosphere. We immediately see here that the size of the interacting obstacle drastically changes with such a change of topology, and consequently we expect the strength of the SPMIs to strongly vary with the topology of the interaction (we will quantify these aspects in the next sections).

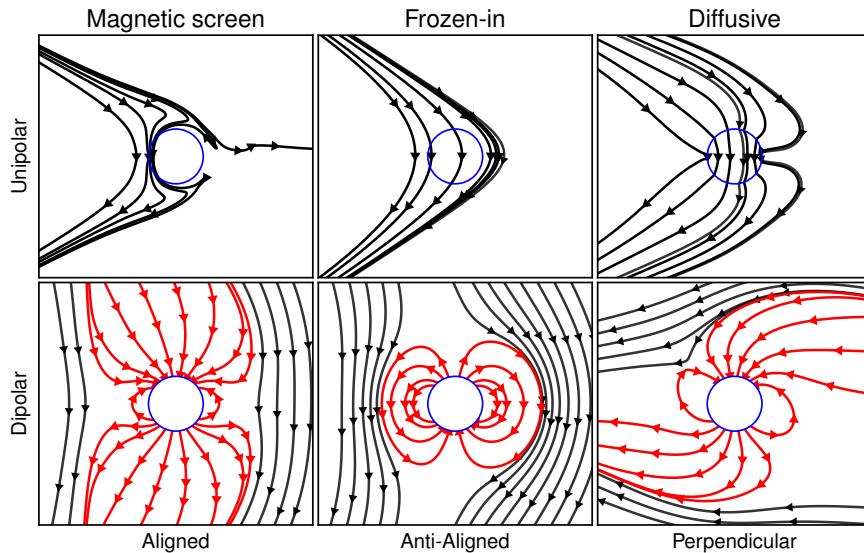


Fig. 6 Magnetic interaction for different topologies. The planet is indicated in blue, the wind magnetic field lines in black. The upper row shows three cases of the unipolar interaction scenario (magnetic screening, magnetic field drag by the orbiting planet, ohmic dissipation inside the planetary body), and the lower row three cases of the dipolar interaction scenario (aligned configuration, anti-aligned configuration –closed magnetosphere–, perpendicular configuration). In the dipolar configuration the magnetic field lines connected to the planetary field are shown in red. The magnetic configurations were taken from numerical models published in Strugarek et al (2014c, 2015).

Connection to planet-satellite interactions

SPMIs bear strong similarities with the interaction of a natural satellite with its hosting planet magnetosphere. As a result, most of the concepts presented in this review take their roots in pioneering studies of Io, Ganymede, and other jovian and cronian moons (see Figure 7). The main difference here is that close-in planets orbit in a more dynamical medium, the stellar wind, and are exposed to extreme eruptive

events triggered by the stellar magnetism. A more in depth parallel between close-in star-planet systems and satellite-planet systems may be found in Neubauer (1998); Zarka (2007); Saur et al (2013).

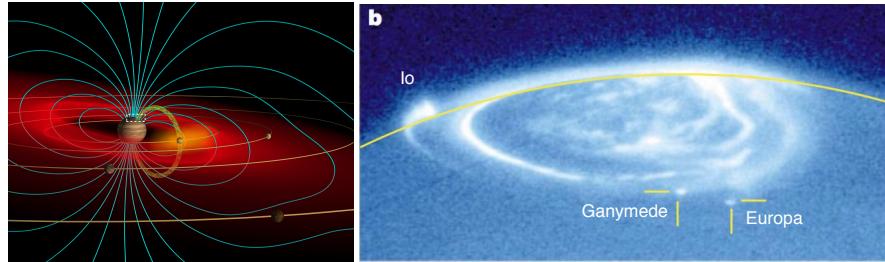


Fig. 7 *Left* Artist image of the jovian system, where the Io torus can be seen in red/orange and the magnetic connection to Jupiter is traced by the green tube. Adapted from a rendering from J. Spencer <http://www.boulder.swri.edu/%7Espencer/digipics.html>. *Right* Aurora at the pole of Jupiter triggered by the magnetic interactions with the Jovian satellites in the magnetosphere (adapted from Clarke et al 2002). Reproduced with the permission of AAS.

Models of the various cases of star-planet magnetic interactions

We now detail recent efforts in modelling SPMIs in close-in star-planet systems. We discuss successively the unipolar and dipolar interaction cases.

The unipolar interaction case

Analytical considerations

The unipolar interaction case has been analytically studied in an extensive work published in Laine et al (2008); Laine and Lin (2012). In their model, an analogy is drawn between the current circuit that develops in SPMIs and a standard electric circuit (see Figure 8) composed of four resistances (planet, interplanetary medium, star, interplanetary medium) for each Alfvén wing, and a generator (the planet differential motion with the ambient wind). The model is considered to be valid as long as the circuit is closed, which the authors choose to close at the stellar surface (note that the circuit could close along the path of the wing due to the reflection of the waves inside the Alfvén wings themselves, see *e.g.* Neubauer 1998). It means that the following expressions are valid as long as the Alfvén waves have the time to travel back and forth between the planet and the star while the planet continues its orbital motion. We saw in the previous sections that this was likely not the case

for solar twins. In the context of TTauri stars on which the authors focused, the stellar field (and the Alfvén speed) is orders of magnitude larger, which ensures this condition (Equation 2) can be easily satisfied. Based on the electric circuit analogy, it was shown that the total torque applied to such close-in planets in the unipolar interaction case could be written

$$\mathcal{T} \propto R_{\text{orb}}^4 (\omega_p - \omega_*) \quad (5)$$

where ω_p is the orbital frequency and ω_* the rotation frequency of the star (we simplified the original expression of Laine and Lin 2012 for a circular orbit). This estimate gives a migration time-scale

$$\tau_p = \frac{J_p}{2\mathcal{T}} \propto R_{\text{orb}}^6, \quad (6)$$

where $J_p = M_p (GM_* R_{\text{orb}})^{1/2}$ is the orbital angular momentum of the planet.

Using this unipolar model, it is then straightforward to show that close-in planets under orbital periods of about three days migrate due to the SPMI on a time-scale of the order of a few million years when the hosting star is a standard TTauri star. We remind the reader here that these estimates rely on several debatable hypotheses, among which the internal resistivity profile of the planet, that enters the proportionality factor in Eq. 5, is highly uncertain today.

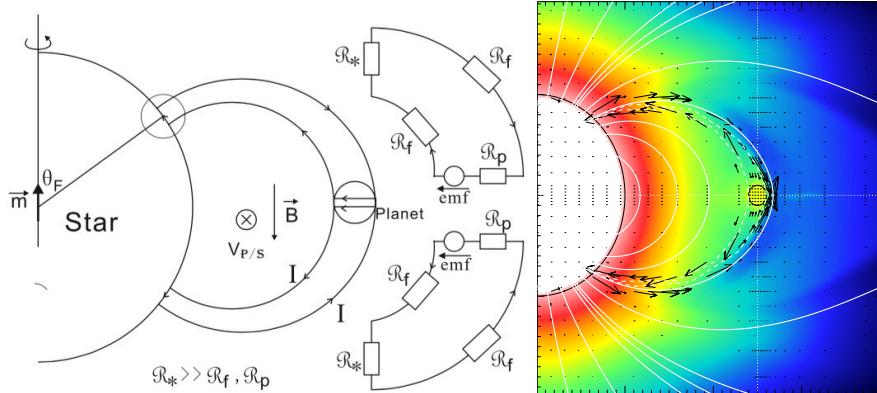


Fig. 8 *Left.* Schematics of the unipolar inductor model, adapted from Laine and Lin (2012). The star-planet system is approximated by an electric circuit composed of an electro-motive force (from the orbital motion of the planet) and several resistances (the planet, the stellar wind, the stellar surface). In this model, it is assumed that the alfvénic perturbations are fast enough to travel back and forth between the planet and the star. *Right.* Numerical simulation of the unipolar inductor model from Strugarek et al (2012, 2014c). The current system that self-consistently develops is shown by the black arrows, the magnetic field lines are shown in white, and the logarithmic colormap traces the plasma density.

Numerical models

Very few numerical studies of the unipolar interaction case have been carried out as of today. One notable exception was the work published in Strugarek et al (2014c) using a reduced 2.5D (axisymmetric) geometry (see Figure 8). In this model, the planet was considered to be fully ionized and as a result was able to drag the stellar wind magnetic field along its orbit. By varying the magnetic diffusivity inside the planet, Strugarek et al (2014a) showed various cases of unipolar interaction (see also Figure 6) from the creation of a magnetic cavity when an ionospheric layer exists in the planet atmosphere, to cases where the stellar wind magnetic field is either primarily dragged or dissipated by the planet (similar to the case modelled with the analytical approach presented in the previous section).

The former case was extensively characterized in Strugarek et al (2014c) in a parameter space exploration by varying the orbital radius of the close-in planet. The magnetic torque applied to the planet was systematically assessed, and the associated migration time-scale was found to be proportional to $R_{\text{orb}}^{5.5}$. In spite of the geometry approximation embedded in the numerical model, these results compare well with the analytical estimations giving $\tau_P \propto R_{\text{orb}}^6$ (Equation 4). Three-dimensional simulations are now required to further refine the parametrization of the magnetic torque in the unipolar case. Such simulations would also help to better characterize the other unipolar interaction cases that have not today been satisfactorily modelled (see above). They are notably needed to assess how the current system that systematically develops can be closed in either the wind itself or in the stellar (sub-)surface layers.

The dipolar interaction case

The dipolar interaction bears some resemblance with the Earth-solar wind interaction, and as a result has received more attention so far. Once again, we detail first the analytical approaches to model this case, and then report on recent numerical developments.

Analytical considerations

Two main analytical approaches have been followed in the literature so far. In both models, the topology of the interaction (relative direction of the planetary field compared to the ambient stellar wind magnetic field) determines the strength of the interaction, with two extreme cases of aligned and anti-aligned configurations (see also bottom panels in Figure 6). These two models can be summarized as follows.

A description based on a magnetohydrostatic equilibrium, characterized by force-free magnetic fields, has been carried out by Lanza (2008, 2009, 2012, 2013). In this model, the orbital motion of the planet stresses the ambient field and the ex-

cess energy (compared to the planet-free, force-free field) is stored in the flux tube connecting the planet to the star. As dissipation sets in, a saturated steady state can be reached and the Poynting flux through the flux tube can be analytically shown to reach values of $10^{20} - 10^{21}$ W for close-in planets around typical solar-type stars (Lanza 2013, 2015).

The other family of models is based on the analogy with planet-satellite interactions and the concept of Alfvén wings. It is a more general class of models, as it does not suppose any particular configuration (*e.g.* potential) for the stellar wind magnetic field. The Alfvén wings current system has been clearly laid out in Saur et al (2013). They found that the Alfvén wing cross-section R_{aw} varies such that

$$R_{aw} \propto \sqrt{\cos\left(\frac{\Theta_M}{2}\right)}, \quad (7)$$

where Θ_M is the relative angle between the planetary (dipolar) magnetic field and the ambient stellar wind direction at the planet position. As a result, they found analytically that the Alfvén wings are vanishingly small in the anti-aligned configuration ($\Theta_M = \pi$), and are maximized in the aligned configuration ($\Theta_M = 0$). In the former case, in reality, some magnetic reconnection still occurs between the wind and the planetary magnetosphere, leading to very diminished Alfvén wings-like structure (see hereafter).

The energetics of the interaction were also shown to depend on the ratio between the Alfvén conductance Σ_A and the (integrated) Pedersen conductance of the ionosphere (Σ_P) through the coefficient (Neubauer 1998; Saur et al 1999)

$$\bar{\alpha} = \left(1 + 2 \frac{\Sigma_A}{\Sigma_P}\right)^{-2}, \quad (8)$$

knowing that within the Alfvén wing model the Alfvén conductance is defined (in Gaussian units) by

$$\Sigma_A = \frac{c^2 M_a}{4\pi v_o (1 + M_a^2 - 2M_a \cos \Theta)^{1/2}}, \quad (9)$$

where Θ is the angle between the relative speed \mathbf{v}_o and the wind magnetic field \mathbf{B}_w . The efficiency coefficient $\bar{\alpha}$ is maximized when the Pedersen conductance is large compared to the Alfvén conductance. For planets in close-in orbit around solar-type stars, Σ_A can reach values of a few 10^{12} cm/s (Strugarek 2016). Based on estimates from solar-system planets and moons, the Pedersen conductance is expected to be of the order of 10^{13} cm/s (see Figure 9 and Saur et al 2013). As of today, $\bar{\alpha}$ has thus been neglected in applications to close-in exoplanets. Finally, using their analytical Alfvén wing model and simple Parker-like wind solution, Saur *et al.* estimated the Poynting flux through the wings for the close-in exoplanets known in 2013. They found that the Poynting could vary from 10^{14} to a few 10^{19} W depending on the orbital distance. Nevertheless, no observational constraints were available to char-

acterize properly the wind of the planet-hosting stars, hence these estimates have to be taken with caution.

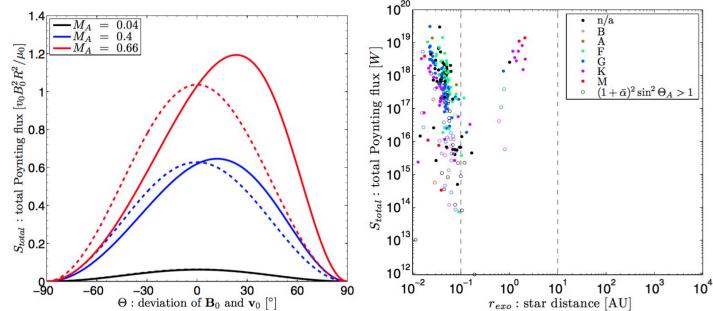


Fig. 9 *Left* Poynting flux as a function of topology (Θ) and Alfvén Mach number M_a . *Right* Estimate of the Alfvén wing Poynting flux for detected exoplanets (as of 2013). Both estimates are based on the analytical model of Saur et al (2013), from where the figures were adapted.

In real exoplanetary systems, the interaction state is likely to vary on short (inhomogeneities along the planetary orbit) and large (reversals of the stellar and/or planetary magnetic fields) time-scales. Large uncertainties on the stellar wind characteristics of the central star and large uncertainties on the ionospheric properties of the exoplanet (value of the efficiency parameter $\bar{\alpha}$) also make the quantitative estimates of SPMIs perilous. Numerical simulations can be used to tackle some of these aspects, which we now turn to.

Numerical models

Numerical models of star-planet interactions take their roots in the pioneering work of Ip et al (2004) who first simulated the local interaction of a close-in giant exoplanet with the ambient stellar wind plasma. Nevertheless, SPMIs depend on the plasma characteristics from the base of the stellar corona to the vicinity of the planet and on the planet magnetic configuration.

Global simulations were developed for the first time by Cohen et al (2009, 2010, 2011), in which advanced, solar-calibrated stellar wind simulations were adapted to include a close-in orbiting planet (treated as a boundary condition). In their later work, they introduced a boundary condition inside the simulation domain moving with time to follow the orbital path of the planet. These early simulations strikingly showed the natural time-variability one expects from SPMIs, as well as possibly very large lags between the orbital phase of the planet and the stellar subpoint where the magnetic interaction connects. Hybrid approaches for which the stellar wind and the planet vicinity are modelled separately for the same system have also been carried out by Kopp et al (2011); Cohen et al (2014, 2015); Alvarado-Gómez et al (2016a,b).

Building on the 2.5D approximation used in Strugarek et al (2014c), Strugarek et al (2015) also developed a global 3D model incorporating both the orbiting planet and the star, using as a first approach simple axisymmetric magnetic configurations (see top panels in Figure 10). A special effort was carried out to develop adequate boundary condition for both the star and the planet, which are critical to correctly quantify SPMIs. The stellar wind boundary condition consists in a three-layer boundary condition, ensuring accurate conservation properties throughout the simulated stellar wind (Zanni and Ferreira 2009; Strugarek et al 2014a,b). The boundary condition at the planet is defined by a buffer layer in which only the magnetic field of the planet is allowed to change, mimicking crudely a thick ionospheric layer (similarly to the approach developed in Jia et al 2009, in the context of Ganymede in the jovian system). More advanced planetary boundary conditions have been developed in the recent years. Duling et al (2014) developed a generic boundary condition for non-conductive planetary bodies, and showed that the choice of boundary condition for the planet has a drastic impact on the development of the magnetic interaction (see, *e.g.*, the change in the current system on their Fig. 3). Ultimately, the interaction of a planetary magnetosphere with the wind of its star could be modelled with a higher precision using a magnetosphere-ionosphere coupling boundary condition, as already developed for simulations of the magnetosphere of the Earth (*e.g.* Goodman 1995; Merkin and Lyon 2010).

The simple geometry used in Strugarek et al (2015) allowed a quantitative comparison between the numerically modelled Alfvén wings and the analytical work of Saur et al (2013). A good agreement was found between the two models, with Poynting fluxes of similar amplitude. In the 3D numerical model, the non-linear interaction between the orbiting planet and the star and its wind leads to a slightly more elongated Alfvén wing cross-section along \mathbf{v}_0 . The two opposite topologies of the dipolar interaction were also shown to lead to radically different properties of the magnetic interaction with this model, leading to at least an order of magnitude changes in magnetic torque and Poynting flux. For both aspects, these simulations helped realized how much the effective area of the interaction (or, if one prefers, the obstacle) significantly change with the topology. In the closed magnetosphere case (anti-aligned configuration), the magnetospheric size can be well approximated using the pressure ratio between the magnetospheric magnetic pressure on the planetary side, and the total (thermal plus magnetic plus *ram*) pressure on the stellar wind side of the interaction. Assuming a spherical magnetosphere composed of a dipole field, this leads to the well known expression

$$R_{\text{obst}} = R_P \Lambda_P^{1/6} = R_P \left(\frac{B_P^2}{8\pi P_t} \right)^{1/6}, \quad (10)$$

where the subscript P denotes values at the planetary surface and P_t is the total pressure of the stellar wind at the planetary orbit. This simple estimate nevertheless fails to describe the area of interaction in the aligned case (see Figure 10), as in this case the magnetic field lines connecting the planet and the wind that are part of the Alfvén wings act as well as an obstacle. As a result, the area of interaction is

far larger in the aligned case. In the extreme case where the travel time of alfvénic perturbations is short compared to the orbital period (see Eq. 2), the waves can propagate back and forth between the planet location and the stellar surface and the effective area of interaction is the full Alfvén wing from the planet location to the stellar surface (see also Fleck 2008). In general, though, the effective obstacle will be only composed of a subpart of the Alfvén wings (see Figure 5 in Strugarek 2016).

Relying on the good agreement between the numerical and analytical models, a parameter study using a self-consistent stellar wind model was undertaken in Strugarek (2016). By changing the orbital radius and magnetic field strength of the planet, empirical scaling laws have been derived from a large set of non-linear numerical simulations for the Poynting flux and magnetic torque associated with SPMI. They can be summarized as follows (see bottom panels in Figure 10 and Strugarek 2016)

$$\mathcal{T} \propto \left(c_d P_t M_a^\beta \right) \cdot (R_P^2 R_{\text{orb}}) \cdot (\Lambda_P^\alpha), \quad (11)$$

$$\mathcal{P} \propto \left(c_d S_w M_a^\xi \right) \cdot (R_P^2) \cdot (\Lambda_P^\chi). \quad (12)$$

We recall here that the coupling coefficient is defined as $c_d = (4\pi/c^2)\Sigma_A v_o$ and the wind Poynting flux is $S_w = v_o B_w^2 / (4\pi)$. The interested reader may find more detailed scaling laws in Strugarek (2016), including their dependency on the resistive properties of the plasma and of the modelled ionospheric layer. The exponents (α, β, ξ, χ) vary with the topology of the interaction and are given in Strugarek (2016). The various terms in Equations 11-12 have been rearranged in three blocks from left to right: terms that depend only on the star and its wind; only on the planet properties; and on a combination of both (Λ_P). As a result these scaling laws may help relate observed anomalous activity on distant stars (*e.g.* Shkolnik et al 2008) with the magnetic properties (strength, topology) of the close-in planet, provided the stellar wind and planetary radius can be inferred or constrained observationally.

Conclusions

The study of star-planet magnetic interactions is a young and promising field of research. In this review we have focused our discussion on the modelling efforts that have been undertaken by the community in the past decades, motivated by the many intriguing phenomena observed in exoplanetary systems. Rather than listing again the effects initiated by magnetic interactions, we list here several routes of improvement of the models that need to be followed in support of the future observation missions dedicated to the characterization of exoplanets and their magnetic properties:

- In the context of both the unipolar and dipolar interaction cases, more realistic models of the interior of planets and their magnetosphere are needed. For exam-

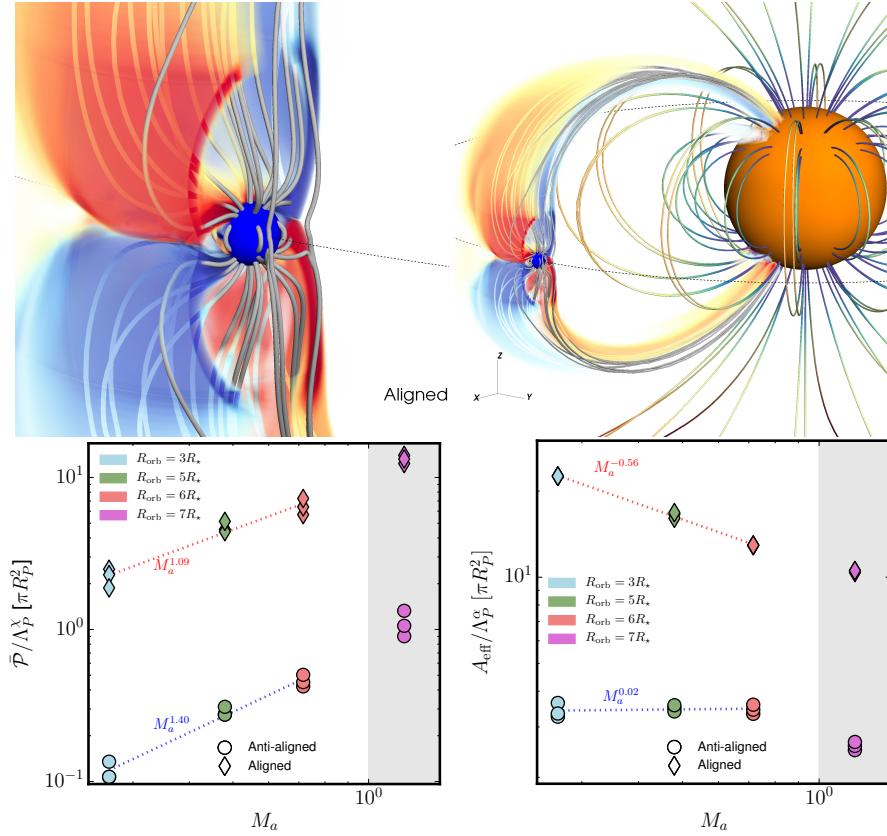


Fig. 10 Top panels 3D numerical model of Alfvén wings in the aligned configuration. The coloured volumes in blue/red trace the currents underlying the wings (the volume is cropped to make the planet apparent). The stellar magnetic field lines are colour-coded by the magnetic field strength, and the planetary field is shown by the grey tubes. Adapted from Strugarek et al (2015). Bottom panels Scaling-laws of the Poynting flux in one Alfvén wing (left) and of the torque applied to the planet (right) deduced from the numerical model of SPMIs of Strugarek et al (2015). Both are shown as a function of the alfvénic Mach number M_a . Adapted from Strugarek (2016). Reproduced with the permission of AAS.

ple, an accurate response of the magnetospheric system to the impacting stellar wind is needed to assess aurorae and possible planetary emissions, to assess the steady state of interaction and the energy conversion the interaction is able to operate, and to constrain the properties of the hypothetical bow-shock at the nose of the interaction. These improvements can be carried out as a first step *e.g.* by considering a magnetosphere-ionosphere coupling model in the case of the dipolar interaction, and more realistic planetary interior models in the context of the unipolar interaction. Ultimately, models including kinetic effects (beyond the standard magneto-hydrodynamic framework) will be needed for some of these aspects.

- For the sake of simplicity, models have so far generally considered circular planetary orbits. This is often justified as a reasonable approximation, as close-in planets are likely in a tidally-locked state. Tidal theory nevertheless predicts departures from this simple picture (Mathis 2017). As a result, eccentric orbits should be more systematically included in star-planet magnetic interaction models.
- With a growing sample of stars hosting close-in exoplanets for which spectropolarimetric observations are available, it is today possible to simulate realistic stellar winds of particular star-planet systems. Because of the variable nature of the magnetic interaction along the planetary orbit, it is essential to use these observational constraints to model close-in systems in order to assess the robustness of the simplified models, and quantitatively test our understanding of magnetic star-planet interactions.
- Last but not least, a significant effort has to be made to self-consistently compare magnetic effects with other physical mechanisms at stake in star-planet interactions. These include, but are not limited to, tides (torque, heating), radiation (ionization, atmospheric escape), and particle acceleration in the planetary magnetosphere (magnetic reconnection, instabilities).

We hope this review will arouse multiple interests on this promising and multi-disciplinary subject of research, and will encourage further efforts in developing models of SPMIs in all their complexity to provide critical insights for the future observations of (close-in) exoplanetary systems.

Cross-References

- Electromagnetic Coupling in Star-Planet Systems
- Magnetic Fields in Planet Hosting Stars
- Tides in Star-Planet systems
- Stellar Coronal and Wind Models: Impact on Exoplanets
- Star-Planet Interactions in the Radio Domain: Prospect for Their Detection
- Planetary Evaporation Through Evolution
- Signatures of Star-Planet Interactions
- Rotation of Planet-Harbouring Stars
- Dynamical Evolution of Planetary Systems
- Planetary Habitability and Magnetic Fields

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References

- Adams FC (2011) Magnetically Controlled Outflows from Hot Jupiters. *ApJ*730(1):27, DOI 10.1088/0004-637X/730/1/27
- Alvarado-Gómez JD, Hussain GAJ, Cohen O et al (2016a) Simulating the environment around planet-hosting stars. *A&A*588:A28, DOI 10.1051/0004-6361/201527832
- Alvarado-Gómez JD, Hussain GAJ, Cohen O et al (2016b) Simulating the environment around planet-hosting stars. II. Stellar winds and inner astrospheres. *A&A*594:A95, DOI 10.1051/0004-6361/201628988
- Barman T (2017) PPlanetary Evaporation Through Evolution. In: Deeg HJ Belmonte JA (eds) *The Exoplanet Handbook*, Springer
- Bouvier J Cébron D (2015) Protostellar spin-down: a planetary lift? *MNRAS*453(4):3720–3728, DOI 10.1093/mnras/stv1824
- Brun AS, Browning MK, Dikpati M, Hotta H Strugarek A (2015a) Recent Advances on Solar Global Magnetism and Variability. *Space Sci Rev*196(1):101–136, DOI 10.1007/s11214-013-0028-0
- Brun AS, Garcia RA, Houdek G, Nandy D Pinsonneault M (2015b) The Solar-Stellar Connection. *Space Sci Rev*196(1):303–356, DOI 10.1007/s11214-014-0117-8
- Cauley PW, Redfield S, Jensen AG et al (2015) Optical Hydrogen Absorption Consistent with a Thin Bow Shock Leading the Hot Jupiter Hd 189733b. *ApJ*810(1):13, DOI 10.1088/0004-637X/810/1/13
- Clarke JT, Ajello J, Ballester G et al (2002) Ultraviolet emissions from the magnetic footprints of Io, Ganymede and Europa on Jupiter. *Nature*415:997–1000
- Cohen O, Drake JJ, Kashyap VL et al (2009) Interactions of the Magnetospheres of Stars and Close-In Giant Planets. *ApJ*704:L85, DOI 10.1088/0004-637X/704/2/L85
- Cohen O, Drake JJ, Kashyap VL, Sokolov IV Gombosi TI (2010) The Impact of Hot Jupiters on the Spin-Down of Their Host Stars. *ApJ*723(1):L64–L67, DOI 10.1088/2041-8205/723/1/L64
- Cohen O, Kashyap VL, Drake JJ et al (2011) The Dynamics of Stellar Coronae Harboring Hot Jupiters. I. a Time-Dependent Magnetohydrodynamic Simulation of the Interplanetary Environment in the Hd 189733 Planetary System. *ApJ*733(1):67, DOI 10.1088/0004-637X/733/1/67
- Cohen O, Drake JJ, Glocer A et al (2014) Magnetospheric Structure and Atmospheric Joule Heating of Habitable Planets Orbiting M-dwarf Stars. *ApJ*790(1):57, DOI 10.1088/0004-637X/790/1/57
- Cohen O, Ma Y, Drake JJ et al (2015) The Interaction of Venus-like, M-dwarf Planets with the Stellar Wind of Their Host Star. *ApJ*806(1):41, DOI 10.1088/0004-637X/806/1/41
- Cuntz M, Saar SH Musielak ZE (2000) On Stellar Activity Enhancement Due to Interactions with Extrasolar Giant Planets. *ApJ*533(2):L151–L154, DOI 10.1086/312609
- Damiani C Lanza AF (2015) Evolution of angular-momentum-losing exoplanetary systems. Revisiting Darwin stability. *A&A*574:A39, DOI 10.1051/0004-6361/201424318
- Donati JF Landstreet JD (2009) Magnetic Fields of Nondegenerate Stars. *Annual Review of A&A* 47:333, DOI 10.1146/annurev-astro-082708-101833
- Duling S, Saur J Wicht J (2014) Consistent boundary conditions at nonconducting surfaces of planetary bodies: Applications in a new Ganymede MHD model. *J Geophys Res*119(6):4412–4440, DOI 10.1002/2013JA019554
- Figueira P, Santerne A, Suárez Mascareño A et al (2016) Is the activity level of HD 80606 influenced by its eccentric planet? *A&A*592:A143, DOI 10.1051/0004-6361/201628981
- Fleck RC (2008) A magnetic mechanism for halting inward protoplanet migration: I. Necessary conditions and angular momentum transfer timescales. *Ap&SS*313(4):351–356, DOI 10.1007/s10509-007-9703-5
- Fossati L, Ayres TR, Haswell CA et al (2013) Absorbing Gas around the WASP-12 Planetary System. *ApJ*766(2):L20, DOI 10.1088/2041-8205/766/2/L20

- Goodman ML (1995) A three-dimensional, iterative mapping procedure for the implementation of an ionosphere-magnetosphere anisotropic Ohm's law boundary condition in global magnetohydrodynamic simulations. *Ann Geophys* 13(8):843–853, DOI 10.1007/s00585-995-0843-z
- Grießmeier JM, Zarka P Spreeuw H (2007) Predicting low-frequency radio fluxes of known extra-solar planets. *A&A*475(1):359–368, DOI 10.1051/0004-6361:20077397
- Ip WH, Kopp A Hu JH (2004) On the Star-Magnetosphere Interaction of Close-in Exoplanets. *ApJ*602(1):L53–L56, DOI 10.1086/382274
- Jia X, Walker RJ, Kivelson MG, Khurana KK Linker JA (2009) Properties of Ganymede's magnetosphere inferred from improved three-dimensional MHD simulations. *J Geophys Res*114(A9):n/a–n/a, DOI 10.1029/2009JA014375
- Jones CA (2011) Planetary Magnetic Fields and Fluid Dynamos. *Annu Rev Fluid Mech* 43(1):583–614, DOI 10.1146/annurev-fluid-122109-160727
- Khodachenko ML, Shaikhislamov IF, Lammer H Prokopov PA (2015) Atmosphere Expansion and Mass Loss of Close-Orbit Giant Exoplanets Heated by Stellar Xuv. II. Effects of Planetary Magnetic Field; Structuring of Inner Magnetosphere. *ApJ*813(1):50, DOI 10.1088/0004-637X/813/1/50
- Kopp A, Schilp S Preusse S (2011) Magnetohydrodynamic Simulations of the Magnetic Interaction of Hot Jupiters with Their Host Stars: A Numerical Experiment. *ApJ*729(2):116, DOI 10.1088/0004-637X/729/2/116
- Laine RO Lin DNC (2012) Interaction of Close-in Planets with the Magnetosphere of Their Host Stars. II. Super-Earths as Unipolar Inductors and Their Orbital Evolution. *ApJ*745(1):2, DOI 10.1088/0004-637X/745/1/2
- Laine RO, Lin DNC Dong S (2008) Interaction of Close-in Planets with the Magnetosphere of Their Host Stars. I. Diffusion, Ohmic Dissipation of Time-dependent Field, Planetary Inflation, and Mass Loss. *ApJ*685(1):521–542, DOI 10.1086/589177
- Lanza AF (2008) Hot Jupiters and stellar magnetic activity. *A&A*487(3):1163–1170, DOI 10.1051/0004-6361:200809753
- Lanza AF (2009) Stellar coronal magnetic fields and star-planet interaction. *A&A*505(1):339–350, DOI 10.1051/0004-6361/200912367
- Lanza AF (2012) Star-planet magnetic interaction and activity in late-type stars with close-in planets. *A&A*544:23, DOI 10.1051/0004-6361/201219002
- Lanza AF (2013) Star-planet magnetic interaction and evaporation of planetary atmospheres. *A&A*557:31, DOI 10.1051/0004-6361/201321790
- Lanza AF (2015) Star-Planet Interactions. 18th Cambridge Workshop on Cool Stars 18:811–830
- Lanza AF Shkolnik EL (2014) Secular orbital evolution of planetary systems and the dearth of close-in planets around fast rotators. *MNRAS*443(2):1451–1462, DOI 10.1093/mnras/stu1206
- Llama J, Vidotto AA, Jardine M et al (2013) Exoplanet transit variability: bow shocks and winds around HD 189733b. *MNRAS*436(3):2179–2187, DOI 10.1093/mnras/stt1725
- Lovelace RVE, Romanova MM Barnard AW (2008) Planet migration and disc destruction due to magneto-centrifugal stellar winds. *MNRAS*389(3):1233–1239, DOI 10.1111/j.1365-2966.2008.13617.x
- Mathis S (2017) Tides in Star-Planet Systems. In: Deeg HJ Belmonte JA (eds) *The Exoplanet Handbook*, Springer
- Matsakos T, Uribe A Königl A (2015) Classification of magnetized star-planet interactions: bow shocks, tails, and inspiraling flows. *A&A*578:A6, DOI 10.1051/0004-6361/201425593
- McQuillan A, Mazeh T Aigrain S (2013) Stellar Rotation Periods of the Kepler Objects of Interest: A Dearth of Close-in Planets around Fast Rotators. *ApJ*775(1):L11, DOI 10.1088/2041-8205/775/1/L11
- Mengel MW, Marsden SC, Carter BD et al (2016) A BCool survey of the magnetic fields of planet-hosting solar-type stars. *MNRAS*465(3):2734–2747, DOI 10.1093/mnras/stw2949
- Merkin VG Lyon JG (2010) Effects of the low-latitude ionospheric boundary condition on the global magnetosphere. *J Geophys Res*115(A):A10,202, DOI 10.1029/2010JA015461
- Miller BP, Gallo E, Wright JT Pearson EG (2015) A Comprehensive Statistical Assessment of Star-Planet Interaction. *ApJ*799(2):163, DOI 10.1088/0004-637X/799/2/163

- Moutou C, Fares R, Donati JF (2017) Magnetic Fields in Planet Hosting Stars. In: Deeg HJ, Belmonte JA (eds) *The Exoplanet Handbook*, Springer
- Neubauer FM (1998) The sub-Alfvénic interaction of the Galilean satellites with the Jovian magnetosphere. *J Geophys Res* 103(E):19,843–19,866, DOI 10.1029/97JE03370
- Pillitteri I, Wolk SJ, Sciortino S, Antoci V (2014) No X-rays from WASP-18. Implications for its age, activity, and the influence of its massive hot Jupiter. *A&A* 567:A128, DOI 10.1051/0004-6361/201423579
- Pont F (2009) Empirical evidence for tidal evolution in transiting planetary systems. *MNRAS* 396(3):1789–1796, DOI 10.1111/j.1365-2966.2009.14868.x
- Poppenhaeger K, Wolk SJ (2014) Indications for an influence of hot Jupiters on the rotation and activity of their host stars. *A&A* 565:L1, DOI 10.1051/0004-6361/201423454
- Preusse S, Kopp A, Büchner J, Motschmann U (2005) Stellar wind regimes of close-in extrasolar planets. *A&A* 434(3):1191–1200, DOI 10.1051/0004-6361:20041680
- Preusse S, Kopp A, Büchner J, Motschmann U (2006) A magnetic communication scenario for hot Jupiters. *A&A* 460(1):317–322, DOI 10.1051/0004-6361:20065353
- Rubenstein EP, Schaefer BE (2000) Are Superflares on Solar Analogues Caused by Extrasolar Planets? *ApJ* 529(2):1031–1033, DOI 10.1086/308326
- Saur J (2017) Electromagnetic coupling in Star–Planet systems. In: Deeg HJ, Belmonte JA (eds) *The Exoplanet Handbook*, Springer
- Saur J, Neubauer FM, Strobel DF, Summers ME (1999) Three-dimensional plasma simulation of Io's interaction with the Io plasma torus: Asymmetric plasma flow. *J Geophys Res* 104(A):25,105–25,126, DOI 10.1029/1999JA900304
- Saur J, Grambusch T, Duling S, Neubauer FM, Simon S (2013) Magnetic energy fluxes in sub-Alfvénic planet-star and moon-planet interactions. *A&A* 552:119, DOI 10.1051/0004-6361/201118179
- Shkolnik EL, Bohlender DA, Walker GAH, Collier Cameron A (2008) The On/Off Nature of Star–Planet Interactions. *ApJ* 676(1):628–638, DOI 10.1086/527351
- Staab D, Haswell CA, Smith GD et al (2017) SALT observations of the chromospheric activity of transiting planet hosts: mass-loss and star–planet interactions. *MNRAS* 466(1):738–748, DOI 10.1093/mnras/stw3172
- Stanley S, Glatzmaier GA (2010) Dynamo Models for Planets Other Than Earth. *Space Sci Rev* 152:617, DOI 10.1007/s11214-009-9573-y
- Strugarek A (2016) Assessing Magnetic Torques and Energy Fluxes in Close-in Star–Planet Systems. *ApJ* 833(2):140, DOI 10.3847/1538-4357/833/2/140
- Strugarek A, Brun AS, Matt S (2012) On close-in magnetized star–planet interactions. In: SF2A-2012: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics. Eds.: S. Boissier, pp 419–423
- Strugarek A, Brun AS, Matt SP, Réville V (2014a) Modeling magnetized star–planet interactions: boundary conditions effects. *Nature of Prominences and their role in Space Weather* 300:330–334, DOI 10.1017/S1743921313011162
- Strugarek A, Brun AS, Matt SP, Réville V (2014b) Numerical aspects of 3D stellar winds. 18th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, Proceedings of Lowell Observatory 1410:3537
- Strugarek A, Brun AS, Matt SP, Réville V (2014c) On the Diversity of Magnetic Interactions in Close-in Star–Planet Systems. *ApJ* 795(1):86, DOI 10.1088/0004-637X/795/1/86
- Strugarek A, Brun AS, Matt SP et al (2014d) Modelling the Corona of HD 189733 in 3D. Proceedings of the SFA conference 1411:2494
- Strugarek A, Brun AS, Matt SP, Réville V (2015) Magnetic Games between a Planet and Its Host Star: The Key Role of Topology. *ApJ* 815(2):111, DOI 10.1088/0004-637X/815/2/111
- Tremblin P, Chiang E (2013) Colliding planetary and stellar winds: charge exchange and transit spectroscopy in neutral hydrogen. *MNRAS* 428(3):2565–2576, DOI 10.1093/mnras/sts212
- Turner JD, Christie D, Arras P, Johnson RE, Schmidt C (2016a) Investigation of the environment around close-in transiting exoplanets using CLOUDY. *MNRAS* 458(4):3880–3891, DOI 10.1093/mnras/stw556

- Turner JD, Pearson KA, Biddle LI et al (2016b) Ground-based near-UV observations of 15 transiting exoplanets: constraints on their atmospheres and no evidence for asymmetrical transits. *MNRAS*459(1):789–819, DOI 10.1093/mnras/stw574
- Vidotto A (2017) Stellar Coronal and Wind Models: Impact on Exoplanets. In: Deeg HJ Belmonte JA (eds) *The Exoplanet Handbook*, Springer
- Vidotto AA, Jardine M, Morin J et al (2014) M-dwarf stellar winds: the effects of realistic magnetic geometry on rotational evolution and planets. *MNRAS*438(2):1162–1175, DOI 10.1093/mnras/stt2265
- Weber EJ Davis LJ (1967) The Angular Momentum of the Solar Wind. *ApJS*148:217, DOI 10.1086/149138
- Zanni C Ferreira J (2009) MHD simulations of accretion onto a dipolar magnetosphere. I. Accretion curtains and the disk-locking paradigm. *A&A*508:1117, DOI 10.1051/0004-6361/200912879
- Zarka P (2007) Plasma interactions of exoplanets with their parent star and associated radio emissions. *Planet Space Sci*55(5):598–617, DOI 10.1016/j.pss.2006.05.045
- Zarka P (2017) Star-Planet Interactions in the Radio Domain: Prospect for Their Detection. In: Deeg HJ Belmonte JA (eds) *The Exoplanet Handbook*, Springer