Stars and their variability observed from space
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STAR–PLANET MAGNETIC INTERACTIONS

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Abstract. This paper reviews briefly the observation and theory of magnetic interactions between stars and their nearby planets, focussing on systems with hot Jupiters and considering phenomena observed in the atmospheres of the host stars. These interactions can provide an indirect method to measure the magnetic fields of hot Jupiters, opening a new window on the magnetohydrodynamics and thermodynamics of their interiors. Statistical analyses of the signatures of star–planet interactions in the coronal emission and in the rotation of planet-hosting stars are also considered, with the main emphasis on some specific cases that may shed light on the complex interplay between stars and their nearby planets.

Keywords: planetary systems; stars: activity, late-type, magnetic fields, planets and satellites: magnetic fields

1 Introduction

The magnetic fields of planets play a fundamental role in several important processes that shape their structure and evolution. They reduce the evaporation rate of nearby planets (e.g., Adams 2011) and protect them from coronal mass ejections; they affect the habitability of the planetary environments (e.g., Airapetian et al. 2019) and provide us with information on the planetary interiors, where magnetic fields are generated by hydromagnetic dynamos (e.g. Driscoll 2018). The interactions between the magnetic fields of late-type stellar hosts and their planets can in principle be observed, but a combination of ground-based and space-born observations is crucial for obtaining a complete descriptions of these phenomena, whose detection is often at the limit of presently available instruments. This contribution focussed on the effects which might be observed in the host star.

2 Types of magnetic interactions

In the solar system planets orbit in the super-Alfvénic region of the solar wind, where the wind velocity $v_{\rm w}$ is greater than the local Alfvén velocity $v_{\rm A} \equiv B/\sqrt{\mu\rho}$; B is the intensity of the magnetic field in the wind, μ is the magnetic permeability of the plasma, and ρ its density. In this regime, a perturbation generated by the planet in the wind magnetic field and propagating at the Alfvén velocity is blown away by the faster-moving wind. On the other hand, in the case of nearby planets (representing the majority of known extrasolar planets), the planet orbits so close to its host that the stellar wind is likely to be in a sub-Alfvénic regime, that is, $v_{\rm w} < v_{\rm A}$. In that regime, a perturbation excited by the motion of the planet through the wind magnetic field can propagate back to the atmosphere of the host star. Specifically, a planet excites Alfvén waves that move along characteristics, that is, lines that are everywhere tangent to the vectors $\mathbf{c}_{\rm w}^{\pm} = \mathbf{v}_{\rm w} \pm \mathbf{v}_{\rm A}$, where $\mathbf{v}_{\rm w}$ is the velocity of the wind flow and $\mathbf{v}_{\rm A} = \mathbf{B}/\sqrt{\mu\rho}$ is the vectorial Alfvén velocity. One of the characteristics may reach the host star, thus allowing the Alfvén waves to dissipate their energy in its chromosphere and corona (Saur 2018).

The available power can be computed using the *Alfvén-wing model,* originally developed in the case of the interaction between Jupiter and its moon Io (Neubauer 1980). It orbits inside Jupiter's magnetosphere and produces bright spots in the auroral ovals of the planet that are observed in the ultraviolet and move in phase with the orbital motion of the satellite rather than with the rotation period of Jupiter. A detailed analysis of this phenomenon has been given by Saur et al. (2013), who presented model applications to hot Jupiters and found powers up to $10^{18} - 10^{19}$ W in the most favourable cases. Numerical magnetohydrodynamic (MHD) models by Strugarek (2016, 2018) confirmed these results, and showed the importance of the relative orientation of the planetary field with respect to the stellar field in determining the dissipated power.

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Inspired by the observations of Io's bright spots in the atmosphere of Jupiter, Shkolnik et al. (2003, 2005) looked for chromospheric hot spots in stars with hot Jupiters moving in phase with the orbits of the planets rather than with stellar rotation. The observed signatures are not steady and have a flux of less that $\sim 1\%$ of the chromospheric emission, making their confirmation difficult (Shkolnik et al. 2008). Nevertheless, further evidence of this phenomenon was recently obtained in the case of HD 189733 (Cauley et al. 2018). Cauley et al. (2019) measured the excess fluxes coming from chromospheric hot spots in HD 179949, HD 189733, τ Bootis and υ Andromedae, finding mean irradiated powers between $(0.28 \pm 0.07) \times 10^{20}$ W and $(1.53 \pm 0.27) \times 10^{20}$ W. Given the impossibility of accounting for such powers with the Alfvén-wing model, other models were explored to interpret the observations.

A simple model of the star–planet interaction assumes that coronal magnetic fields at the distance of their nearby planets have an energy density much larger than the thermal energy density and the kinetic energy density of the plasma, that is, $B^2/2\mu \gg p, \rho v^2/2$, where p is the plasma pressure, ρ its density, and v its velocity. (We have neglected the gravity because of the very low density of the plasma). We considered a stationary system and filtered out Alfvén waves, since their dissipated power is insufficient by at least 1 or 2 orders of magnitude to account for the observations.

This model extends the MHD regime (as usually adopted to model stellar coronal fields) up to the distance of hot Jupiters (Wiegelmann et al. 2017), which is not unreasonable in the case of stars such as HD 189733, whose level of magnetic activity is remarkably greater than that of our Sun. The situation has been explored in detail in a series of papers by Lanza (2008, 2009, 2012, 2013, 2018). Since pressure forces and gravity are too small to balance the Lorentz force in the regime considered, a stationary configuration is possible only if the Lorentz force vanishes:

$$\mathbf{J} \times \mathbf{B} = \frac{1}{\mu}(\nabla \times \mathbf{B}) \times \mathbf{B} = 0, \tag{2.1}$$

where we have expressed the current density $\mathbf{J} = (1/\mu)(\nabla \times \mathbf{B})$ by means of Ampere's law because the displacement current is negligible in MHD given the very small speed of the plasma in comparison with the speed of light. A magnetic field satisfying equation (2.1) is said to be *force-free.* We can recast equation (2.1) as

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}, \tag{2.2}$$

where α is a scalar that is in general a function of position. By taking the divergence of both sides of equation (2.2) and considering that $\nabla \cdot \mathbf{B} = 0$, we obtain:

$$\mathbf{B} \cdot \nabla \alpha = 0, \tag{2.3}$$

telling us that α is constant along magnetic field lines.

In the framework of this simplified model, a magnetic field that interconnects the star with the planet has α constant along the interconnecting field lines. The magnetic field of the planet is potential because in the nearly neutral planetary atmosphere electric currents cannot propagate, implying $\mathbf{J} = 0$, that is, $\nabla \times \mathbf{B} = 0$, giving $\alpha = 0$ (cf. equation 2.2). An interconnecting field line therefore has $\alpha = 0$, implying that the stellar magnetic field is also potential along all the interconnecting structure. In general, the magnetic field of a stellar corona is not potential because the field stores energy in excess of the minimum corresponding to the potential field under the action of the stresses produced by photospheric motions. As a consequence, the stellar coronal field is generally topologically disconnected from the planetary field and the two fields interact only in the region of space where they come into contact (see Fig. 1), producing a release of power by magnetic reconnection $P_{\rm rec}$ given by:

$$P_{\rm rec} = \gamma \frac{\pi}{2\mu} B^2(a) R_{\rm m}^2 v_{\rm rel}, \tag{2.4}$$

where $0 < \gamma < 1$ is a factor depending on the angle between the field lines of the stellar and planetary fields, $B(a)$ is the stellar coronal field at the separation a of the planet, $R_{\rm m}$ the radius of the planetary magnetosphere, and $v_{\rm rel}$ the relative velocity between the field lines of the star and of the planet (see Lanza 2009, 2012). The power released by magnetic reconnection in the case of two topologically separated star–planet flux systems is $P_{\rm rec} \sim 10^{16} - 10^{19}$ W, assuming the stellar fields were measured by means of spectropolarimetric techniques in the above stars (Moutou et al. 2018) and a magnetic field strength of the hot Jupiters of the order of $\sim 10 - 100$ G.

When the stellar coronal field is potential, the formation of an interconnecting loop joining the stellar and planetary fields is possible (see Fig. 2). In this case the footpoints on the star and on the planet move with a relative velocity $v \approx v_{\rm orb}$, where $v_{\rm orb}$ is the orbital velocity of the planet and the power dissipated into the interconnecting loop is:

$$P_{\rm inter} \simeq \frac{2\pi}{\mu} f_{\rm AP} B_{\rm p}^2 R_{\rm p}^2 v, \tag{2.5}$$

where $f_{\rm AP}$ is the fraction of the planet's surface covered with the interconnecting field lines, $B_{\rm p}$ the strength of the planetary field at its poles, and $R_{\rm p}$ the radius of the planet (Lanza 2013). The dissipated power is of the order of $10^{21} - 10^{22}$ W in the case of the systems considered above, assuming $B_{\rm p} \sim 10 - 100$ G. This model is therefore a candidate for accounting for the observed power radiated by chromospheric hot spots, while the model based on the reconnection between two separated flux systems provides insufficient power, as in the case of the Alfvén-wing model.

By applying equation (2.5), Cauley et al. (2019) derived the first indirect estimates of the planetary magnetic fields in the four systems considered above, finding $B_{\rm p}$ between 20–120 G. They assumed that $\approx 0.2\%$ of the dissipated power $P_{\rm inter}$ was radiated by chromospheric hot spots in the Ca II H&K lines – an estimate based on observations of solar flares. Such magnetic field strengths are in agreement with a model proposed by Yadav & Thorngren (2017), which assumes that a fraction of the stellar insolation received by the planet is conveyed into the planetary interior, where it provides energy to power the planetary dynamo. It is interesting to note that the same extra power could provide an explanation for the inflated radii of hot Jupiters (for an introduction to this problem, see Laughlin 2018).

Numerical models of star-planet magnetic interactions that include the effects of plasma pressure and gravity have been presented by Cohen et al. (2009, 2011) and generally confirm the existence of interconnecting field configurations that can release large amounts of energy, sufficient to account for the power radiated by chromospheric hot spots. Models of stellar winds, including interactions with nearby planets, have been considered by, e.g., Vidotto et al. (2010, 2012, 2014); Cohen et al. (2014); Strugarek et al. (2017, 2019) and illustrate cases in which a planet passes from sub-Alfvénic to super-Alfvénic regimes along its orbit, and *vice versa*. This produces remarkable variations in the interaction strength and in the efficiency of the evaporation of the planetary atmosphere.

A classification of the different cases of interaction, based on the relative intensities of tides, winds and magnetic fields, has been proposed by Matsakos et al. (2015), and shows the important role of the evaporation of the planetary atmospheres in shaping the circumstellar environments in systems with hot Jupiters. The material evaporated from the planet can fall on the star, producing an energy release at specific orbital phases that can account for the flares observed preferentially just after the occultation of the planet in HD 189733 (Pillitteri et al. 2014, 2015, but see Lanza (2018) for an alternative explanation). In a different regime, the evaporated material can form a torus encircling the star, similar to what the simulations by Debrecht et al. (2018) show.

3 Statistical analyses of star–planet interactions, and some specific cases

In principle, the effects of the energy dissipated by nearby planets into the outer atmospheres of stars could be detected in a statistical study that considered planets at different separations and with different masses, because the interaction strength is expected to depend on those two parameters. Miller et al. (2015) reviewed previous investigations and performed a detailed analysis that looked for such a statistical correlation, but they obtained a generally negative result. A similar conclusion was reached in a more recent study by France et al. (2018). Nevertheless, Miller et al. (2015) found a subset of stars with hot Jupiters that showed a potentially significant correlation. Those stars do not usually show anomalously high activity in comparison to the expected level according to their rotation periods; nevertheless, their coronal emissions appear to be correlated with measures of the interaction strength such as $M_{\rm p} a^{-2}$ or a^{-1}, where $M_{\rm p}$ is the mass of the planet and a its separation from the star.

Some active stars with hot Jupiters, such as HD 189733 and CoRoT-2, have visual companions whose X-ray emission can be used to estimate the ages of the systems. The intriguing result is that the age found for both of them is of the order of several Gyrs, while their levels of activity point to much younger ages of $1.5 - 2.0$ and 0.5 Gyr, respectively (Poppenhaeger & Wolk 2014). Statistical studies of the rotation of stars with hot Jupiters indicate that they may be rotating faster than single stars of the same age (Pont 2009; Lanza 2010; Maxted et al. 2015). Tidal interactions do not appear capable of maintaining such a relatively rapid rotation in all the observed stars (Lanza 2010; Maxted et al. 2015), and it has therefore been suggested that a nearby massive planet may reduce the efficiency of the stellar wind responsible for braking the stellar rotation during their main-sequence life-times (Lanza 2010; Cohen et al. 2010).

The effect of a nearby massive planet on its host is not always that of increasing its rotation and activity level. The WASP-18 system is an example of a massive ($\sim 10.4 \pm 0.4$ M_{Jup}), very close ($a \sim 0.0205$ AU) hot Jupiter orbiting an F6 V star that has a relatively normal rotation ($v \sin i \sim 10.9 \pm 0.7$ km s^{-1}) but whose level of activity is much lower than expected on the basis of its spectral type and rotation rate. The X-ray emission of WASP-18 is not detectable, i.e., it is at least two orders of magnitude lower than expected in a star in which the strength of Lithium absorption in its spectrum and its rotation rate (Pillitteri et al. 2014; Fossati et al. 2018) indicate an estimated age that is younger than ~ 1 Gyr. The conclusion is that the massive and very close planet is somehow quenching the stellar dynamo, although a detailed model of such a phenomenon has not yet been proposed.

In view of these observations, the lack of a general correlation between the level of stellar activity and the parameters measuring the strength of the star–planet interaction could be the result of considering together systems in which opposite effects manifest themselves. A more detailed investigation is clearly needed before we can exclude any possible effects of nearby planets on stellar activity. More specifically, a better understanding of the physical mechanisms through which nearby planets affect their hosts is required.

In this context, it is worth mentioning the intriguing correlation found by Hartman (2010), and confirmed by Figueira et al. (2014), between the chromospheric stellar emission as measured by the index $\log R'_{\rm HK}$ and the gravity of a transiting planet that can be derived directly from the measurements of the stellar radial velocity and the depth of the transit, without the need for any specific stellar model (Sozzetti et al. 2007). According to such a correlation, stars with nearby planets having a stronger gravity are statistically more active. Lanza (2014) proposed an explanation based on the evaporation of the planetary atmosphere producing an accumulation of plasma in a torus encircling the star, thus generalizing the model proposed by Fossati et al. (2013) in the case of WASP-12. Plasma condensations forming inside the torus can absorb selectively the flux in the cores of the Ca II *H&K* lines, reducing the observed chromospheric emission. Planets with a stronger gravity have a lower evaporation rate, leading to smaller absorption by the circumstellar torus and an apparent higher level of activity. A more detailed investigation by Fossati et al. (2015) gave support to this interpretation, although an alternative explanation has been proposed by Collier Cameron & Jardine (2018).

Collier Cameron & Jardine (2018) showed that more massive nearby planets are statically younger than less massive planets, and are therefore found preferentially around more active stars because the level of stellar activity declines with stellar age. Since the radius of massive planets is more or less independent of their mass, more massive planets generally have a stronger gravity, and that could explain the observed correlation. In the framework of this interpretation, the correlation between $\log R'_{\rm HK}$ and $M_{\rm p}$ should be stronger than the correlation between the chromospheric index and the surface gravity of the planets, yet the observations show the opposite (Hartman 2010; Fossati et al. 2015), giving more support to the other interpretation.

The possibility of photospheric activity phenomena produced by the interaction with a nearby planet is based on circumstantial evidence, mainly coming from the modelling of the observations obtained with *CoRoT* and *Kepler*. CoRoT-2 (Lanza et al. 2009) and CoRoT-6 (Lanza et al. 2011) show evidence of a short-term activity cycle and an active longitude, respectively, that could be related to star–planet interactions (see Lanza 2011, for details). Kepler-17 (Désert et al. 2011) and HAT-P-11 (Béky et al. 2014) show spots that rotate with periods commensurable with the orbital periods of their hot Jupiters, respectively. Sound conclusions cannot be based on a few cases, especially because we lack a theoretical framework for understanding the processes that could be responsible for such phenomena. We therefore hope to make decisive progress in this field with *PLATO* (Rauer et al. 2014), which should provide us with a larger sample of systems upon which to base our investigations of these effects.

4 Conclusions

Some recent results in the field of star–planet magnetic interactions have been reviewed, focussing on the relevant observations and some analytical or numerical models proposed for their interpretation. This is a rapidly growing field that promises to shed light on the processes occurring in the interiors of exoplanets, mainly hot Jupiters, where magnetic fields are generated, and on the effects produced by a nearby planet on the stellar hydromagnetic dynamo and chromospheric or coronal heating.

AFL is grateful to the Scientific Organizing Committee for their kind invitation to attend the Conference and deliver a keynote talk on the topic of this paper.

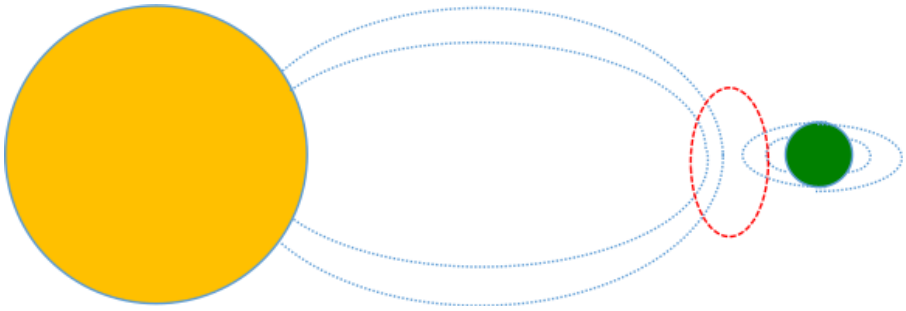

Fig. 1. Sketch of a configuration with separate flux systems for the star and the planet. Some magnetic field lines are indicated by the dotted blue lines. This configuration typically occurs when the stellar field in our simplified model is non-potential. The section of the star is rendered in yellow-orange, while the planet is in green, and the region where the magnetic fields of the stellar and planetary flux systems interact is encircled by the dashed red line. Magnetic reconnection occurs inside that region (see text for more detail).

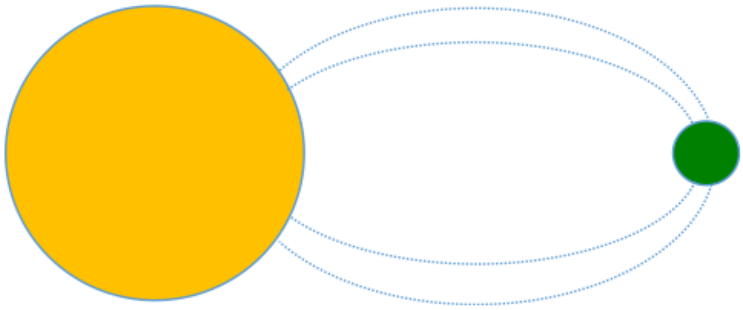

Fig. 2. Sketch of a magnetic loop connecting the stellar coronal field with a nearby planet (see Fig. 1 for more details). In the framework of the simplified model introduced in the text, this configuration is possible when the stellar magnetic field is potential. The planet field is connected directy with the stellar field without any ionosphere that prevents the field from reaching the planetary surface.

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