Chasing Star–Planet Magnetic Interactions: The Case of Kepler-78

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Received 2019 February 26; revised 2019 June 30; accepted 2019 July 1; published 2019 August 21

Abstract

Observational evidence of star–planet magnetic interactions (SPMIs) in compact exosystems have been looked for in the past decades. Indeed, planets in close-in orbit can be magnetically connected to their host star and can channel Alfvén waves carrying large amounts of energy toward the central star. The strength and temporal modulation of SPMIs are primarily set by the magnetic topology of the host star and the orbital characteristics of the planet. As a result, SPMI signals can be modulated over the rotational period of the star, the orbital period of the planet, or a complex combination of the two. The detection of SPMIs thus has to rely on multiple-epoch and multiple-wavelength observational campaigns. We present a new method to characterize SPMIs and apply it to Kepler-78, a late G star with a super-Earth on an 8.5 hr orbit. We model the corona of Kepler-78 using the large-scale magnetic topology of the star observed with Zeeman–Doppler imaging. We show that the closeness of Kepler-78 allows the interaction with channel energy flux densities up to a few kW m⁻² toward the central star. We show that this flux is large enough to be detectable in classical activity tracers such as Hα. It is nonetheless too weak to explain the modulation observed by Moutou et al. We furthermore demonstrate how to predict the temporal modulation of SPMI signals in observed systems such as Kepler-78. The methodology presented here thus paves the way toward denser, more specific observational campaigns that would allow proper identification of SPMIs in compact star–planet systems.

Key words: magnetohydrodynamics (MHD) – planet–star interactions – stars: winds, outflows

1. Introduction

Planets on a short-period orbit are expected to interact strongly with their host star (Cuntz et al. 2000) due to the strong irradiation they receive (Yelle et al. 2008; Trammell et al. 2014; Matsakos et al. 2015; Bourrier et al. 2016; Daley-Yates & Stevens 2018), the strong tidal forces they experience (Bolmont et al. 2017; Mathis 2018; Strugarek et al. 2017b), and the strong interplanetary magnetic field they orbit in (see Lanza 2010; Cohen et al. 2011; Strugarek 2016, 2018 and references therein). Such close-in planets will generally orbit in the sub-Alfvénic region of the accelerating wind of their star. In that case they can magnetically back-react on their host, which is often referred to as star–planet magnetic interaction (SPMI). In exoplanetary systems the SPMIs are expected to channel magnetic energy carried by Alfvén waves excited by the interaction and traveling from the planet to the star. The superposition of these waves form the so-called Alfvén wings. Alfvén wings are a very robust feature of SPMIs as they are triggered whether or not the planet’s atmosphere escapes and whether or not the planet possesses a magnetosphere (Neubauer 1998). SPMIs were shown to be able to channel magnetic powers up to 10¹⁹–10²⁰ W in the most favorable star–planet systems (Saur et al. 2013; Strugarek 2016). These large energy fluxes can in principle leave observable traces in stellar atmospheres, through, e.g., local heating (Ip et al. 2004), flare trigger (Lanza 2018; Fischer & Saur 2019), or particle acceleration (Hess & Zarka 2011) as in the case of Io–Jupiter magnetic interaction (Clarke et al. 2002).

Numerous attempts to observe SPMIs signals have been carried out in the past decade, for specific star–planet systems (e.g., Fares et al. 2010; Figueira et al. 2016; Zarka 2018; Fischer & Saur 2019 and references therein) as well as for ensembles of star–planet systems (Poppenhaeger & Schmitt 2011; Miller et al. 2015). None of these studies were able to unambiguously detect SPMIs. Recently, Cauley et al. (2018) reported a first detection in the CaII K band of HD 189733, where an anomalous flux correlated with the orbital period of the planet was observed. This signal was not detected in previous observational campaigns of HD 189733 (Fares et al. 2010).

At first order, SPMIs depend only on the magnetic properties of the host star as was shown unambiguously by Strugarek et al. (2015). This dependency naturally leads to on/off SPMIs (Shkolnik et al. 2008) as the large-scale stellar magnetic field changes over decadal timescales. More precisely the magnetic topology of the corona of the star determines where the footpoint of the interaction lies on the star, and thus where any tracer of the interaction would actually be localized. It thus appears clearly that any attempt to characterize observable effects of SPMIs on the stellar flux must take into account the magnetic topology of the central star.

Fortunately, Zeeman–Doppler imaging (ZDI; see Donati & Landstreet 2009) has become in the past decades an extremely valuable tool to characterize the large-scale magnetic topology of bright stars thanks to spectro-polarimetric observations. Leveraging these constraints for given star–planet systems, it is now possible to predict both the energetic and the temporal variability of SPMIs.

In this paper we present a new method to characterize and predict SPMIs. We apply the method to SPMIs for Kepler-78, an ultra-short-period star–planet system with an orbital period of 0.36 days (Sanchis-Ojeda et al. 2013). We demonstrate that SPMI channels enough power to be detectable in classical magnetic activity tracers such as the CaII H&K or Hα bands.
We carry out a detailed modeling of the magnetized wind of Kepler-78 to assess the temporal variability of the SPMI signal. Our model predicts a specific temporal modulation over the orbital and rotational timescales of the system, and we show that SPMIs could be detectable in the CaII H&K or Hα bands of Kepler-78. We show that the overall method can provide a powerful and robust guide to design dedicated observational campaigns to detect SPMIs during the most favorable rotational and orbital phases of star–planet systems.

The paper is organized as follows. We first introduce in Section 2 the characteristics of the Kepler-78 system, along with the activity tracers observed by Moutou et al. (2016). We then present in Section 3 simulation results of the corona of Kepler-78 based on the ZDI maps of the star as of 2015 July. In Section 4 we use the simulation results to predict the properties of the SPMI along the orbit of Kepler-78b. We further estimate in Section 5 the energetic and temporal variability of the magnetic interaction. We finally discuss in Section 6 the implications of this study for future prospects in characterizing SPMIs as compact star–planet systems, and we summarize our results and conclude in Section 7.

### Table 1

Properties of the Kepler-78 System

| Parameter               | Value          |
|------------------------|----------------|
| $T_{\text{eff}}$ [K]    | 5089 ± 50      |
| $M_\star$ [$M_\odot$]  | 0.81 ± 0.08    |
| $R_\star$ [$R_\odot$]  | 0.74 ± 0.1, −0.08 |
| $P_{\text{orb}}$ [days]| 12.5           |
| $R_p$ [$R_\oplus$]     | 1.16 ± 0.19, −0.14 |
| $M_p$ [$M_\oplus$]     | 1.86 ± 0.25    |
| $P_{\text{orb}}$ [days]| 0.36           |
| Semimajor axis [$R_\star$]| 2.66$^b$       |

#### Notes

The parameters of the Kepler-78 system were published in Sanchis-Ojeda et al. (2013). The error bars correspond to the 68.3% confidence limits (see Sanchis-Ojeda et al. 2013).

$^a$This mass that was deduced from HARPS-N data by Pepe et al. (2013). Howard et al. (2013) and Sanchis-Ojeda et al. (2013) give much larger error bars on the mass, with a maximum value of 8 $M_\odot$.

$^b$The semimajor axis of Kepler-78b was reported to be 3 $R_\odot$ in Sanchis-Ojeda et al. (2013), with significant error bars. Applying Kepler’s law for a circular orbit, we find that $R_{\text{orb}}$ ~ 2.66 $R_\star$ based on the well-constrained orbital period of Kepler-78b. We use the latter value in this work.

2. The Kepler-78 System

Kepler-78 and its close-in planet Kepler-78b form one of the ultra-short-period orbital systems that has been discovered in the past decade (Winn et al. 2018). It consists of an Earth-like planet around a late G–early K star with an orbital period of 0.36 days. This planet was first reported by Sanchis-Ojeda et al. (2013), and we list in Table 1 the characteristics of the host star and its planets found in the literature. The very short orbit of Kepler-78b makes it a fantastic testbed for star–planet tidal and magnetic interactions (Mathis 2018; Strugarek 2018).

After its discovery, follow-up studies of Kepler-78 were carried out by Moutou et al. (2016) to characterize its magnetic properties. Using spectropolarimetric observations with the Canada–France–Hawaii Telescope (CFHT)/ESPaDOnS, they measured the circular polarization in the line profile of the star and mapped the photospheric magnetic field using ZDI. They further gathered spectroscopic proxies of the chromospheric activity of Kepler-78, which revealed a peculiar modulation with the rotational phase of the star. Moutou et al. (2016) observed a significant change in the H and K bands of CaII, in Hα, Hβ, and in the infrared triplet of CaII. In this work we will focus on Hα for the sake of simplicity, the other tracers giving qualitatively similar results (see Appendix B).

The excess and dearth of Hα was reported in normalized units in Table 1 of Moutou et al. (2016) for a series of 13 observations between 2015 July and August. We recast here these variations using the following procedure. First, the smallest value of the Hα line is chosen as the zero-level absorption. We will assume here that the continuum spectrum of Kepler-78 is well described by a blackbody with $T_{\text{eff}} = 5089$ K (see Table 1). In the Hα band the blackbody approximation to the continuum flux does not introduce an error larger than about 10% when compared to more realistic spectra (e.g., Husser et al. 2013). Second, the blackbody radiance at $\lambda_{\text{H}α} = 6563$ Å is integrated over the width of the residual line as in Moutou et al. (2016). Third, we integrate the result over all emission angles and obtain the observed flux. This procedure allows us to quantify a flux hypothetically distributed over the whole stellar disk. If the source is localized over a given area $A$ on the stellar disk, this observed flux must be scaled by the relative area $A/(\pi R_\star^2)$.

We show the observed flux in Figure 1, where we phase-folded all the observations published in Moutou et al. (2016). The phase-folding must be taken with caution as we did not correct the flux for any intrinsic variability of the star nor from the latitudinal differential rotation. We scaled the Hα flux in absolute units (left axis) and in units of the stellar bolometric flux $F_\star = L_\star/(4\pi R_\star^2)$ (right axis; we estimated $L_\star \approx 0.33 L_\odot$ assuming the radius and effective temperature reported in Table 1). The flux of Kepler-78 in Hα reaches a few hundreds of W m$^{-2}$. The power needed to explain this flux depends on the size of the area at the source of this signal. In the remainder of this paper we will characterize the strength and size of a
hotspot magnetically induced by Kepler-78b to assess whether this signal can originate from SPMI or not.

3. Models of the Wind of Kepler-78

We model the wind of Kepler-78 using the same approach as Réville et al. (2016), based on the ZDI map of Kepler-78 observed in 2015 July (Moutou et al. 2016). The radial component of the surface magnetic field of Kepler-78 reaches typical values of 3 mT (30 G; see Figure 5). Kepler-78 rotates a bit more than twice as fast as the Sun, with a Rossby number of approximately 0.1 (the convective turnover time was taken from the parameterization given in Gunn et al. 1998; Cranmer & Saar 2011). As a result Kepler-78 is close to saturation (e.g., Johnstone et al. 2015; Matt et al. 2015), and its coronal properties can be estimated with empirical formulae using power-law exponents derived by Holzwarth & Jardine (2007); see also Réville et al. 2016), i.e.,

\[ T_e = T_\odot \left( \frac{\Omega}{\Omega_\odot} \right)^{0.1}, \quad n_e = n_\odot \left( \frac{\Omega}{\Omega_\odot} \right)^{0.6}, \]

where \( T_\odot = 1.5 \times 10^6 \) K, \( n_\odot = 10^8 \) cm\(^{-3} \), and \( \Omega_\odot = 2.6 \times 10^{-6} \) s\(^{-1} \). We obtain \( T_e = 1.63 \times 10^6 \) K and \( n_e = 1.6 \times 10^8 \) cm\(^{-3} \) for the corona of Kepler-78. The sensitivity of our results with respect to this choice of coronal parameters is discussed in Section 6.

We first model the wind of Kepler-78 using the starAML package published in Réville et al. (2015), accessible upon request. This package solves the pressure balance of a magnetized 1D Parker-like wind (Parker 1958; Weber & Davis 1967; Sakurai 1985) to calculate an optimal source-surface, which is in turn used to estimate the magnetic open flux deduced from the observed ZDI maps of the magnetic field at the surface of the star.

The optimal source-surface for Kepler-78 is found to be \( R_{SS} = 6.9 R_\odot \). The three-dimensional structure of the magnetic field in the low corona of the star can then be estimated using a potential-field source surface (PFSS) extrapolation method (Schrijver & DeRosa 2003). The chosen source-surface radius ensures that the PFSS extrapolation of the magnetic field matches as closely as possible the magnetic topology of the corona obtained with an MHD model (Réville et al. 2015).

We refer to this coupled model as starAML+PFSS, which is conveniently very inexpensive numerically. It is worth noting that this model is multi-D: the starAML Parker-like wind model is 1D, but the magnetic topology from the PFSS extrapolation is 3D (see Réville et al. 2015 for the details concerning this procedure). Similar multi-D approaches have been recently explored to model in near real-time the solar wind (Pinto & Rouillard 2017). The resulting global properties of the wind of Kepler-78, based on the ZDI map from 2015 July, are given in the first column of Table 2. We find that Kepler-78 has mass loss \( M \) and angular momentum loss \( J \) similar to the Sun (recall that \( M_\odot \simeq (2-3) \times 10^{-14} M_\odot \) yr\(^{-1} \); see McComas et al. 2008) and an averaged Alfvén radius \( \langle r_A \rangle = \sqrt{\frac{\Omega}{M}} \) also similar to the Sun (e.g., Réville et al. 2016).

The complex topology of the magnetic field of Kepler-78 warrants a more detailed investigation of the structure of its wind, especially in the context of SPMIs. We have hence computed a 3D wind solution of Kepler-78 using the PLUTO code (Mignone et al. 2007) under the magnetohydrodynamic (MHD) formalism (Strugarek et al. 2014; Réville et al. 2016), based on the same ZDI map of Kepler-78 (Moutou et al. 2016). The averaged properties of the 3D simulated wind are reported in the last column of Table 2. The averaged 3D model and starAML+PFSS agree very well (see Section 4.1 for their modulation along the planetary orbit), which shows that simplified multi-D approaches already provide a very useful first estimate of the averaged properties of stellar winds.

We illustrate the 3D wind steady-state solution of Kepler-78 in Figure 2, seen at rotational phase \( \phi_{rot} \sim 0.3 \) (the rotational phase is defined as in Moutou et al. 2016, with \( \phi_{rot} = 0 \) corresponding to the observation made on 2015 July 23). The density in the wind is shown by the purple colormap on the orbital plane, and the orbit of Kepler-78b is labeled by the white dashed line. The stellar wind magnetic field lines are shown as gray and colored tubes. The colored field lines show the magnetic connectivity between the planet and the star.
We now study in detail the properties of SPMIs along the orbit of Kepler-78b using the 3D model of the wind of Kepler-78.

4. SPMI along the Planetary Orbit

4.1. Wind Properties along the Orbit

The planet Kepler-78b orbits in an inhomogeneous medium due to the complex magnetic topology of the magnetic field of Kepler-78. The magnetic interaction of the planet with its host star depends on the plasma properties of the wind along its orbit. The Alfvén waves excited by the interaction form what is called the Alfvén wings of the magnetic interaction. These waves propagate in the $(B_\perp, v_\parallel)$ plane where $B_\perp$ is the wind magnetic field, and $v_\parallel = v_w - v_{\text{kep}}$ is the differential motion between the rotating wind velocity $v_w$ and the Keplerian orbital velocity $v_{\text{kep}}$. As a result, the inclination of the wind magnetic field with respect to the orbital motion $(\Theta_0)$ and with respect to the normal to the orbital plane $(\Theta_f)$ were shown to be important parameters determining the strength and shape of the magnetic interaction (Saur et al. 2013; Strugarek 2016, 2017). We show the inclination angles in the upper panel of Figure 3. $\Theta_0$ (in orange) varies from 45° to 134° along the orbit. The interaction strength is maximized when $\Theta_0 = 90°$ and minimized when $\Theta_0 = 0°$ or $\Theta_0 = 180°$. As a result the amplitude of the SPMI for Kepler-78b varies strongly in efficiency along the orbit.

We define the local Alfvénic Mach number as $M_a = v_\parallel/v_A$, where $v_\parallel = |v_\parallel| = |B_\perp|/\mu_0 v_A$ is the local Alfvén speed that depends on the local wind magnetic field $B_\perp = |B_\perp|$ and density $\rho_w$. The energy flux channeled by the magnetic interaction depends on this local Alfvénic Mach number $M_a$ (shown in the second panel of Figure 3) and on the Poynting flux density

$$ S_w = v_\parallel B_\perp^2 \sin(\Theta_0)/\mu_0 $$

shown in the third panel. The Poynting flux density quantifies the total input energy available for the magnetic interaction (Saur et al. 2013). In both panels, the values obtained with the starAML+PFSS model are indicated by the dashed line. This simplified (albeit calibrated) model gives a very good estimate of all parameters, as seen in Table 3 where we report the interaction parameters averaged along the planetary orbit for the two wind models.

The largest difference is found for the Alfvén Mach number $M_a$ (second panel), as the MHD model allows the density profile to be more realistic and self-consistent in 3D (see Figure 2). We further note that the starAML+PFSS model gives accurate results thanks to the optimized source-surface radius $R_{ss} = 6.9 R_\odot$ (Réville et al. 2015) used for the potential-field extrapolation in the corona of Kepler-78. When the canonical solar value $R_{ss} = 2.5 R_\odot$ (or $R_{ss} = 2.5 R_\odot$) is used the starAML+PFSS model gives significantly different results: Kepler-78b is then found to enter and leave the Alfvén surface along the orbit. This is not the case when the fully 3D solution is taken into account, as shown in the second panel of Figure 3.

Finally, the calibrated starAML+PFSS model is very accurate here because Kepler-78b orbits very close to its host star and, in particular, well within $R_{ss}$. As the orbital period increases we expect this model to be less and less precise and a fully 3D model of the stellar atmosphere would then be necessary.

![Figure 3](image_url) Properties of the stellar wind along the orbit of Kepler-78b. The inclination angles of the stellar wind magnetic field with respect to the orbital plane (blue) and the orbital motion (orange) are shown in the first panel. The Alfvén Mach number of the SPMI (orange) is shown in the second panel, and the Poynting vector in the third panel. Finally, the minimum planetary surface field required to sustain a magnetosphere is shown in the last panel. In all the panels, the blue line correspond to the 3D stellar wind model of Kepler-78b. The values for the simplified stellar wind starAML+PFSS model are indicated by the dashed lines.

| Table 3  | Averaged Properties at the Planetary Orbit |
|----------|------------------------------------------|
| Parameter                        | starAML+PFSS | 3D Wind |
| $M_a$ | 0.32 | 0.35 |
| $S_w$ [kW m$^{-2}$] | 0.37 | 0.35 |
| $B_{\text{ecl}}$ [\mu T] | 69 | 70 |

We observe that $M_a$ and $S_w$ vary by more than a factor of 2 along the orbit, which demonstrates the need for a 3D model to quantify properly SPMIs in real, particular star–planet systems. We further note that $M_a$ remains below one along the orbit, such that Kepler-78b remains in a sub-Alfvénic interaction regime at all times.

It is already worth noting that the power density available to the magnetic interaction, $S_w$, reaches about 1 kW m$^{-2}$ at its
maximum. This power density is larger than the signal seen in the Hα flux of Kepler-78 (see Figure 1). With a simple order-of-magnitude estimate, we immediately see that magnetic interactions could be at the source of the observed signal.

Due to the varying plasma conditions along the orbit, one may estimate the lowest planetary magnetic field that is required for Kepler-78b to sustain its own magnetosphere. The pressure equilibrium between the magnetosphere of the planet and its surroundings is characterized by the parameter

$$\Lambda_p = \frac{B_p^2}{2\mu_0 P_t},$$

where $B_p$ is the magnetic field at the surface of the planet and $P_t$ the total pressure in the stellar wind at the planetary orbit. A magnetosphere can be sustained only if $\Lambda_p \geq 1$. We display the planetary field estimate $B_p^{\text{min}}$ such that $\Lambda_p = 1$ in the last panel of Figure 3, for both the 3D wind and the starAML +PFSS model. This last panel actually also shows the wind magnetic field amplitude $B_n$, at the planetary orbit since we considered $\Lambda_p = 1$, and the magnetic pressure dominates $P_t$ for planets on short-period orbits. Overall, we predict that Kepler-78b needs a surface magnetic field of at least 70 $\mu$T (0.7 G) to sustain a magnetosphere during a complete orbit. For comparison, the Earth possesses an equatorial magnetic field of about 30 $\mu$T (0.3 G) at its surface.

The magnetic field of close-in planets is largely unknown as of today. Theoretical works on planetary dynamos (e.g., see the reviews of Stevenson 2003; Christensen 2010) tend to show that the magnetic field intensity primarily depends on the available power inside the planet, and only marginally depends on the rotation rate. This is particularly awaited in a saturated regime that can be expected for close-in planets such as Kepler-78b due to an efficient tidal locking. Kepler-78b is slightly larger and more massive than the Earth (see Table 1, with large uncertainties on its mass). If its internal structure is Earth-like, Kepler-78b is likely to possess a magnetic field slightly stronger than the Earth and, consequently, a field that could be just strong enough to maintain a magnetosphere. The available power for a dynamo inside Kepler-78b furthermore can be much larger than in the Earth, due to, e.g., more intense tidal interactions with its very close host (note that this also depends on tidal locking; for in-depth discussions see Mathis 2017). As a result we consider in the following that Kepler-78b sustains a strong enough magnetic field to possess a magnetosphere.

### 4.2. Location of the Interaction Footpoint on the Stellar Surface

The Alfvénic perturbations due to SPMI follow the Alfvén characteristics

$$c_A^\pm = v_A \pm v_A$$

and form the Alfvén wings (Neubauer 1980). Following these characteristics from the planetary orbit using the 3D simulation of the stellar wind of Kepler-78, one can trace back the impact location of the Alfvén wings on the stellar surface (see, e.g., Kopp et al. 2011). This is shown schematically for the northern hemisphere Alfvén wing in Figure 4 where four Alfvén characteristics connecting the planet magnetosphere to the stellar surface are illustrated. The characteristic area $A_{fp}$ of the footpoint of the interaction is shown in the close-up of the stellar surface in the top left insert. We will assume a characteristic size of the planet’s magnetosphere based on the pressure equilibrium between the magnetic pressure due to the planetary magnetic field and the ambient pressure in the stellar wind. This approximation gives a satisfying estimate of the magnetospheric size at the front of the interaction in 3D simulations (Strugarek 2016) and generally underestimates it in the magnetospheric tail. A more realistic estimate of the magnetospheric shape and size in the equatorial plane would not affect the main conclusions of our study.

We display the footpoints of the two wings (AW− and AW+) in Figure 5 for two different rotational phases of the star, along with the observed radial magnetic field of the star at its...
surface in blue/red contours. As the planet orbits, the footpoints of the wings move along the black lines on the stellar surface (the locations corresponding to the orbital phases 0.0, 0.2, 0.4, 0.6, and 0.8 are labeled by blue/red dots along path for the northern/southern Alfvén wing). We will refer to these paths as the Footpoint Paths (FPPs) later on. A front and a back view of the stellar surface are shown in Figure 5, which illustrates that each Alfvén wing primarily impacts opposite regions of the stellar surface for this specific magnetic topology of Kepler-78 of 2015 July. The star is viewed in Figure 5 with a rotation axis inclined at 80° to the line of sight, which is the inclination angle of Kepler-78 seen from the Earth.

The characteristic area of the footpoints $(A_{fp})$ along the FPP depends on the planetary field $B_P$ that sets the local size of magnetic interaction in the planet vicinity (see Figure 4). For a planetary field of 100 μT (1 G), the characteristic footpoint area is about 0.1% of the disk of Kepler-78. Hence, the footpoint of the interaction extends on characteristic sizes comparable to standard sunspots.

The magnetic topology of Kepler-78 and the subsequent location of the FPPs on the stellar surface has further important implications on the relative phase of the footpoint with respect to the planetary orbital phase. We illustrate this in Figure 6 for the two Alfvén wings (top panel) as a function of the orbital phase, neglecting for the moment the rotation of the star. We remark that the phase lag between the planet and the footpoint of the interaction greatly varies along the orbit, especially for AW⁻. This is of course a direct consequence of the compactness of the FPP on the stellar surface as shown in the left panel of Figure 5 for AW⁻. The four schematics in the bottom row of Figure 6 strikingly illustrate the phase-lag variations at four different phases along the orbit. We thus cannot expect the signal from SPMIs to be preferentially observed with a constant phase lag with respect to the orbital phase and must rely on our global modeling to predict the detailed time variability of SPMIs.

4.3. The Combined Effect of Orbital Motion and Stellar Rotation

As the star rotates, the FPP, which is tied to the global magnetic topology, rotates as well. This simple observation has a strong consequence on the tracers of SPMIs in the Kepler-78 system: any observable feature related to the SPMI in the spectrum of Kepler-78 will thus be correlated to both the orbital period (displacement of the footpoint along the FPP) and the stellar rotation period that will set the visibility of the FPPs. How the two effects combine to produce an observable signal is explored in Section 5.2. We already note that if the magnetic topology of the star changes due to, e.g., a magnetic cycle, this feature of the SPMI would also change accordingly. In addition, the variations along the orbital path will lead to different properties of the Alfvén wings along the FPP, which adds orbital-period modulations of any observable trace of the SPMI.

An additional and often overlooked aspect further blurs the picture. The propagation timescale $\tau_{\text{prop}}$ of Alfvén waves from the planetary orbit down to the FPP depends on the plasma characteristics between the planet and the star. As a result, perturbations triggered at different orbital phases can actually reach the stellar surface at the same time. To quantify this we integrate the inverse of the Alfvén speed along the Alfvén characteristic $c_A^\pm$ to estimate $\tau_{\text{prop}}$. The propagation timescale is shown in Figure 7 as a function of the orbital phase for the two wings. During most of the orbit Alfvén waves reach the stellar surface in a few percent of the orbital period, i.e., in about a few tens of minutes. At two noticeable orbital phases (around 0.4 for AW⁻ and 0.8 for AW⁺) the propagation time is much longer, which leads to delays as large as the orbital period itself.

The unipolar interaction model of Laine et al. (2012) requires that Alfvén waves can travel back and forth between the planet and the star, which could be the case here for a subpart of the orbit. Conversely, the dipolar interaction model...
studied in Strugarek (2016) does not require such a strong assumption and was robustly parameterized over a large range of star–planet configurations (Strugarek 2017). Consequently, we use this latter model to estimate the energetics of the SPMI in the Kepler-78 system.

5. Energetics of the SPMI

5.1. Magnetic Power of the SPMI along the Orbit

We now estimate the energetics of the SPMI in the Kepler-78 system to assess whether or not SPMIs could leave detectable signals in the activity tracers of the star. We will base our analysis on the scaling law for the Poynting flux in the Alfvén wings derived in Strugarek (2016, 2017a), which we recall here as

\[ P = A_1 \pi R_p^2 \left( 1 + C_1 \cos \Theta_M \right) \left( \xi_0^2 \Lambda_p \right) \]

where \( A_1 = 2.5 \), \( C_1 = 0.83 \), \( \xi_0 = 0.44 \), \( \xi_1 = -0.3 \), and \( \chi = 0.25 \) are constants that were fitted with 3D numerical simulations in Strugarek (2016, 2017a), and \( \Theta_M \) is the relative inclination of the planetary field with respect to the ambient magnetic field \( B_w \). The drag coefficient is defined as \( c_d = M_a / \sqrt{1 + \frac{M_p^2}{\Lambda_p^2}} \), and we left out any dependencies on the resistive properties of the planet ionosphere and stellar wind for the sake of simplicity (see Strugarek 2016 for more details). The approximate Poynting flux (5) was shown to be accurate within 50% when comparing the fully self-consistent 3D simulations (Strugarek 2016) with analytical formulae derived by Saur et al. (2013).

We use Equation (5) to estimate the Poynting flux density in the planet vicinity

\[ S_{AW} = \frac{P}{\pi R_m^2}, \]

where \( R_m = R_p \Lambda_p^{1/6} \) is the size of the obstacle that consists of the planet and its magnetosphere. We also use Equation (5) to estimate the Poynting flux impacting the stellar surface

\[ S_{AW} \approx \frac{P}{\Lambda_f}, \]

We recall here that \( \Lambda_f \) is estimated by following the Alfvén characteristics from the magnetospheric borders in the vicinity of the planet down the stellar surface.
The three Poynting flux densities $S_w$, $S_{AW}^P$, and $S_{AW}^*$ are illustrated in Figure 4. We suppose that the magnetic field of the planet is a dipole of strength $B_p$ at its equator, with a moment anti-aligned with the rotation axis. As a result, the inclination parameter in Equation (5) is simply $\Theta_M = \Theta_F$. This assumption makes the interaction in a $\sim 45^\circ$ inclination during most of the orbit. Note that a perfectly aligned configuration along the orbit would increase the Poynting flux amplitude (typically by a factor 2 at most; see Strugarek et al. 2017a), but it would not affect its temporal variability.

We display in Figure 8 the three Poynting flux densities $S_w$, $S_{AW}^P$, and $S_{AW}^*$ as a function of the orbital phase for three different planetary field intensities. The planet–wind interaction gives a 10% conversion efficiency from the incoming Poynting flux $S_w$ (top panel) to the Poynting flux in the vicinity of the planet $S_{AW}^P$ (middle panel). In spite of its small size, the magnetic interaction of Kepler-78b leads to Poynting flux densities $S_{AW}^*$ of the order of $10^{-2}-10^{-1}$ kW m$^{-2}$ for realistic magnetic field intensities. The Poynting flux density weakly decreases with $B_p$ ($S_{AW}^* \propto B_p^{-0.1}$) due to the competition of two opposite effects. As $B_p$ increases, the magnetospheric size increases, allowing a larger area of interaction that increases $\mathcal{P}$. At the same time, increasing the area of interaction decreases the flux density. The second effect is slightly stronger, which leads to the observed weak negative dependency with $B_p$. Note that this dependency is sensitive to a correct estimation of the nonspherical magnetospheric size of Kepler-78b, which is beyond the scope of the present work.

As the Alfvénic perturbations follow converging magnetic field lines when propagating toward the star, the Poynting flux density increases up to a few kW m$^{-2}$ when it impacts the stellar lower atmosphere ($S_{AW}^*$; bottom panel of Figure 8). The observed Hα flux at $\phi_H = 0$ (see Figure 1) corresponds to a power density of 60 kW m$^{-2}$ if it originates from a localized area of 0.1% of the stellar disk (averaged footprint area; see above). As a result, the predicted SPMI flux density is one order of magnitude smaller than the observed flux density. In addition, it must be noted that only part of the Alfvén wings energy will likely be converted to the activity band. For instance, in accretion-powered emissions in young systems the conversion factor in Hα is typically of a few percent (e.g., Fang et al. 2009). If such a conversion factor applies to SPMIs, their detection would be challenging but could be foreseen provided a distinctive temporal modulation can be identified. We now describe how to predict the temporal variability of SPMI signals with the example of Kepler-78.

### 5.2. Modeling the SPMI Emission Modulation

The power channeled in the SPMI can in principle be transferred into an observable signal through various mechanisms (e.g., see Saur 2018 and references therein). Nevertheless, the timing of any SPMI-induced feature is at first order independent of the detailed physical mechanism producing it: it is determined by the topology of the Alfvén wings (Figure 5) and the Alfvén waves travel time (Figure 7), which can be predicted from the present simulations. Indeed, the footpoint of the interaction sweeps over the stellar surface as the planet orbits, as shown in Figure 5. Meanwhile, the star itself rotates as well, which induces a complex temporal variability.

The exact mechanism leading to an observable tracer nonetheless matters: emissions from accelerated particles will likely be isotropic, while local heating of the chromosphere/photosphere will likely be subject to limb-darkening effects. In the latter case, we need to correct the expected SPMI flux along the FPP with limb-darkening based on the quadratic law of Espinoza & Jordán (2015) (the coefficients for Kepler-78 were obtained using the limb-darkening Python package by Espinoza & Jordán (2015), with the closest match being $T_{\text{eff}} = 5000$ K, $\log g = 4.5$, [Fe/H] = 0, and microturbulent velocity of 2 km s$^{-1}$). We have included the effect of limb-darkening in our modeling in what follows. Nevertheless, our conclusions hold with and without limb-darkening effects.

The resulting expected instantaneous emission variability in the Hα band is shown in Figure 9 by gray dots, along with the 1.9 hr averaged (orange, corresponding to the observational exposure time; see Moutou et al. 2016) and orbit-averaged (black) emissions. We assumed here a planetary field $B_p = 50$ $\mu$T (blue curves in Figure 8) and computed the emission for one rotational phase of the star, i.e., about 34 orbits of Kepler-78b. The fast variations in the gray dots and in the orange curve mainly originate from the planetary orbital

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https://github.com/nespinoza/limb-darkening
motion through the inhomogeneous corona of the star. The orbit-averaged signal (black curve) naturally filters the orbit motions and shows a clear modulation with the rotational period of the star, as expected.

We overlay the observed flux in the Hα band (red circles; see also Figure 1), multiplied by a factor of 1000 to mimic an emission originating from the SPMI footpoints (over an average area of 0.1% of the stellar surface), and divided by 10 to ease the comparison between the two signals. We remark that the temporal modulation of the observed signal is not well correlated with the SPMI signal. In particular, the excess flux around ϕrot = 0.8 corresponds to the minimum excess flux awaited from the SPMI.

Interestingly, a dephasing of ~0.3 in the rotational phase of the star is enough to restore an excellent correlation between the observed signal and the SPMI flux modulation. The magnetic field topology of Kepler-78 determines the temporal modulation of the SPMI flux. As a result, dephasing the SPMI signal by 0.3 would require major changes in the magnetic field topology (see Appendix A). We have assessed the robustness of the variability of the SPMI signal along the orbital phase (black line) by varying the inclination angle of Kepler-78 with respect to the Earth, the orbital period of Kepler-78b, and the number of spherical harmonics used in the ZDI magnetic map. The detailed results are shown in Appendix A. The main conclusion is that the overall trend with the rotational phase is extremely robust.

Finally, we note that the three last points of observation were taken about 2.5 rotation periods later during the summer of 2015. It is possible that the magnetic topology of Kepler-78 changed significantly over this period of time, with, for example, the appearance/disappearance of active regions affecting the large-scale magnetic topology or due to changes through the shear of the differential rotation. A detection of SPMI would thus require denser observational data sets to properly address this uncertainty.

6. Discussions on the Detectability of SPMIs

We have shown that SPMI in the Kepler-78 system is powerful enough to be potentially detectable in characteristic activity tracers such as Hα (Moutou et al. 2016). Our study opens up promising possibilities of detection for more favorable systems and/or through dedicated and carefully planned observational campaigns. We discuss here these aspects to pave the road toward future positive detections of SPMIs.

Stellar magnetic field. First and foremost, we reiterate that several critical ingredients are needed to properly hunt for traces of SPMIs: (i) the magnetic topology of the star, (ii) the mass and radius of the host star, and (iii) the orbital properties of the planet. Once these three aspects are properly constrained, one can relate an SPMI emission to the magnetic properties of the orbiting planet. Without these three aspects, it is impossible to predict how any signal for the SPMI is modulated as a function of, e.g., the orbital period of the planet or the rotational period of the star. It is further useful to recall that the SPMI emission increases with the stellar magnetic field. Indeed, extracting to first order the dependency in Bw in Equation (6), one finds 〈Wfi〉 ∝ Bw0.7. More favorable systems with large stellar magnetic field can thus be expected to show strong SPMI signals.

Planetary magnetic field. The amplitude of the SPMI emissions also depends on the assumed planetary field amplitude and topology. Note that at first order, the temporal variability of the signal itself does not depend on the planetary field. The Poynting flux P channeled by the magnetic interaction is roughly proportional to Bp2/2 (see Equation (5)). As Bp increases, the size of the magnetosphere increases and the shape and strength of the Alfvén wings are slightly altered (see Figure 8), leading to small changes in the properties of the footprint of the interaction. We expect giant close-in planets with a strong magnetic field to be the most favorable targets to detect SPMI tracers.

Stellar wind model uncertainties. The analysis carried in this work relies on the wind modeling of the central star. Parameters such as the coronal temperature and density, or equivalently the mass-loss rate of the star, are not well constrained for Kepler-78. We have assessed the sensitivity of our wind modeling choice by varying the base density of the model (n; see Figure 9. Instantaneous flux density (transparent gray dots) as a function of the rotational phase of the star. We also show the SPMI signal smoothed over 1.9 hr (orange) and over the orbital period (black). The observed Hα flux is shown by the red circles. It is the same data as in Figure 1, multiplied by 1000 to mimic a signal originating from the footpoints of the SPMI (covering on average 0.1% of the stellar disk), and then divided by 10 to easily compare the temporal modulations of the observed and predicted signals.
Equation (1)) by a factor of 4. This affects the Alfvénic Mach number in the stellar wind and the amplitude of the SPMI flux density can thus vary by the same factor. Nevertheless, the temporal variability of the SPMI signal is found to be very robust with respect to the plasma properties at the base of the corona (see also Appendix A).

**Observational strategy.** We have shown that any signal of SPMIs in the Kepler-78 system should be modulated over both the orbital and the stellar rotational periods. The unambiguous detection of SPMI thus requires denser observational campaigns covering both the orbital timescale (in and out of transit observations) and the rotational timescale (recurrent visits over a timescale of weeks). When the magnetic topology of the star is known, it is not to vary much over a given observational period, our methodology allows us to predict the favorable rotational and orbital phases for SPMI signals. These interesting phases can be predicted combining simple stellar wind models with potential-field source-surface extrapolations (e.g., with our simplified but calibrated starAML+PFSS package; see Section 3), i.e., without relying on computationally expensive modeling. As a result, observational campaigns to detect SPMIs can leverage the known properties of the star–planet systems to identify on the fly the preferred observation windows where the signal is the most likely to be detected.

The analysis presented in this paper opens a promising avenue to estimate the magnetic properties of an exoplanet, provided (i) we have the necessary observational constraints on the system and (ii) a signal well correlated with the expected time variability of the SPMI can be unambiguously detected. Favorable star–planet systems would consist of a central dwarf or young star with a strong, dipolar-like magnetic field (e.g., à la AD Leo; see Morin et al. 2008) around which a very close-in hot Jupiter would orbit. We intend to analyze more systematically such systems in the near future.

### 7. Conclusions

We have applied in this work the concept of Alfvén wings to SPMIs in the Kepler-78 star–planet system. We modeled the environment of Kepler-78 with a 3D wind model (Réville et al. 2016) based on the observed magnetic topology of the star with ZDI (Moutou et al. 2016). We have shown that the environment of Kepler-78b varies along its orbit, which leads to large modulations of the magnetic interaction. Furthermore, these modulations lead to time lags between observable SPMI features along one orbit of Kepler-78b. Consequently, signals from SPMI have to rely on a dedicated modeling of the star–planet system leveraging the orbital properties of the planet as well as the magnetic properties of the star.

Despite the relatively small size of Kepler-78b, we have shown that the SPMI can channel energy flux densities up to a few kW m$^{-2}$ toward Kepler-78. This flux is a priori large enough to be detectable with present telescope capabilities in Kepler-78 (see Figure 9 and Moutou et al. 2016), provided enough energy is transferred from the SPMI to the activity tracer considered.

The detailed modeling of the wind of Kepler-78b allows us to go beyond order-of-magnitude estimates and predict the temporal variability awaited from SPMIs (see Figure 9). We show that the most favorable period for detecting occurs around $\phi_{\text{rot}} = 0.25$ for the magnetic topology of Kepler-78 as of 2015 July. We have shown that the temporal variability predicted by our model is very robust to typical uncertainties in the planet orbital characteristics, inclination angle, as well as ZDI map spatial resolution (see Appendix A).

We have focused our analysis here on reproducing the temporal variability of standard magnetic activity tracers of a star. It is nevertheless not obvious today which wavebands should be the most favorable to detect SPMIs. Our modeling allows us to characterize the available power in SPMIs and its temporal signature. How is this power transmitted from Alfvén waves to radiation? These waves can transfer their energy by wave–wave (Elmegreen 1994) or wave–turbulence interactions in the low corona of the star, can accelerate energetic particles as in the magnetosphere of Jupiter, or can even act as a trigger of stellar flares. A careful scrutiny of these different mechanisms and their subsequent preferential observable wavebands (radio, X, visible, UV, etc.) is needed today to further probe SPMIs in distant exoplanetary systems.

The methodology presented in this work nevertheless opens a clear path for the future detection of SPMIs. Denser observational campaigns of star–planet systems covering targeted orbital and rotational phases would allow us to unambiguously separate stellar activity from SPMIs in favorable star–planet systems such as Kepler-78. The chase for SPMIs is still at its early stages and we can foresee their systematic detection in the coming years.

The authors thank an anonymous referee for valuable comments that improved the analysis presented in this paper. A.S. thanks A. Mignone and his team for giving the PLUTO code to the research community and J. Saur for discussions about star–planet and planet–satellite magnetic interactions. A.S. acknowledges access to supercomputers through GENCI (grant 20410133). A.S. and A.S.B. acknowledge funding from CNES-PLATO and CNES-Space Weather grants. A.S. and A.S.B. acknowledge funding from the Programme National Soleil-Terre (PNST). A.S. acknowledges funding from the Programme National de Planétologie (PNP). J.F.D. acknowledges funding from the European Research Council (ERC) under the H2020 research & innovation program (grant agreement #740651 NewWorlds).

### Appendix A

**Sensitivity of the Modeled SPMI Signal**

The modeling of SPMIs in Kepler-78 is subject to several observational uncertainties. We explore the sensitivity of our results in this appendix and show that the overall temporal modulation of the awaited SPMI signal is very robust for this star–planet system if we neglect strong temporal variability of the stellar magnetic field.

We have used our calibrated starAML+PFSS model to explore the sensitivity of our results. We have tested three uncertain observational parameters: the orbital period of the planet, the inclination angle of the rotation axis of Kepler-78 with respect to the Earth, and the number of spherical harmonics used in the ZDI magnetic map. For each of these parameters, we applied our analysis pipeline and compare the orbit-averaged signal (black line in Figure 9 and in the panels of Figure 10) due to SPMI.

We have varied the orbital period of Kepler-78b from 0.23 days to 0.78 days (top left panel of Figure 10), which corresponds to semimajor axes from 2 to 4.5 stellar radii.
amplitude of the SPMI varies by an order of magnitude. This simply reflects the change in the amplitude of the stellar wind magnetic field amplitude at the planetary orbit that sets the Poynting flux $S_n$ at the source of the magnetic interaction. Nonetheless, the temporal modulation of the signal is very robust, with a maximum around $\phi_{\text{rot}} \approx 0.15$ and a minimum around $\phi_{\text{rot}} \approx 0.75$ for all orbital periods. Note that this exploration is wider than the error bars on the inclination angle and is intended to be educational. This time the effect is mainly on the temporal modulation itself. In the extreme case of a perpendicular inclination $i = 0^\circ$, we always see the same pole of the star. As a result, we see that the main changes in the observed $\phi_{\text{rot}}$ occur around $\phi_{\text{rot}} = 0.5$ for H$\alpha$, $\phi_{\text{rot}} = 0.3$ for Ca II H&K, and $\phi_{\text{rot}} = 0.5$ for Ca II IRT. In all bands, the maxima always occur near $\phi_{\text{rot}} \sim 0.15$ and $\phi_{\text{rot}} \sim 0.8$. As a result, we see that the main conclusions of this work are not affected by the differences between the observed flux in the various activity tracers characterized by Moutou et al. (2016).

Appendix B
Activity Tracers for Kepler-78

We have focused our study on one particular activity tracer (H$\alpha$) of Kepler-78. In the original work of Moutou et al. (2016), several other activity tracers including the H&K bands and infrared triplet (IRT) of Ca II were also characterized. We report in Figure 11 these tracers in the same layout as in Figure 1. We remark that the overall rotational modulation of these tracers is similar to H$\alpha$. The flux in the H&K bands is of similar amplitude to H$\alpha$, and the IRT flux is about four to five times smaller. The main difference lies in the rotational phase where the observed flux is minimized: it occurs around $\phi_{\text{rot}} \approx 0.5$ for H$\alpha$, $\phi_{\text{rot}} = 0.3$ for Ca II H&K, and $\phi_{\text{rot}} = 0.5$ for Ca II IRT. In all bands, the maxima always occur near $\phi_{\text{rot}} \sim 0.15$ and $\phi_{\text{rot}} \sim 0.8$. As a result, we see that the main conclusions of this work are not affected by the differences between the observed flux in the various activity tracers characterized by Moutou et al. (2016).
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Figure 11. Flux observed in the H&K bands (left) and infrared triplet (right) of Ca II as reported by Moutou et al. (2016). The layout of the figures is the same as in Figure 1.