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The magnetic properties of the star Kepler-78

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ABSTRACT

Kepler-78 is host to a transiting 8.5-h orbit super-Earth. In this paper, the rotation and magnetic properties of the planet host star are studied. We first revisit the Kepler photometric data for a detailed description of the rotation properties of Kepler-78, showing that the star seems to undergo a cycle in the spot pattern of ~1300 d duration. We then use spectropolarimetric observations with Canada–France–Hawaii Telescope (CFHT)/ESPaDOnS to measure the circular polarization in the line profile of the star during its rotation cycle, as well as spectroscopic proxies of the chromospheric activity. The average field has a strength of 16 G. The magnetic topology is characterized by a poloidal and a toroidal component, encompassing 60 per cent and 40 per cent of the magnetic energy, respectively. Differential rotation is detected with an estimated rate of 0.105±0.039 rad d⁻¹. Activity tracers vary with the rotation cycle of the star; there is no hint that a residual activity level is related to the planetary orbit at the precision of our data. The description of the star magnetic field’s characteristics then may serve as input for models of interactions between the star and its close-by planet, e.g. Ohmic dissipation and unipolar induction.

Key words: techniques: radial velocities – techniques: spectroscopic – planet–star interactions – stars: magnetic field – planetary systems – starspots.

1 INTRODUCTION

Extrasolar planets at very short orbital distance from their stars have questioned the formation theories since their discovery 20 yr ago (Mayor & Queloz 1995), although a theoretical framework existed to explain their existence (Goldreich & Tremaine 1980): planets could be formed outside the snow line and migrate inwards due to interactions with the disc. After several decades of theoretical studies on planetary migration, these phenomena have been extensively described (for a recent review, see Baruteau & Masset 2013, and references therein). Once started, the migration of the outer planets may occur on very short time-scales. The efficiency of the mechanism thus requires a strong braking mechanism to halt the migration and insure the planet survival. It has been proposed that the migration stops when the planet enters the magnetospheric cav-ity of the star, where the disc is truncated (Lin, Bodenheimer & Richardson 1996). Making further progress in the description of these phenomena requires both to get measured constraints on this magnetospheric cavity and to probe the limit conditions of planet survival by discovering and characterizing extreme systems.

A new class of ultrashort-period planets has been recently unveiled by the Kepler satellite: these are super-Earth candidates with orbital periods of a few hours (106 candidates) (Sanchis-Ojeda et al. 2014). With such compact orbits, the evolution of these planets is strongly influenced by the radiative evaporation, tidal torque, and magnetic interaction with their host stars. The fact that the vast majority of these ultrashort-period candidates have radii smaller than 2 Earth radii could mean that they are either some failed cores or the residuals of more massive planets having suffered strong evaporation, mass-loss, and/or tidal disruption.

Following the recent theoretical developments on star–planet magnetic interactions, Laine & Lin (2012) have proposed that the motion of the small planet relative to the magnetic field of its host star may induce unipolar induction, similar to the mechanism between Io and Jupiter. This induction generates an electric field across the planet’s surface and an electric current which circulates across the planet’s mantle, along the flux tube between the planet and its host star, and across the footprint of the flux tube on the surface of the star. The intensity of the current and its associated Ohmic dissipation are determined by both the strength of the stellar magnetic field and the electric conductivity in the planetary mantle. In this study, we present new observations aimed at describing the magnetic properties and activity signatures of one host star of such planetary system, Kepler-78.
Kepler-78 is a 625 ± 150 Myr, late G dwarf, which ultrashort-period planet has been detected and characterized in 2013 (Howard et al. 2013; Pepe et al. 2013; Sanchis-Ojeda et al. 2013). It is a planet very similar to Earth in radius, mass and density. Its extremely short orbital period of 8.5-h period and 3R, semimajor axis, however, makes it different to temperate telluric planets. The equilibrium temperature of the planet surface is of the order of 2300–3100 K, depending on its albedo, on its dayside (Sanchis-Ojeda et al. 2013). The rocks composing the telluric planet would be molten on the dayside, and condensed on the nightside, generating a desequilibrium of the planet structure and other extreme physical phenomena as first described by Léger et al. (2011) for the so-called lava-ocean planets.

In this paper, we present an observational followup of this interesting system. In Section 2, we revisit the Kepler observations of this star. In Section 3, we present new observational data and analyses to constrain the magnetic properties of the planet host Kepler-78, obtained with ESPaDOnS at the Canada–France–Hawaii Telescope. In Section 4, we describe the results obtained by Zeeman Doppler Imaging on the magnetic topology of the stellar surface and differential rotation. In Section 5, we report the analysis of activity proxies from this data and search for potential planetary signatures. In Section 6, we present our search for reflected light signature. Then we summarize and present our conclusions in Section 7.

2 PHOTOMETRIC VARIABILITY FROM KEPLER OBSERVATIONS

Kepler-78 (also known as TYC 3147-188-1 or KIC 8435766) was observed by the Kepler satellite for almost 4 yr. Due to an early limitation of the Kepler period-search space towards short periods, the planet signal was not primarily part of the list of Kepler Objects of interest (Batalha et al. 2013). Further studies, however, focused on the search for transits at extremely short orbital periods (e.g. Sanchis-Ojeda et al. 2014), and their first success was the discovery of Kepler-78 b (Sanchis-Ojeda et al. 2013). Both the primary transit, the occultation and the phase variations during the 8.5-h orbit were detected. Kepler-78 b mass was then measured after intensive radial velocity campaigns were carried out using HARPS-N on the Telescope National Galileo (Pepe et al. 2013) and HIRES on the Keck telescope (Howard et al. 2013), although stellar activity has been a serious limitation of these analyses. Both spectroscopic studies, using different data sets and independent methods for the correction of the stellar jitter, resulted in very similar parameters for the planet mass (1.86 ± 0.25 and 1.69 ± 0.41 Earth mass, respectively, in circular orbits). Grunblatt, Howard & Haywood (2015) and Hatzes (2014) also determined planet masses from the same data set. Combined with the radius inferred by Kepler, the planet density is very similar to Earth’s density, although Kepler-78 b evidently has had a very different orbital evolution and most probably has a different internal structure.

Concerning the stellar properties, Kepler-78 has been identified as a young, late G dwarf, with an age of about 625 ± 150 Myr and a stellar mass of 0.76–0.83 M⊙ (Howard et al. 2013; Pepe et al. 2013; Sanchis-Ojeda et al. 2013). Due to a relatively young age, the star is active as seen from its Kepler light curve. The mean rotation period of the star based on the light-curve autocorrelation analysis has been found to be 12.588 ± 0.03 d (McQuillan, Mazeh & Aigrain 2014). Despite the low error bar associated with this measurement, it is clear from the light curve that a single period cannot explain all the observed variability.

We have computed the periodograms of Kepler data using the Exoplanet Archive online tool1 for the 4 yr of data (Fig. 1, left). The main peak covers the range 11–14.5 d, and a secondary set of peaks at about half the main period, between 6 and 6.5 d. Then we did the computation quarter by quarter, excluding the first slot of data which covers less than a stellar period (see Fig. A1 for each individual periodogram). Fig. 1 (right) shows the location of the main peak of these periodograms as a function of time, compared to the mean rotation period of 12.588 ± 0.03 d. Error bars were also estimated from the periodograms. For some quarters, the main peak is not at the full period, but one of the harmonics (not shown on the figure, see Fig. A1). When the main peak shows the rotation period, this value seems to be first decreasing, then increasing, showing a minimum of 13.8 d at about JD = 245433+250 and +1550. The minimum is around 11.7 d. We do not include the quarters where the main periodogram peak corresponds to about half the rotation period (doubling the period), because then the stellar surface probably has two main active regions which do not have to lie exactly 180° apart, so twice these periods do not correspond exactly to the full rotational period – or the ~12 d period would show a significant power in the periodogram.

Apart from one deviant point at the beginning of the series (which corresponds to a shorter period of time, 33 d instead of a full quarter of 90 d, hence a large error bar), the behaviour of the measured rotational periods looks sinusoidal. We may interpret this behaviour as a stellar activity cycle, similar to the solar cycle. Due to some

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1 http://exoplanetarchive.ipac.caltech.edu/cgi-bin/Pgram/nph-pgram
amount of differential rotation and to the dynamo cycle of the star, the spots appearing at higher latitude at the beginning of the Kepler time series have a 13.8-d period, then migrate to the equator where their rotation period is shorter (down to 11.7 d). When fitting a sine wave, we find a period of 1300 ± 200 d, amplitude of 0.9 ± 0.2 d and a mean period of 12.57 ± 0.17 d. If what we see on Kepler-78 is similar in nature to the solar cycle, we expect maximum activity to correspond to epochs where the apparent rotation period is smallest, i.e. when spots tend to cluster near the equator.

If our interpretation is correct, we could be witnessing an activity cycle of about 3.5 yr duration, three times shorter than the 11-yr solar cycle. A sophisticated spot modelling of the full light curve could probably reproduce the butterfly diagram of Kepler-78, which is not the purpose of this paper. Two values could be derived from this analysis: (i) the differential rotation is at least 0.08 rad d\(^{-1}\) (since spots probably cover only a range of latitude and do not extend all the way to the poles, it is a lower limit), and (ii) the mean rotational period of the star during our ESPaDOnS campaign can be extrapolated to 12.2 ± 0.3 d (shown by the vertical lines on the right of Fig. 1, right, assuming the period and amplitude of the cycle are as quoted above). We could also expect most of the active regions (or the dominating ones) to be near the ~30° latitude at this epoch (assuming a differential rotation law in sin\(\theta\) where \(\theta\) is the latitude of the region, see Section 4.1). The rotation period during the HARPS-N and HIRES campaigns may have been close to the maximum rotation period (~13.5 d) in our extrapolation, and probably close to a minimum of the stellar spot activity. In his pre-whitening analysis, Hatzes (2014) finds maximum power at 6.44 d in HIRES data and 3.42 d in HARPS-N data. These frequencies are interpreted as \(P_{\text{rot}}/2\) and \(P_{\text{rot}}/4\), respectively, which points towards a rotational period in the range 12.7–13.6 d. The detection of the rotational period in the radial velocity data is, however, not as precise as with Kepler, because of the sparse sampling of these two data sets.

3 SPECTROPOLARIMETRIC OBSERVATIONS

We observed Kepler-78 with the ESPaDOnS spectropolarimeter at the Canada–France–Hawaii Telescope on top of Mauna Kea. In its polarimetric mode, ESPaDOnS allows us to observe the spectral range from 370 to 1050 nm at a resolving power of 65 000 (see Fig. B1 for an example spectrum). We measured the circularly polarized signal in the Stokes V configuration as well as the Stokes I unpolarized spectra. Obtaining the circular polarization is achieved by acquiring sequences of four consecutive exposures in different polarimeter configurations which allows not only to detect polarization signatures for the chosen Stokes parameter, but also to determine the potential level of spurious signatures in the null profiles N (and correct for them if needed).

Two sequences were first acquired in 2014 September,\(^2\) during which feasibility was assessed. Since the polarized signal was detected in these spectra, we applied for more telescope time to observe Kepler-78 with ESPaDOnS over a full rotational cycle (about two weeks). These observations were performed between 2015 July 22 and August 28.\(^3\) We secured 13 spectropolarimetric sequences with a peak signal-to-noise ratio ranging from 250 to 285 per 2.6 km s\(^{-1}\) pixel, at 780 nm. The last three exposures are separated from the first ten by about a month. Since the last three sequences nicely fill the gap in the phase coverage of the rotational cycle, in the following, we analyse the data set of the all 13 sequences acquired in 2015. The log of the observations is in Table 1. Reference ephemeris for the phases are \(T_0 = 2457 226.9\), \(P_{\text{rot}} = 12.588\) d (MacQuillan et al. 2014) for the stellar rotation and \(P_{\text{orb}} = 0.355\) 074 d and \(T_0 = 2454 953.959\) 95 (transit time) for the planet orbit (Sanchis-Ojeda et al. 2013).

The ESPaDOnS data were processed by the Libre-Esprit pipeline (Donati et al. 1997, 2007), which includes flat-field correction, wavelength calibration and optimal extraction of all (highly distorted) orders along the (tilted and wiggly) slit formed by the image slicer at the entrance of the spectrograph. The pipeline also provides a correction for the instrumental spectral drift using the telluric spectrum achieving an average \(\text{rms}\) radial-velocity precision of 20–30 m s\(^{-1}\) (Moutou et al. 2007). We then used the Least Square Deconvolution technique (Donati et al. 1997) to take advantage of the very large number of stellar lines in the spectrum (6740 in average). We used a mask of stellar lines from ATLAS9 LTE model atmosphere (Kurucz 1993) featuring a 5000 K star with log\(g\) = 4.5. This provides us with a mean intensity profile for each sequence, where the radial velocity of the star can be measured (Table 1). All spectra are corrected for spectral shifts resulting from instrumental effects using telluric lines as a reference. The \(\text{rms}\) of the radial velocities is 12 m s\(^{-1}\) and the peak-to-peak variation is 40 m s\(^{-1}\), while individual measurement accuracies range from 30 to 40 m s\(^{-1}\). Kepler-78 radial velocity jitter in previous studies is found to be characterized by a standard deviation of 4.3 and 10 m s\(^{-1}\), respectively, for Pepe et al. (2013) and Howard et al. (2013). Peak-to-peak variations of 23 and 49 m s\(^{-1}\) were found in these data sets. Systemic velocity is found to be ~3.44 km s\(^{-1}\) in our data, and ~3.51 km s\(^{-1}\) (respectively, ~3.59 km s\(^{-1}\)) for these previous studies. The difference in systemic velocity are mostly due to instrumental shifts, since different instruments and pipelines are used (and ESPaDOnS has no absolute velocity calibration), and to activity. Our values of RV jitter and peak-to-peak variations are similar to those measured in previous data sets. This is not the goal of the paper to try to correct for the jitter and search for the planet-induced Doppler signal. This is not possible given the limited RV precision of ESPaDOnS and the short time series.

Polarized signatures in Stokes V profiles are corrected for small residual signals in null profiles N, such corrections having no more than a small impact on final results. Zeeman signatures are detected in four of Stokes V Least Square Deconvolution profiles, featuring amplitudes of less than 0.05 per cent of the continuum. There are marginal detections in six others and no detection in three profiles. Marginal and definite detections correspond to a false-alarm probability threshold of, respectively, \(10^{-3}\) and \(10^{-5}\). We show in Fig. 2 our sets of Stokes V Least Square Deconvolution profiles.

4 MAGNETIC IMAGING AND DIFFERENTIAL ROTATION

4.1 Method

To reconstruct the magnetic maps of Kepler-78, we use the tomographic Zeeman Doppler Imaging (ZDI) code. It is set up to invert the time series of Stokes V profiles into magnetic maps of the stellar surface, i.e. the distribution of magnetic fluxes and orientations (Donati et al. 1997). The magnetic map is iteratively derived from a comparison with the observed and modelled Stokes V profiles until we reach a pre-defined \(\chi^2\) level. The ZDI code decomposes the stellar surface into multiple grid cells of similar projected areas and
calculates the contribution of each grid to the spectral profile. The reconstructed profiles are obtained by summing the spectral contribution of all cells, for each rotation phase. Given that the problem is ill-posed, we use the maximum-entropy criterion to select the image with the least amount of information among all those fitting the data at the required level. Like Doppler Imaging, ZDI relies on the assumption that the observed variability is solely attributable to rotational modulation, and potentially to differential rotation (if included in the modelling); any source of intrinsic variability beyond differential rotation cannot be explained with ZDI. The ZDI code has been based on early work by Skillig & Bryan (1984), Brown et al. (1991) and Donati et al. (1997) and further developed in the last twenty years from magnetic studies of stars of various properties (e.g. Donati et al. 2006, 2008; Fares et al. 2010; Morin et al. 2010). We refer the reader to these studies for further details on the method.

In the ZDI code, the magnetic field is described by its radial poloidal, non-radial poloidal and toroidal components, all expressed in terms of spherical harmonics expansion. In the case of Kepler-78, we truncated the spherical harmonics expansion to the five lowest terms ($\ell < 5$), which is adequate for slow rotators (e.g. Fares et al. 2010). Fig. 2 shows our fit of the data using the ZDI modelling. We adopted the v sin i value of $3 \pm 1$ km s$^{-1}$, from literature values (Howard et al. 2013), with little impact on the ZDI analysis. For the inclination, we used $i = 80^\circ$, assuming that the orbit of the planet is more or less aligned with the rotation of the star. The star inclination is known to have little impact on the output of the reconstruction, within typically $10^\circ - 15^\circ$. The fits we obtain correspond to a $\chi^2$ equal to 1.0 starting for a $\chi^2$ of 2.1. A map in brightness cannot be obtained for Kepler-78 which has a too small rotation rate and too low profile distortions.

The fit to the data is slightly improved if we assume that the star is rotating differentially rather than as a solid body (improvement of 1.9 per cent of the $\chi^2$ compared to the configuration where rotation is solid with a 12.588-d period). We proceed as in our previous studies (e.g. Donati et al. 2000, 2014; Petit, Donati & Collier Cameron 2002; Donati, Collier Cameron & Petit 2003). For a differentially rotating star, magnetic regions located at different latitudes have different angular velocities. In the model, the rotation rate at the surface of the star may vary with latitude $\theta$ as in the Sun, i.e. $\Omega(\theta) = \Omega_{eq} - d\Omega \sin^2 \theta$, where $\Omega_{eq}$ is the rotation rate at the equator and $d\Omega$ the difference in rotation rate between the equator and the pole. We may thus estimate the spectral contribution of each elementary region at the surface of the star to the synthetic disc-integrated Stokes V stellar profiles for given values of $\Omega_{eq}$ and $d\Omega$. For each pair of ($\Omega_{eq}$, $d\Omega$), we then reconstructed a magnetic image at a given information content from the observed profiles and get the $\chi^2$. The obtained surface of $\chi^2$ is fitted by a paraboloid to obtain the optimum rotation values of the star (Fig. 3).

### 4.2 Results

The optimal rotation parameters derived from the magnetic reconstruction as shown in Fig. 3 are $\Omega_{eq} = 0.543 \pm 0.009$ rad d$^{-1}$ and $d\Omega = 0.105 \pm 0.039$ rad d$^{-1}$. There is thus a hint of

| UT date | HJD-2400000. (d) | $\Phi_{tot}$ | $\Phi_{orb}$ | $\Phi_{syn}$ | Texp(s) | SNR | H$\alpha$ | Ca ii HK | Ca ii IRT | RV (km s$^{-1}$) | Magn Det |
|---------|-----------------|-------------|-------------|-------------|---------|-----|--------|---------|----------|---------------|------|
| 2014 Sep 07 | 56907.889 | -25.34 | 0.91 | 0.68 | 4 x 1700 | 293 | -0.063 | +0.362 | +0.071 | -3.477 M | N |
| 2014 Sep 12 | 56912.861 | -24.95 | 14.91 | 14.29 | 4 x 1700 | 253 | -0.016 | +0.620 | +0.097 | -3.426 M | M |
| 2015 Jul 23 | 57226.905 | 0.000 | 0.53 | 0.96 | 4 x 1715 | 275 | ±0.017 | ±0.087 | ±0.009 | ±0.181 ZDI | ±0.181 ZDI |
| 2015 Jul 24 | 57227.893 | 0.079 | 3.31 | 3.67 | 4 x 1715 | 280 | +0.014 | ±0.067 | ±0.008 | ±0.032 M | M |
| 2015 Jul 25 | 57228.979 | 0.165 | 6.37 | 6.64 | 4 x 1715 | 284 | ±0.014 | ±0.051 | ±0.013 | ±0.032 M | M |
| 2015 Jul 26 | 57229.984 | 0.245 | 9.20 | 9.39 | 4 x 1715 | 279 | +0.000 | ±0.057 | ±0.011 | ±0.032 M | M |
| 2015 Jul 27 | 57230.907 | 0.318 | 11.80 | 11.92 | 4 x 1715 | 276 | ±0.014 | ±0.057 | ±0.011 | ±0.032 M | M |
| 2015 Jul 28 | 57231.977 | 0.403 | 14.81 | 14.85 | 4 x 1715 | 258 | -0.213 | -0.847 | -0.096 | -3.441 D | D |
| 2015 Jul 29 | 57233.037 | 0.487 | 17.80 | 17.75 | 4 x 1715 | 274 | ±0.015 | ±0.061 | ±0.010 | ±0.032 M | M |
| 2015 Jul 30 | 57233.863 | 0.553 | 20.13 | 20.01 | 4 x 1715 | 276 | ±0.222 | ±0.054 | ±0.015 | ±0.032 M | M |
| 2015 Jul 31 | 57234.824 | 0.629 | 22.83 | 22.64 | 4 x 1715 | 267 | ±0.015 | ±0.059 | ±0.008 | ±0.032 M | M |
| 2015 Aug 01 | 57235.895 | 0.714 | 25.85 | 25.57 | 4 x 1715 | 271 | ±0.014 | ±0.061 | ±0.009 | ±0.032 M | M |
| 2015 Aug 07 | 57261.836 | 2.775 | 98.92 | 96.58 | 4 x 1715 | 273 | ±0.017 | ±0.068 | ±0.010 | ±0.032 M | M |
| 2015 Aug 08 | 57262.800 | 2.852 | 101.64 | 99.22 | 4 x 1715 | 286 | ±0.022 | ±0.049 | ±0.012 | ±0.032 M | M |
| 2015 Aug 28 | 57263.882 | 2.938 | 104.68 | 102.18 | 4 x 1715 | 276 | ±0.021 | ±0.069 | ±0.013 | ±0.032 M | M |

Table 1. Journal of the observations: UT date of observations, Julian date, rotational, orbital and synodic phases, total exposure time per visit, peak signal-to-noise ratio per 2.6 km s$^{-1}$ pixel in the combined spectra, activity measurement proxies (Ca ii H and K, H$\alpha$ and Ca ii IRT), radial velocities and status of magnetic detections. Rotation period is 12.588 d, orbital period is 0.355 074 d and synodic period is 0.365 d. Radial velocities (RV) have typical errors of 30 m s$^{-1}$. In the last column, D stands for Definite detection (defined by a false alarm probability smaller than 10$^{-5}$), M for Marginal detection (false alarm probability between 10$^{-5}$ and 10$^{-3}$) and N for Non-detection of polarized signatures.
Circular polarization profiles of Kepler-78. The observed and synthetic profiles are shown in black and red, respectively. On the left of each profile we show a ± 1σ error bar, while on the right the rotational cycles are indicated.

The magnetic field of Kepler-78 is found to be typical for a 0.8M⊙ star with this rotation period, in agreement with the diagram shown in fig. 3 of Donati & Landstreet (2009). In particular, the significant toroidal field and non-axisymmetric poloidal field are properties shared by such types of stars. We may compare to the sample presented in Fares et al. (2013), where stars most similar to Kepler-78 are HD 102195 (mean field strength of 12G, 44 per cent of magnetic energy in the poloidal component and 25 per cent axisymmetry in the poloidal field) and HD 189733 observed at different epochs (22–36G, 33–77 per cent and 17–56 per cent, respectively). With values of [16G, 60 per cent and 60 per cent], the field of Kepler-78 is comparable in strength, and has more axisymmetry in its poloidal component. As seen with HD 189733 though, these values evolve on the year time-scales for such stars and may span a wide range (Fares et al. 2010).

From the surface magnetic field, one can then extrapolate the magnetic field in the stellar atmosphere assuming a potential field (Jardine et al. 2013). This assumption is mildly relevant given the contribution of the toroidal field. In this technique, we assume that there is a source surface beyond which the field becomes purely radial; closed field lines are inside this volume. In this analysis, the source surface is put at a distance of 4 stellar radii from Kepler-78, which includes the planet orbit (at 3 stellar radii). The planet thus crosses regions where the field lines are open and others where they are closed. Fig. 5 shows the extrapolation features obtained with these assumptions, as would be seen for the rotational phase 0.1.

The magnetic field strength seen by the planet strongly depends on the position of this reference source surface with respect to the planet orbit. While we cannot easily predict the amplitude of magnetic variations seen by Kepler-78 b, we know at which phases it sees a null energy, modulo some uncertainties due to the stellar inclination. Both the location of the source surface and the ratio of the dipole/quadrupole/octupole components are critical to characterize the field topology at the planet location. The latter ratio is not determined very accurately from the present data set given the temporal coverage.

Relative motion between the planet and the time-averaged stellar field leads to unipolar induction. Permeation of time-dependent stellar field into the planet’s interior also leads to Ohmic dissipation. Both effects can induce heating of the planet’s interior and orbital decay over few Myrs due to the Lorentz torque (Laine et al. 2008; Laine & Lin 2012).
Variations of $\chi^2_r$ as a function of $\Omega_{eq}$ and $d\Omega$, derived from the modelling of our observed profiles. A well-defined paraboloid is observed, with the outer colour contour tracing the $2\sigma$ ellipse for both parameters as a pair.

Magnetic map of Kepler-78. The three components of the field in spherical coordinates system in a flattened polar view of the star are presented, down to latitude $-30^\circ$. The bold circle represents the equator. The small radial ticks around the star represent the rotational phases of our observations. The radial, azimuthal and meridional field maps are labelled in G and have the same colour scale.

5 ACTIVITY PROXIES

We have then analysed the activity proxies in the stellar spectra: Ca ii H and K lines in the 395 nm region, the Ca ii infrared triplet at about 850 nm, the H\textalpha and H\beta lines at 656 and 486 nm (see Fig. B2 for an example spectrum). Due to the magnitude and colour of the star ($V = 11.72$, $B - V = 1.15$), the SNR per pixel in the range of the Ca ii H and K lines is low ($\sim 30$). The Least Square Deconvolution profiles of all spectra were computed with a mask comprising only the relevant line(s); when several lines are included, a relative weight is applied to each line. Then, the average profile was subtracted to each individual profile, to get the residuals and enhance any detection of the variability. The residual profiles were fitted by a Gaussian and the area of this curve is our activity proxy; the values and their errors for H\textalpha, Ca ii H&K and Ca IRT are given in Table 1, and all indices are plotted in Fig. 6.

This activity is modulated with time, and at first order, it varies with the stellar rotation period ($\sim 12.5$ d), as shown on Fig. 6. Some data points, however, are not in good agreement with a simple sine wave. When a second sine wave at half the rotation period is added, then we obtain a better fit to the whole ESPaDOnS data set, as shown in Fig. 6. The modulation at $P_{rot}/2$ has an amplitude 2–6 times smaller than the $P_{rot}$ variation depending on the activity proxy. Such behaviour with a double modulation is common to the activity proxy of solar-type stars (e.g. Boisse et al. 2011). It was not necessary here to add a third signal with a $P_{rot}/3$ frequency, as was done in previous activity studies of Kepler-78 (Howard et al. 2013; Pepe et al. 2013), because our data set contains very few points. The improvement of the fit due to the second period is mostly seen on the H\textalpha residual signatures; for Ca ii residuals, the addition of the first harmonic does not change the fit significantly. When the period is let free to vary, we find an optimal value of $11.9 \pm 0.4$ d with all activity proxies included. It means that the main active regions are located at a latitude of $20 \pm 16^\circ$. These values are in good agreement with both the values derived from the magnetic map (Section 4.2) and the values expected from the extrapolation of the spot cycle found in the Kepler light curve (Section 2). Finally, it is observed that a maximum of activity is seen in all proxies at rotational phases 0.1 and 2.9. Reversely, the minimum observed in most proxies at phase 0.5. We would rather expect the minimum of chromospheric activity to correspond to a region where field lines are open, at phase $\sim 0.2$ (Fig. 5). Poor temporal coverage, possibly coupled to intrinsic variability, could easily explain the discrepancy we outline between activity proxies and the field line configuration. With the limitations
Figure 5. The extrapolated magnetic field of Kepler-78. White lines correspond to the closed magnetic lines and blue ones to the open field lines. The star is shown as viewed from the observer at rotation phase 0.1. An animated image is available at http://www.ast.obs-mip.fr/users/donati/kepler78_jul15_dr.gif

of the data (noise and limited time series) and the reservations on the extrapolation techniques (Jardine et al. 2002) (mainly, the position of the source surface, see Réville et al. (2015), and the potential field assumption in the presence of a toroidal component), there is no cause for alarm about this apparent discrepancy. More data, densely sampled over three rotational periods, would be necessary to assess this point in detail, for example by testing different source surface locations or different extrapolation techniques, or using activity proxies and polarized profiles conjointly to reconstruct the surface topology. This has never been tested to our knowledge, and would benefit a stronger data set as a testbench. The possibility may still exist that the surface topology reconstruction described in Section 4.2 is inaccurate, but it corresponds to the best we can infer from our limited set of data. The extrapolation map should be read with reservations in that context; it mainly illustrates the alternance of open and closed lines in the location of the planet orbit.

We also examined the activity signal in the light of the model of Laine & Lin (2012) that predicts the existence of intermittent hot spots on the stellar surface induced by the interactions with the close-in planet, and phased with the orbital or synodic period rather than the stellar rotational period. Fig. 7 shows the residual activity signal, once the rotational variability is removed, in phase with the synodic period, with ephemeris from Sanchis-Ojeda et al. (2013) and phase 0 at transit configuration ($T_e = 245 453.959 95$). There is no hint for enhanced stellar variability at any synodic phase.

The residual scatter is due either to some non-periodic intrinsic stellar variability, or an underestimation of the errors. We find a very similar result when the freely adjusted value of 11.9 d is used as rotational period.

5.1 Looking for reflected light and exospheric signature from the planet

While the stellar radial velocity variation induced by the planet is only $\sim 1.8 \text{ m s}^{-1}$ (Pepe et al. 2013; Howard et al. 2013), the radial velocity semi-amplitude of the planet along its orbit is $\sim 250 \text{ km s}^{-1}$. This wide variation put an hypothetical peak of the planet in the intensity profile far enough from the stellar profile to be looked at. We therefore conducted a search for an attenuated secondary peak in the stellar profile, using the same mask as for the star (5000 K ATLAS9 model) since it is expected that the planet surface mainly emits by reflection at such a short distance. The search was done in a velocity range wide enough to include the putative planet peak, from $-350$ to $+350$ km s$^{-1}$. Note that the modulation of this signal is clearly seen on the Kepler light curve, using the combination of about 3500 planetary orbits (Sanchis-Ojeda et al. 2013), with a maximum level at $6 \times 10^{-6}$ of the star. For the related spectroscopic signature, however, we expect an unfavorably large rotation effect: the stellar flux is seen by the planet at the synodic period of 0.365 d which corresponds to a velocity of 110 km s$^{-1}$, a factor of 10 broadening compared to the stellar intensity profile. The amplitude
Figure 6. The activity signals are modulated as a function of the rotation cycle of the star for H$\alpha$ (top left), H$\beta$ (top right), Ca II H and K (bottom left) and Ca II IRT (bottom right). The dashed lines show the best-fitting model made of two sine waves at $P_{\text{rot}}$ and $P_{\text{rot}}/2$. Minimum of activity is observed when closed field lines are facing the observer.

Figure 7. The residuals of the Ca II IR signal after the models shown on Fig. 6 are removed, as a function of the synodic phase for various activity tracers: H$\alpha$ (top left), H$\beta$ (top right), Ca II H and K (bottom left) and Ca II IRT (bottom right).
The magnetic properties of Kepler-78

The residual profiles of the intensity spectrum are shown, after the mean profile has been subtracted. The expected velocity of the planet is shown with superimposed green profiles where the amplitude has been amplified by a factor of 1000. No signal is seen on this series of profiles. The orbital phase is given on the left of each spectrum, using the ephemeris of Sanchis-Ojeda et al. (2013) (phase equals 0 at transit times).

The residual profiles were computed by subtracting a linear combination of the mean profile and its first derivative. Taking into account the first derivative allowed us to cancel out the signal near the systemic velocity $-3 \text{ km s}^{-1}$ due to the instrumental instability and varying activity in the stellar peak. The $rms$ in the residual profiles ranges from 1.2 to $2.5 \times 10^{-4}$. The residual spectra are displayed in Fig. 8.

Then we applied a matched filter analysis to the residuals to enhance the signal-to-noise ratio. We assumed that the planet signal due to reflected light has a known amplitude, width and position on each spectrum. By summing all pixels in the expected planetary profile and all epochs we expect to gain a factor of $\sqrt{70} \times 15$ if the noise follows Poisson statistics – where 70 is the number of pixels in the planetary profile and 15 is the total number of spectra when all 2014 and 2015 data are included. We thus expect to gain a factor of 32 at most on the detection of the planetary signal reflected from the star; red noise is also present on the residual spectra, so we are not in a situation of Poisson noise statistics and the gain will be lower.

For each residual spectrum, we multiplied the spectrum by the expected signal in the form of a Gaussian function extended over 70 pixels. We modulated the amplitude of the reflected light with the orbital phase, with a maximum of $6 \times 10^{-4}$ times the stellar profile. The expected reflected light peak is shown on the residual spectra in Fig. 8, amplified by a factor of 1000 for visibility.

We varied the position of this Gaussian in radial-velocity semi-amplitude and phase of the planet orbit. Then we calculated the integrated value of all filtered spectra for a given pair of amplitude and phase, normalized by the square root of the number of pixels in the profile. The map of these values are plotted in Fig. 9 as a function of phase (in abscissa) and amplitude (in ordinate). The reference time varies over the full orbit with step of 10 min and the semi-amplitude varies from 100 to 340 km s$^{-1}$ with steps of 4 km s$^{-1}$.

The expected position of the planet is shown by the superimposed circle in the map, assuming the transit ephemeris from (Sanchis-Ojeda et al. 2013) and the planet mass of Pepe et al. (2013). The signal is not enhanced at this location. The noise in the map has a standard deviation of $2.5 \times 10^{-5}$ and the signal at the expected planet location is at $0.9\sigma$ level ($2.22 \times 10^{-5}$). Hence, despite of a significant gain in sensitivity compared to the individual spectra (factor of $\sim 10$), we do not detect the reflected light emitted by the planet modulated by the planet motion.

Finally, since exospheric evaporation is also predicted for this kind of close-in system (e.g. Raymond, Barnes & Mandell 2008; Ehrenreich & Desert 2011, and references therein), we have looked for any signature in the spectra that could be due to photoevaporated ions. We built an ‘exospheric mask’ for profile calculations, made of all species expected to be present in the exosphere of a strongly irradiated telluric planet, as inspired from the work by Guenther et al. (2011) on CoRoT-7 b: Sulfur II and III, Ca II, Na I. Again, no signature was detected at the planet velocity. The $rms$ in the residual profiles are 15 times larger than with the full stellar mask, and ranges from 1.8 to $3.1 \times 10^{-5}$.

The magnetic properties of Kepler-78 dominate the rapidly evolving spot signal shows a smooth modulation with a period of $1300 \text{ d}$. We may interpret such behaviour as the activity cycle of the star produced by dynamo effects, with differential rotation and spots migrating towards lower latitudes under the action of dynamo processes and the resulting cyclically varying large-scale magnetic field. Since the Kepler light curve covers a 1560 d period, it is yet a bit short to confirm any

6 SUMMARY AND DISCUSSION

With the objective of characterizing the properties of Kepler-78’s magnetic field, it was necessary to revisit the photometric periodicity of the Kepler light curve, which both contains a wealth of information on the stellar activity and the signature of the ultrashort period planet Kepler-78 b Sanchis-Ojeda et al. (2013). It was shown that the evolution in time of the apparent period of rotation which dominates the rapidly evolving spot signal shows a smooth modulation with a period of approximately $1300 \text{ d}$. We may interpret such behaviour as the activity cycle of the star produced by dynamo effects, with differential rotation and spots migrating towards lower latitudes under the action of dynamo processes and the resulting cyclically varying large-scale magnetic field. Since the Kepler light curve covers a 1560 d period, it is yet a bit short to confirm any
Figure 9. Noise map of reflected light search as a function of orbital phase and semi-amplitude of the planet. The expected position of the planet is shown with the white circle. The map shows only noise.

periodic behaviour at such scale; further photometric monitoring could confirm, or refute this interpretation. Also, ultimately, it is only the reversal of the large-scale magnetic field which would demonstrate the existence of an activity cycle similar to the solar cycle, for which further spectropolarimetric campaigns would be required on a few years time-scale. From this analysis, we find a differential rotation larger than the Sun, of at least $\sim 0.08$ rad d$^{-1}$. This is confirmed by the differential rotation rate of $0.105 \pm 0.039$ rad d$^{-1}$ found by analysing the spectropolarimetric observations with Zeeman Doppler Imaging, although this detection of differential rotation is just a hint and more spectropolarimetric data would be necessary to confirm it. The rotation properties and main active latitudes found in our ESPaDOnS data (magnetic analysis and chromospheric proxies) are in agreement with the expectation from extrapolating the Kepler light-curve activity cycle.

Such complex and high-quality light curve would benefit, however, from a more complete spot modelling as done for other Kepler active planet hosts like Kepler-17 (Bonomo & Lanza 2012). The similarity between Kepler-78 and Kepler-17 is important to note. Both stars are young GK dwarfs (Kepler-17 being both a bit more massive and older than Kepler-78) and rotate in about 12 d. Their Kepler light curves behave similarly, although Kepler-78’s amplitude is 10 times lower than Kepler-17’s; the differential rotation derived from spot modelling by Bonomo & Lanza (2012) lies in the range $0.052-0.084$ rad d$^{-1}$ for Kepler-17, while it is $\sim 0.1$ rad d$^{-1}$ for Kepler-78. As a sanity check, we performed a similar analysis on the Kepler light curve of Kepler-17: we calculated the highest power peak in the periodogram for each quarter where Kepler observed this star (see Fig. A2 in Appendix). We find a value for this peak (the main rotational period) ranging from 11.4 to 12.9 d, which correspond to a differential rotation larger than 0.064 rad d$^{-1}$. We also find no cyclic behaviour of this period over the 4 yr of Kepler data (see Fig. A3). The measured value of 0.064 rad d$^{-1}$ is in good agreement with the range given by the spot modelling by Bonomo & Lanza (2012). More young solar-type stars have differential rotations in the range $0.08-0.45$ rad d$^{-1}$ as shown by, e.g. Fröhlich et al. (2012) and Marsden et al. (2011). Also, the well-studied hot-Jupiter host HD 189733 has a differential rotation of $0.146 \pm 0.049$ rad d$^{-1}$ (Fares et al. 2010), a mean rotation period of about 12.5 d, and no reported cycle over a time span of a few years.

The lap time derived from our estimate of the differential rotation is $2 \times \pi / \Omega_1 \sim 60$ d; this corresponds to the time needed for the pole to make a revolution less than the equator. On the other hand, Pepe et al. (2013) report an e-folding time-scale of about 50 d from the analysis of the Kepler light curve, that these authors attribute to the typical lifetime of spots. The agreement between these two values would suggest that differential rotation could control the lifetime of
spots – at least for those which dominate the radial-velocity signal – rather than normal or turbulent magnetic diffusivity (e.g. Bradshaw & Hartigan 2014).

Another interesting comparison can be done with ε Eri, a young K2 dwarf that has chromospheric activity with a 3 yr period (Hatzes et al. 2000) that is modulated by a longer 13 yr period (Metcalfe et al. 2013). The long-term evolution of the magnetic topology of this star, however, is complex and not cyclic over 7 yr of monitoring (Jeffers et al. 2014). It should thus be repeated that the best indication of a dynamo cycle remains a clear inversion of polarity, a mechanism which has been witnessed in very few stars so far: several polarity reversals for τ Bootis (Donati et al. 2008; Fares et al. 2009) and 61 Cyg A (Boro Saikia et al., in preparation) and one reversal for HD 190771 (Petit et al. 2009). To witness these polarity reversals, one must observe repeatedly the same stars, derive the topology of their surface over time, and search for a change of sign in the main polarity of a given magnetic hemisphere.

Cyclic activity is important for star–planet interactions. Previous studies have invoked intrinsic variations in the stellar extended magnetic envelopes at the origin of intermittent phenomena, as the enhancement of Ca ii emission modulated by the orbital period (Shkolnik et al. 2008) or changes in the upper atmosphere of a planet (Lecavelier des Etangs et al. 2012). It is then important to get a more global understanding of the stellar activity time-scales, and of the amplitude of this variation. This task is, however, enormous due to the large quantity of data necessary to reconstruct the magnetic topology at a given epoch (typically 22 h of observations on a 3.6m telescope for a rather faint star like Kepler-78). Ideally, each search for a specific star–planet interactions signature should be joined by a contemporaneous campaign in spectropolarimetry to constrain the input stellar conditions. Future transiting planetary systems to be discovered by TESS and PLATO will be hosted by brighter targets for which spectropolarimetric observations will be easier to conduct repeatedly.

The magnetic topology of Kepler-78 is comparable to other stars of similar mass and rotation rate. The mean strength of the magnetic field is 16 G at the time of observations, with 60 per cent of the magnetic energy being in the poloidal component. The planet crosses alternately closed field lines and open field lines along its orbit at 3 stellar radii. The strength of the magnetic field as viewed by the planet varies along the orbit with an amplitude which depends of the assumptions made for the location of the source surface in extrapolating the surface field. We would expect that the minimum of chromospheric activity corresponds to phases where the line of sight crosses the wide area with open field lines (coronal hole), but rather, this minimum is shifted by about 0.2 in phase. This shift could be a consequence of the strong differential rotation inducing shearing in the chromosphere, but at the moment it is not understood and would require additional monitoring.

We used a matched filter to search for the signature of the stellar light reflected by the planet in the spectra, and reached a detection limit of 2.5 × 10⁻⁵. The apparent broadening of the stellar peak reflected by the planet is a severe limitation of the method, compared to photometry. This detection level is expected not sufficient to find the signal and we report a negative result still in agreement with the previous detection by Kepler (Sanchis-Ojeda et al. 2013). The observation strategy was also not optimized for this search, and many spectra do not correspond to an orbital phase where the planet is bright.

Finally, this study was conducted in the context of star–planet interactions, and the recent prediction that hot spots could be induced at the stellar surface due to Ohmic dissipation transmitted in the footprint of the planet in ultrashort orbit (Laine & Lin 2012). The measured value of the mean magnetic field implies that the unipolar induction is an important process for the planet–star interaction. The permeation of the time-dependent component of the field into the planet’s interior may also lead to episodic Ohmic dissipation. These quantities combined with the upper limits on the planet’s orbital decay rate and intrinsic intensity provide useful constraints on the theoretical inference of the planet’s conductivity to be ~ 0.01–0.1 S m⁻¹ which is comparable to that of partially molten rock (Laine & Lin, in preparation).

Our ESPaDOnS observations did not reveal hot spots in the activity tracers at the orbital nor synodic phases. This non-detection should not, however, prevent any further theoretical work in this direction. Kepler-78 is intrinsically an active star, its activity signal is primarily related to the stellar rotation cycle, and any residual to the main spot rotation modulation could still be due to flares or other intermittent activity demonstration at the star surface, that are not uncommon. Potential planet-induced hot spots even at a level of ~ 10 per cent may remain hidden by the intrinsic variability of the stellar surface. Finally, the time-scales of apparition of the planet-induced hot spots, as well as their lifetime, could well be much shorter than the individual exposure time of our data. Due to the relatively faint magnitude of Kepler-78, we had to collect photons for about 30 min per exposure, or 2 h in total for a nightly visit. If planet-induced hot spots are of the same order of duration than the planet transit (48 min), then our observational sampling is not adequate. Short cadence H α photometric monitoring could be more appropriate, and, if combined with contemporaneous spectropolarimetry, could help distinguishing intrinsic stellar variations from planet-induced activity. Future observational work in this direction could also focus on less intrinsically variable stars with ultrashort planets, although the stellar magnetic field would then be more difficult to constrain.

The detection of hot spots, with a luminosity higher than the stellar irradiation received by the planet, would have been an unequivocally signature of the unipolar induction process. However, the ESPaDOnS’ quantitative upper limit places a useful constraint on the intensity of Ohmic dissipation at the footprint of the flux tube which connects Kepler-78 and its close-in planet. This constraint is consistent with that inferred from the upper limit of the orbital decay rate for Kepler-78 b (Laine & Lin, in preparation).

Non detection of stellar spots which corotate with the planet’s orbit at intensity level substantially below the stellar irradiation on the planet would indicate that unipolar induction between Kepler-78 b and its host star may be interrupted by field reconnection or there is insufficient time for the Alfvén waves to complete the circuit. These theoretical implications will be presented elsewhere.

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APPENDIX A: QUARTERLY PERIODOGRAMS FROM THE KEPLER LIGHT CURVES

Fig. A1 shows the periodograms obtained on Kepler data of Kepler-78 for each quarter. These periodograms were used to measure the apparent rotational period plotted in Fig. 1 and its variation in time.

As mentioned in the discussion, the same method was then applied to another host star with strong rotational modulation, Kepler-17. The periodograms for each Kepler quarter are shown on Fig. A2. Fig. A3 shows the behaviour in time of the derived rotation period.

Contrarily to Kepler-78, there is no apparent periodic modulation of the rotation period of Kepler-17 over 4 yr, which may indicate a longer activity cycle than for Kepler-78.
Figure A1. Periodograms of the Kepler light curve of Kepler-78 for each quarter. Each vertical line shows the main peak obtained from fitting a Gaussian to the peak, and reported in Fig. 1.

Figure A2. Periodograms of the Kepler light curve of Kepler-17 for each quarter when the star was observed.
APPENDIX B: EXAMPLE SPECTRA OF KEPLER-78

Fig. B1 shows an example ESPaDOnS spectrum of Kepler-78 (2015 Sep 7), as extracted and normalized by Libre-Esprit, in the full spectral domain. Fig. B2 shows the same spectrum zoomed around the activity lines of $\text{Ca II}$ and $\text{H I}$ whose evolution is discussed in the text.

Figure A3. The main rotation period of Kepler-17 as a function of time during the full duration of the Kepler mission.

Figure B1. An example spectrum of Kepler-78, obtained on 2014 September 7.
Figure B2. One example spectrum is shown, around the four activity proxy lines which time evolution is described in the text: from top to bottom, Ca II H and K lines, H $\beta$, H $\alpha$ and Ca II infrared triplet. Vertical ticks show the position of the lines.

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