Modeling the RV jitter of early M dwarfs using tomographic imaging

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ABSTRACT

In this paper we show how tomographic imaging (Zeeman Doppler Imaging, ZDI) can be used to characterize stellar activity and magnetic field topologies, ultimately allowing to filter out the radial velocity (RV) activity jitter of M-dwarf moderate rotators. This work is based on spectropolarimetric observations of a sample of five weakly-active early M-dwarfs (GJ 205, GJ 358, GJ 410, GJ479, GJ 846) with HARPS-Pol and NARVAL AL. These stars have $v \sin i$ and RV jitters in the range 1-2 km s$^{-1}$ and 2.7-10.0 m s$^{-1}$ rms respectively.

Using a modified version of ZDI applied to sets of phase-resolved Least-Squares-Deconvolved (LSD) profiles of unpolarized spectral lines, we are able to characterize the distribution of active regions at the stellar surfaces. We find that dark spots cover less than 2% of the total surface of the stars of our sample. Our technique is efficient at modeling the rotationally modulated component of the activity jitter, and succeeds at decreasing the amplitude of this component by typical factors of 2-3 and up to 6 in optimal cases. From the rotationally modulated time-series of circularly polarized spectra and with ZDI, we also reconstruct the large-scale magnetic field topology. These fields suggest that bi-stability of dynamo processes observed in active M dwarfs may also be at work for moderately active M dwarfs. Comparing spot distributions with field topologies suggest that dark spots causing activity jitter concentrate at the magnetic pole and/or equator, to be confirmed with future data on a larger sample.

Key words: stars: magnetic fields - starspots – techniques : radial velocity - polarimetric – line : profile

1 INTRODUCTION

Lots of exoplanets were either detected or confirmed thanks to the radial velocity (RV) technique which allows one to detect exoplanets of various masses and sizes, from hot-Jupiters to super Earths. This is made possible thanks to the sensitivity and stability of current velocimeters. However, as an indirect method based on measuring spectral shifts, velocimetry is also sensitive to phenomena of intrinsic stellar origin capable of affecting spectra, and in particular to stellar activity. Whatever the precision of forthcoming instruments, we will remain confronted with this limitation, rendering Earth-like planets hard to detect, their spectral signatures being much smaller than the activity-induced RV jitter, even for weakly active Sun-like stars.

Signals of stellar origin can occur on different timescales; some have a short period, typically ranging from minutes to hours (e.g., flares, granulation), whereas some feature a longer period, ranging from days to year (e.g., activity cycle, spot or convection inhibition from a strong magnetic field modulated by the rotation). Whatever the temporal timescale, most stellar phenomena causing spectral variability are related to magnetic fields and to the associated activity demonstrations. The modeling of the RV jitter is essential to all extrasolar planets searches, especially when orbital periods are larger than a few days and when the host stars exhibit activity phenomena occurring on timescales commensurate with the planetary signals of interest. The only way to improve the sensitiv-
ity of RV surveys to small planets is to characterize and model the activity jitter as well as possible.

To diagnose the RV jitter, several complementary approaches are commonly used, mostly making use of chromospheric activity indicators like excess flux in the cores of the Hα and Ca ii H&K, or measurements of spectral line asymmetries (with the bisector of the cross-correlation function). The idea is to check for periodic modulation of these proxies, in order to assess whether the observed RV signal is caused by activity rather than by a planet (see Queloz et al. 2001). The correlation between RVs and the slope of the bisector can in principle be used to correct for the effect of activity at a level of a few m s$^{-1}$ (Boisse et al. 2009). The accuracy to which the RV jitter can be corrected with this method largely depends on various parameters, e.g., the distribution of spots, the stellar inclination, the rotational broadening of line profiles. An alternative method is based on exploiting complementary information from velocimetric and high-cadence photometric simultaneous/contemporaneous observations, and make use of the predicted relationship between the photometric and RV signatures of spots (Aigrain et al. 2012; Haywood et al. 2014). These studies found that RV modulation caused by spots can be reliably modeled using the photometric flux $F$ and its first derivative $F''$. Other studies (Meunier et al. 2010; Borgniet et al. 2015) use the Sun as a star to predict the effect of activity on conventional activity diagnostics, taking advantage of the wealth of existing data. However, activity, and its correlation to RV jitter, depends strongly on spectral type, stellar mass and rotation rate, and so far, no studies are available to reliably extrapolate the solar case to all types of active stars.

Besides, the large majority of extrasolar planets up to now was found around main-sequence stars of spectral types ranging from late-F to early-M. Despite M dwarfs are the most abundant type of stars, their intrinsic faintness in the visible domain caused them to be underrepresented in RV surveys with existing instruments. RV and transiting survey demonstrate that planets is very frequent around M-dwarfs, in particular Earth and Super-Earth at short period (Bonfils et al. 2013; Dressing & Charbonneau 2015). Moreover, due to their low masses, these targets are interesting for Earth-like planet hunting; an orbiting planet of a given mass and orbital distance generates a higher reflex motion when orbiting around a M dwarf than around a solar type star. Therefore, observations of low-mass stars is a promising option to increase our sensitivity to Earth-like planets. Due to the low photospheric temperature of M-dwarfs, the planetary orbits that are located in the habitable zone (HZ) of the host star (i.e., within the proper range of orbital distances where liquid water may be stable at the planet surfaces) move closer in. For instance, for a M-dwarf with a typical mass of 0.5 $M_\odot$ (like those studied in our paper), the HZ lies in a range 0.2 – 0.45 AU (see Kasting et al. 2014). It corresponds to orbital periods in the range 36 – 157 d, i.e., to RV semi-amplitude of 1.5 – 0.96 m s$^{-1}$ for a planet mass of 5 $M_\oplus$ (as opposed to 0.4 m s$^{-1}$ for a planet of the same mass orbiting in the HZ of a Sun-like star).

Despite the gain in the RV sensitivity to small planets that M dwarfs allow to achieve, modeling and filtering efficiently the activity jitter of the host stars remain essential, given that this activity jitter is still at best comparable in size to the RV signal we aim at detecting, and with a similar period as orbital periods of planets within the HZ (see, e.g., Forveille et al. 2009; Robertson et al. 2014). So far, studies of late M dwarfs have shown that these stars exhibit significant RV jitter mostly induced by dark spots at their surfaces, implying that efficient observational strategies are mandatory to reliably disclose planets orbiting around them (e.g., Barnes et al. 2014, for M5-M9). These studies rely on simulations and/or spectroscopic and/or photometric survey to diagnose the activity jitter. However, mainly due to their low luminosity in the optical to nIR domain, whether the predominant spot pattern is random, uniform or concentrated at active latitudes remains unclear (Barnes et al. 2011; Andersen & Korhonen 2015, and references therein).

In this paper, we propose to explore a new method based on simultaneously studying the RV jitter caused by activity, and Zeeman signatures reflecting the large-scale magnetic field at the origin of activity to (i) investigate the level to which spot distributions causing the RV jitter relates to magnetic topologies and (ii) devise a new technique based on spectropolarimetric data to filter out activity on a sample of early M dwarfs.

We present the results of a spectropolarimetric campaign carried out on September 2013 - September 2014. After a brief description of the stellar sample in Sec. 2.1 and of the data reduction procedure in Sec. 2.2, we present the results obtained by analyzing circularly polarized spectra (Stokes $V$) in Sec. 3. The stellar activity diagnostic is introduced in Sec. 4, and is followed by the analysis of the rotational modulation of the RV jitter, and of its modeling in Sec. 5. The magnetic field and brightness reconstruction procedure using Zeeman-Doppler imaging (ZDI) are presented in Sec. 3.3 and 5.1. We summarize the main outcome of this analysis and discuss its implications in Sec. 6.

2 SPECTROPOLARIMETRIC OBSERVATIONS

2.1 Stellar sample

Our stellar sample includes five weakly-active, early-M dwarfs with different rotation periods (spanning 11-33 d) and stellar masses (0.35-0.61 $M_\odot$). The selected targets are among the most observed and best characterized ones in the ESO/HARPS RV survey of M dwarfs (Bonfils et al. 2013), guaranteeing that their activity jitters are known (with rms in the range 2.7-10.0 m s$^{-1}$) and detectable. So far no planets are detected for the stars of the sample. The five targets are known to show RV variations mostly caused by activity (Bonfils et al. 2013; Donati et al. 2008). The main properties of this stellar sample, both inferred from this work or extracted from previous publications, are listed in Table 1. The sample is complementary to those studied in spectropolarimetry by Donati et al. (2008); Morin et al. (2008b, 2010).

Stellar masses are derived from the empirical mass-luminosity relationship of Delfosse et al. (2000) together with parallaxes and K-band photometry (both taken from Hipparcos catalogue, Koen et al. 2010). The luminosity is deduced from the infrared K band photometry and J-K colors are converted into luminosities with the bolometric correction of Leggett et al. (2001). The stellar radius $R_*$ is estimated from the mass-radius relation given in Baraffe et al. (2015).

The line-of-sight-projected equatorial rotation velocity value ($v \sin i$) is either taken from the literature (Bonfils et al. 2012; Forveille et al. 2009; Donati et al. 2008; Bonfils et al. 2007), or constrained thanks to the ZDI code (see Sec. 3.3). For the whole sample, the $v \sin i$ is lower than 2 km s$^{-1}$ (see Table 1) and the precision on $v \sin i$ estimate does not exceed 0.5 km s$^{-1}$. The $v \sin i$ values are compatible with the amount of rotational broadening observed in the spectra of our sample of stars. The measurement of the stellar rotation period $P_{\text{rot}}$ is presented in detail in Sec. 3.2. We found rotation periods ranging from 13.83 to 33.63 d. Finally, the inclination of the rotation axis with respect to the line of sight, $i$, is estimated from the tomographic technique, with a precision of typically $\pm 10^\circ$ (Morin et al. 2010, for more details).
Table 1. Stellar parameters of the M dwarfs sample. Columns 1-8 list the star name, its spectral type (ST), its J & K band magnitude and its distance (coming from the Hipparcos catalogue Koen et al. 2010), the stellar mass, luminosity and theoretical radius (Baraffe et al. 2015). The columns 9-12 respectively list the measured $v \sin i$ (with a estimated error of ±0.5 km s$^{-1}$), the assessment of the stellar inclination angle $i$ (with a estimated error of ±10°), the rotation period of the star $P_{rot}$, the rms of RV measurements and the average noise $\sigma_0$ on the RV measurements. These four last parameters come from this study.

\begin{table}
\begin{tabular}{lcccccccccc}
Nom & ST & J & K & distance & $M_*$ & $L_*$ & $R_*$ & $v \sin i$ & $i$ & $P_{rot}$ & $\sigma_0$ \\
& & & & pc & $M_\odot$ & $L_\odot$ & R$_\odot$ & km s$^{-1}$ & ° & d & m s$^{-1}$ \\
GJ 205 & M1 & 5.0 & 3.90 & 5.66±0.04 & 0.63±0.06 & 0.061±0.006 & 0.55±0.08 & 1 & 60 & 33.63 ± 0.37 & 2.71 & 1.45 \\
GJ 358 & M2 & 6.90 & 6.06 & 9.47±0.15 & 0.42±0.04 & 0.023±0.002 & 0.41±0.06 & 1 & 60 & 25.37 ± 0.32 & 5.10 & 2.08 \\
GJ 410 & M0 & 6.52 & 5.68 & 11.77±0.15 & 0.58±0.06 & 0.055±0.005 & 0.53±0.08 & 2 & 60 & 13.83 ± 0.10 & 10.0 & 3.28 \\
GJ 479 & M2 & 6.86 & 6.02 & 9.69±0.22 & 0.43±0.04 & 0.025±0.003 & 0.42±0.06 & 1 & 60 & 24.04 ± 0.75 & 5.45 & 2.02 \\
GJ 846 & M0 & 6.20 & 5.56 & 10.24±0.16 & 0.60±0.06 & 0.059±0.006 & 0.54±0.08 & 2 & 60 & 10.73 ± 0.10 & 3.30 & 2.45 \\
\end{tabular}
\end{table}

2.2 Instrumental set-up and data reduction

Observations presented here were collected during two observing campaigns with the HARPS$^1$ velocimeter (Mayor et al. 2003; Snik et al. 2011) used in spectropolarimetric mode and in a smaller extent with the NARVAL$^2$ spectropolarimeter (Donati 2003; Donati & Landstreet 2009).

We observed from October 2013 to September 2014 with HARPS-Pol. In this instrument two optical fibers convey the stellar light, split into two orthogonal polarization states, from the Cassegrain focus of the telescope to the spectrograph. The instrument covers the 368-691 nm wavelength domain in a single exposure, at a resolving power of 100 000. An additional campaign was carried out from September 2013 to April 2014 with NARVAL, providing full coverage of the optical domain from 350 to 1050 nm in a single exposure, at a resolving power of 65 000, and into two orthogonal polarization states. The main characteristic of the instruments are listed in Table 2.

A spectropolarimetric observation consists of four sub-exposures taken at different azimuths of the quarter-wave plate (for HARPS-Pol) / half-wave rhombs (for NARVAL) relative to the optical axis of the beam splitter. The corresponding frames are combined together to produce a set of Stokes $I$ (unpolarized intensity) and Stokes $V$ (circularly polarized) spectra. Although it is possible to extract polarization spectra from two sub-exposures only, using four allows us to eliminate all systematic errors or spurious polarization signatures at first order (Donati et al. 1997).

The peak signal-to-noise ratios (S/N) per CCD pixel range from 70 to 200 at 600 nm for HARPS-Pol spectra (for which the

| Instrument | Tel. domain (nm) | R | $\eta$ (%) |
|------------|-----------------|---|------------|
| NARVAL     | 360-691         | 68 000 | 10-15 |
| HARPS-Pol  | 350-1050        | 60 000 | 2-3     |

Table 2. Main characteristics of NARVAL (Donati 2003) and HARPS-Pol (Snik et al. 2011); Column 1 gives the instrument name, column 2 the diameter of the telescope primary mirror, column 3 the spectral domain (covered in a single exposure), column 4 the resolving power $R$ and column 5 the estimated peak instrument throughput $\eta$ (at ~ 550nm).

Table 3. Synthetic journal of HARPS-Pol (top panel) and NARVAL (bottom panel) observations. The first day of observation is given in columns 2. Column 3 indicates the number of collected spectra. Columns 4 lists the peak S/N (resp., per 0.85 and 2.6 km s$^{-1}$ velocity bin for HARPS-Pol (at 650 nm) and NARVAL (at 750 nm)) - we precise the minimum and maximum obtained values. Column 5 indicates the rotational cycle bounds (computed with the rotation period mentioned in Table 1 according to ephemeris given by Eq 1).

| Name | BJD$_0$ (+ 2456000) | $n_{obs}$ | S/N | Cycle |
|------|---------------------|----------|-----|-------|
| GJ 205 | 569.88 | 22 | 170 - 228 | 0.000 - 3.523 |
| GJ 358 | 675.70 | 23 | 70 - 133 | 0.000 - 2.880 |
| GJ 410 | 673.88 | 29 | 79 - 125 | 1.000 - 6.199 |
| GJ 479 | 778.00 | 23 | 63 - 146 | 0.024 - 2.684 |
| GJ 846 (#2) | 829.87 | 11 | 189 - 318 | 25.764 - 31.848 |
| GJ 846 (#1) | 569.88 | 4 | 308 - 454 | 1.623 - 2.186 |
| GJ 410 | 673.88 | 13 | 169 - 303 | 0.558 - 7.542 |
| GJ 846 (#1) | 546.46 | 15 | 91 - 158 | 0.000 - 8.709 |

CCD pixel size is 0.85 km s$^{-1}$, and from 230 to 480 at 700 nm for NARVAL spectra (for which the CCD pixel size is 2.6 km s$^{-1}$). It mostly depends on the star magnitude and weather/seeing conditions. An overview of the observations is presented in Table 3, and the detail journal of observations of each star is given in Appendix B.

Rotational cycles of each target are computed from Barycentric Julian Dates (BJDs) according to the ephemeris:

$$BJD (d) = BJD_0 + P_{rot} \cdot E,$$

in which E is the rotational cycle, BJD$_0$ is the initial date chosen arbitrarily and $P_{rot}$ is the stellar rotation period derived from the magnetic analysis (see Sec. 3.2).

The data extraction is carried out with Libre-Espirit, a fully automated dedicated pipeline that performs optical extraction of the spectra. The initial procedure is described in Donati et al. (1997), and was adapted to HARPS-Pol data to make it compliant with precision velocimetry.

We apply Least-Squares Deconvolution (LSD, Donati et al. 1997) to all the observations in order to gather all the available polarimetric information into a single synthetic profile. LSD is similar to cross-correlation in the sense that it extracts information from a large number of spectral lines through a deconvolution procedure (see Donati et al. 1997 for more details). To extract Stokes $V$ LSD profiles from circular polarization spectra, we use a mask of
atomic lines computed with an ATLAS local thermodynamic equilibrium (LTE) model of the stellar atmosphere matching the properties of our whole sample (Kurucz 1993). The final mask contains about 4000 moderate to strong atomic lines, with a known Landé factor, from 350 nm to 1082 nm. The use of atomic lines only for the LSD masks relies on former studies of early and mid M dwarfs (Donati et al. 2008; Morin et al. 2008b). Zeeman signatures are clearly detected in Stokes V LSD profiles for all stars of our sample with a maximum peak-to-peak amplitude varying from 0.1% to 0.5% of the unpolarized continuum level. We observe temporal variations of the intensity and of the shape of the Stokes V LSD profile due to rotational modulation for the whole stars of the sample (see Sec 3).

For the unpolarized spectra, we use a denser line mask to increase our sensitivity to profile distortions and to RV variations of these five slow rotators. The mask is derived from M-dwarf spectra previously collected with HARPS (Bonfils et al. 2013), and contains 9000 lines from 440 to 686 nm. With this procedure, Stokes I LSD profiles distortions are detected with a maximum amplitude varying from 0.001% to 0.01% of the unpolarized continuum level (see Sec. 5).

For the stars observed with both HARPS-Pol and NARVAL (i.e., GJ 205, GJ 410 and GJ 846), we can use the collected spectra to compare the instrument efficiency. NARVAL being on a 2m telescope and HARPS-Pol on a 3.6m telescope, the ratio of the collected flux is about 0.31 at the telescope. The NARVAL peak throughput at 550 nm is thus, in fine, about 5.0 times higher than that of HARPS-Pol, once the pixel size is taken into account (see Table 4, second column). LSD allows to add up information from the whole observed spectral domain. Including the gain associated to the larger spectral region, NARVAL is in average 8.4 times more efficient than HARPS-Pol (see Table 4, third column). This explains why longitudinal field measurements secured with NARVAL are significantly more accurate than those derived from HARPS-Pol spectra despite the large ratio in telescope photon collecting power in favour of HARPS-Pol. For RV measurements, only HARPS-Pol spectra are used, NARVAL being limited to typical RV precisions of 20 m/s (Moutou et al. 2007).

| \( \rho \) in spectrum | \( \rho \) in LSD profile |
|-------------------------|-------------------------|
| GJ 205                  | 3.57                    |
| GJ 410                  | 6.32                    |
| GJ846                   | 5.04                    |

Table 4. Resulting peak flux ratio \( \rho \) between NARVAL and Harps-Pol. Column 1 indicates the star name. Column 2 gives \( \rho \) computed from spectra, after having taken into account the pixel size differences and the telescope photon collecting power. Column 3 lists \( \rho \) obtained from LSD profiles and then this value also takes into account the size of the spectral domain.

To recover the topology of the large-scale field that generates the observed Zeeman signatures and their rotational modulation (see Sec 3.3).

3.1 Longitudinal magnetic field

From each pair of Stokes I and V LSD profiles, we compute \( B_l \) (in Gauss) as follow (Donati et al. 1997):

\[
B_l = \frac{2.14 \times 10^{11}}{A_0 g_{\text{eff}} c} \int \frac{\nu V(\nu) d\nu}{[I_c - I(\nu)] d\nu},
\]

with \( I \) and \( V \) denoting the unpolarized and circularly polarized LSD profiles, \( I_c \) the continuum level, \( v \) the radial velocity in km s\(^{-1} \), \( c \), the speed of light in km s\(^{-1} \), \( A_0 \) the central wavelength in nm and \( g_{\text{eff}} \) the effective Landé factor. \( B_l \) is a simple magnetic field proxy one can easily extract, but which conveys little information on the likely complexity of the magnetic field geometry.

3.2 Period determination

To estimate the stellar rotation period we first fit \( B_l \) with a multiple sine fit (fundamental period + the first harmonic). The explored period range spans 0.5x to 2x the value found in the literature. We choose \( P_{\text{rot}} \) that minimizes \( \chi^2 \), defined as the reduced \( \chi^2 \) of the multiple sine fit to the \( B_l \) data. We compare this value to the period found computing the Lomb-Scargle periodogram of the \( B_l \) data (Lomb 1976; Scargle 1982; Zechmeister & Kürster 2009). This periodogram estimates the power associated to each period in the explored \( P_{\text{rot}} \) interval. To assess the chance that the strongest peak of the derived periodogram is caused by noise in the observations rather than by a true signal, we compute the 10% and 1% false alarm probabilities (FAPs) as defined in Zechmeister & Kürster (2009).

- GJ 358 : The resulting curves for GJ 358 are presented Fig. 1. We note that \( B_l \) remains mainly negative (averaged value of \(-32.0 \pm 1.5 \) G), with a peak-to-peak amplitude of 70 G. The variations are periodic and well-fitted (\( \chi^2 = 1.0 \)) with a multiple sine fit at \( P_{\text{rot}} = 25.37 \pm 0.32 \) d (1σ error bar). This period is in agreement with the period of \(-25.26 \) d given by Kiraga & Stepień (2007) from a photometric survey, as well as with the period found computing the Lomb-Scargle periodogram and associated with a FAP much lower than 1% (Fig. 1, bottom panel).

- GJ 479 : We observe a similar behaviour for \( B_l \) of GJ 479, with a rotation period of 24.04 ± 0.75 d (see Fig. C1), in good agreement with the period estimated in a range 23-24 d by Bonfils et al. (2012). As indicated in the periodogram of \( B_l \) data, and contrary to the previous case, the first harmonic is essential to fit the data down to \( \chi^2 = 1.0 \).

- GJ 410 : For GJ 410 (Fig. 2), \( B_l \) varies periodically and exhibits regular sign switches; the averaged value is 3.0 ± 0.5 G. The best period we derive from fitting \( B_l \) measurements is equal to 13.83 ± 0.10 d, in agreement with the former study of Donati et al. (2008) (13.51 ± 0.12 d) and the Lomb-Scargle periodogram (see Fig. 2, FAP < 1%). This is one of the most active stars of our sample.

- GJ 205 : For GJ 205, we derive \( P_{\text{rot}} = 33.63 \pm 0.37 \) d. To fit the data down to \( \chi^2 = 1.0 \), the fundamental period and
its first harmonic $P_{\text{rot}}/2$ are needed. This is confirmed with the Lomb-Scargle periodogram whose strongest peak is at 16.8 d, i.e., $P_{\text{rot}}/2$ (FAP $< 1\%$, see Fig. C2), and with the former photometric study of Kiraga & Stepien (2007) (~33.61 d).

- **GJ 846**: For GJ 846, we only secured 11 measurements in July-September 2014 with HARPS-Pol and 15 measurements in September-December 2013 with NARVAL, spread over 6 and 9 rotation cycles respectively. The amplitude of the $B_l$ variations between the two observation epochs: we first observe variations with a peak-to-peak amplitude of 10 ± 2 G (averaged value 1.4 ± 0.5 G), then variations with a peak-to-peak amplitude of 20 ± 4 G (averaged value = 6.0 ± 1.5 G). $B_l$ keeps the same (positive) sign during the two runs. We derive a period equal to 10.73 ± 0.10 d. This period is in good agreement with the periodicity of 10.7 d found in Bonfils et al. (2012).

Our observations thus demonstrate clearly that the spectropolarimetric data provides us with an accurate measurement of $P_{\text{rot}}$. In Sec. 4 we will demonstrate that spectropolarimetry is more efficient that usual proxies ($H_\alpha$ or the full width at half-maximum FWHM) to determine the rotational period, and that $P_{\text{rot}}$ is a key parameter to track the origin of the activity signal (i.e., the magnetic field).

### 3.3 Magnetic imaging

To recover the parent large-scale magnetic field from time series of rotationally-modulated Zeeman signatures, we use the ZDI to-

**Figure 1.** Top: $B_l$ measurements of GJ 358 from HARPS-Pol spectra are shown as red dots (with ±1σ error bars). The green line depicts a multiple sine fit (fundamental + 1st harmonic) to the $B_l$ measurements. The horizontal grey line represent the 0 G level. Bottom: Lomb-Scargle periodogram of $B_l$ and the FAP at 1% (dashed line) and 10% (dotted-dashed line). The vertical lines depict $P_{\text{rot}}$ and its three first harmonics $P_{\text{rot}}/2, P_{\text{rot}}/3$ and $P_{\text{rot}}/4$.

**Figure 2.** Same as Fig. 1 for GJ 410. Measurements from HARPS-Pol spectra are shown in red, while those from NARVAL $B_l$ measurements, despite the 3.2× smaller photon collecting power of TBL.
and its projected area, on the rotation cycle, and on the local surface brightness of the photosphere (assumed to be uniform at this stage). To model the local unpolarized Stokes I and the local circular polarized Stokes V profiles (resp. $I_{i}$ and $V_{c}$) at each cell $j$ in presence of magnetic fields, we use Unno-Rachkovsky’s (UR) equations (e.g. Landi degl’Innocenti & Landolfi 2004). We set the central wavelength, the Doppler width and the Landé factor of the equivalent line to 650 nm, 1.6 km s$^{-1}$ and 1.25, respectively, and we adjust the average line-equivalent width to the observed value. Summing the spectral contributions of all grid cells yields the synthetic Stokes V profiles at a given rotation phase.

ZDI proceeds by iteratively comparing the synthetic profiles to the observed ones, until they match within the error bars. Since the inversion problem is ill-posed, ZDI uses the principles of regularization to derive a solution compatible with the data. The form we use for the regularization function is $S = \sum_{l} (a\, l_{m}^{2} + b\, l_{m}^{2} + c\, l_{m}^{2})$ (more details in Donati (2001)).

ZDI depending on the assumed rotation period, it can be used to confirm and often to improve the accuracy of the estimate derived from $B_{i}$ curves, as Stokes V profiles intrinsically contain more information than $B_{i}$ curves. In some cases, surface differential rotation (DR) is required in order to fit Stokes V data down to the noise level. To achieve this, we assume that the rotation rate at the surface of the star depends on latitude and can be expressed as $\Omega_{\vartheta} = \Omega_{\vartheta_{0}} - \Omega_{\vartheta_{m}} \sin^{2}(\theta)$, with $\theta$ denoting the latitude, $\Omega_{\vartheta_{0}}$, the rotation rate at the equator and $\Omega_{\vartheta_{m}}$, the difference in rotation rate between the equator and the pole. This law is used to compute the phase shift of each ring of the grid at any observation epoch with respect to its position at a reference epoch. We carry out reconstructions for a range of $\Omega_{\vartheta_{m}}$ and $\Omega_{\vartheta_{m}}$ values; the optimum DR parameters are those minimizing the information content. They are obtained by iterating the solution of the $\chi^{2}$ map with a paraboloid around the minimum value (Donati et al. 2003).

### 3.4 Results

The M dwarfs of our sample exhibit magnetic fields with Zeeman signatures that do not exceed 0.5% of the unpolarized continuum. We distinguish two kinds of magnetic topologies (see Table 5): two stars harbour a large-scale magnetic field dominated by an axial dipole ($\chi^{2} = 1$), whereas three stars exhibit a more complex field featuring a significant - in most case dominant - toroidal axisymmetric component ($\chi^{2} = 1.6$). Assuming DR, we are able to fit the data of this early-M dwarf down to $\chi^{2} = 1.0$, with $\Omega_{0} = 0.47 \pm 0.03$ rad d$^{-1}$ and $\Omega_{2} = 0.05 \pm 0.03$ rad d$^{-1}$ (see Fig. 5), corresponding to rotation periods at the equator and pole of 13.37 $\pm$ 0.86 and 14.96 $\pm$ 1.25 d, respectively. This result is in good agreement with $P_{\text{rot}}$ previously found (13.83 $\pm$ 0.10 d, Sec. 3.2), and with the former DR estimate of GJ 410 (see Donati et al. 2008).

Finally, we note that the large-scale field of GJ 410 significantly evolved between 2007-2008 (Donati et al. 2008) and 2014 (our data), both in strength (decreasing from 100 to 60 G) and in topology (the energy in the dipolar component increased from 50 to 88%).

#### Table 5. Properties of the large-scale magnetic field topologies of the moderately active M dwarfs sample. In columns 1-3 we report the name of the star (with runs #1 and #2 for GJ 410 corresponding to the first and second observing epochs, see Table B4), the mass and the rotation period, initially presented in Table 1. Column 4 mentions the assessment of the average magnetic flux reconstructed from the Zeeman signatures. Column 5 lists the magnetic energy lying in poloidal component. Columns 6-7 present the magnetic energy reconstructed as a poloidal dipole and the percentage of poloidal energy in axisymmetric modes (defined as $m < l/2$).

| Nom     | $M_{\ast}$ (M$_{\odot}$) | $P_{\text{rot}}$ (d) | $B_{y}$ (G) | Pol. (%) | Dip. (%) | Axi (%) |
|---------|--------------------------|----------------------|-------------|----------|----------|---------|
| GJ 205  | 0.61                     | 33.63 ± 0.37         | 20          | 99       | 90       | 73      |
| GJ 358  | 0.41                     | 25.37 ± 0.32         | 130         | 97       | 98       | 85      |
| GJ 410  | 0.58                     | 13.83 ± 0.10         | 65          | 25       | 88       | 11      |
| GJ 479  | 0.43                     | 24.04 ± 0.75         | 65          | 37       | 74       | 29      |
| GJ 846 (#1) | 0.59               | 10.73 ± 0.10        | 45          | 27       | 69       | 68      |
| GJ 846 (#2) | 0.59              | 10.73 ± 0.10        | 30          | 63       | 52       | 86      |

Early-M dwarfs like GJ 410 and GJ 486 were already reported early-rotation cycles 2.067 and 2.493 of GJ 410 in Fig. 4 top left panel). The large-scale magnetic field reconstruction indicates that the axisymmetric poloidal component includes less than 40% of the magnetic energy (see column 7 of Table 5), and features a mostly dipolar structure; the toroidal component includes more than 60% of the reconstructed magnetic energy, and is mostly axisymmetric, showing up as an azimuthal field ring of $\sim$ 80 G encircling the star at equatorial or intermediate latitudes (see Table 5, two last rows, and Fig. 4 and Fig. D2 bottom panel, for, resp., GJ 410 and GJ 479). The magnetic field flux is moderate, reaching $\sim$ 70 G in the in the strongest field regions.

Moreover, thanks to the dense spectropolarimetric data set of GJ 410 (42 measurements spread over 7.5 rotation cycles), we can easily estimate the amount of latitudinal DR shearing the magnetic maps. Indeed, the Stokes V LSD data set of all stars of our sample can be fitted down to $\chi^{2} = 1$ when assuming solid body rotation, except for GJ 410 ($\chi^{2} = 1.6$). Assuming DR, we are able to fit the data of this early-M dwarf down to $\chi^{2} = 1.0$, with $\Omega_{0} = 0.47 \pm 0.03$ rad d$^{-1}$ and $\Omega_{2} = 0.05 \pm 0.03$ rad d$^{-1}$ (see Fig. 5), corresponding to rotation periods at the equator and pole of $13.37 \pm 0.86$ and $14.96 \pm 1.25$ d, respectively. This result is in good agreement with $P_{\text{rot}}$ previously found (13.83 $\pm$ 0.10 d, Sec. 3.2), and with the former DR estimate of GJ 410 (see Donati et al. 2008).
Figure 3. Top: maximum-entropy fit (thin red line) to the observed (thick black line) Stokes V LSD photospheric profiles of GJ 358. Rotational cycles and 3σ error bars are also shown next to each profile. Bottom: map of the large-scale magnetic field at the surface of GJ 358. The radial (left corner), azimuthal (center) and meridional (right corner) components of the magnetic field B are shown. Magnetic fluxes are labelled in G. The star is shown in a flattened polar projection down to latitude -30°, with the equator depicted as a bold circle and parallels as dashed circles. Radial ticks around each plot indicate phases of observations. This figure is best viewed in color.

4 CHARACTERIZATION OF THE RV JITTER

Our sample stars are known to exhibit RV variations caused by stellar activity. To characterize the origin of the RV modulation, we compute the bisector, the full width at half-maximum FWHM, and the H\(\alpha\) index as described in section 4.1. We then analyze how these quantities vary with time through their Lomb-Scargle periodograms, and compare with temporal variations of the RV itself (see Sec. 4.2.1). As the model we propose aims at modeling the component of the RV signal that is rotationally modulated (see Sec. 5), the first step is to assess quantitatively the amount to which the RVs of our sample stars are periodic (see Sec. 4.2.2).

4.1 Computing RVs and activity proxies

RVs are computed by fitting a Gaussian to the Stokes I LSD profiles (equivalent to the CCF), the Gaussian centroid giving the RV estimate \(v_r\). The FWHM measurements is directly computed from the Gaussian fit to the Stokes I LSD profiles.

To derive the bisector, we first interpolate the CCF profile using a cubic spline interpolation; we then compute the set of midpoints of horizontal line segments extending across the profile (Gray 1982). To assess temporal evolution of the line profile, we calculate the velocity span (as introduced, e.g., by Gray 1982; Queloz et al. 2001) \(v_s\), given by \(v_t - v_b\), where \(v_t\) and \(v_b\) are respectively the average velocity at the top and bottom parts of the bisector. For RV variations caused by stellar activity, we commonly observe an anti-correlation between \(v_s\) and \(v_r\) (see, e.g., Queloz et al. 2001). However, as expected for slow rotators whose rotation profile is not resolved by the velocimeter (typically \(v \sin i < 2 \text{ km s}^{-1}\), see e.g., Desort et al. 2007), this \(v_s\) vs. \(v_r\) anti-correlation is not observed in our sample, \(v_s\) exhibiting no variations (for example, for GJ 358, \(v_s\) has a peak-to-peak amplitude of ~ 10 m s\(^{-1}\) and a rms of 3.6 m s\(^{-1}\), see Fig. 6). For this reason, this proxy is not discussed in

\[\text{The top and bottom parts include all points within 10-40% and 60-90% of the full line depth, respectively.}\]
Figure 4. Same as Fig. 3 for GJ 410. LSD Stokes V profiles in the top left and top right panels correspond to HARPS-Pol and NARVAL observations respectively.

Figure 5. Variations of $\chi^2_r$ as a function of $\Omega_{eq}$ and $d\Omega$, derived from the modelling of GJ 410 Stokes V LSD profiles at constant information content. The outer colour contour traces the 1.75% increase in $\chi^2_r$ that corresponds to a 3$\sigma$ ellipse for both parameters as a pair.

The following sections, even though $v_*$ is computed and shown on Fig. 6 and similar following graphs.

The Hα index is also often used to characterize RV variations caused by activity. This index is defined as the ratio between the flux in the Hα absorption line and that in the surrounding continuum, as described in Boisse et al. (2011). We use a 0.16 nm window centered at 656.2808 nm for the central line, and two windows of 1.075 and 0.875 nm around 655.087 and 658.031 nm respectively for the continuum as presented in Gomes Da Silva et al. (2011).

### 4.2 Activity jitter in the M dwarfs sample

#### 4.2.1 Diagnostic of the activity

Only 11 RV measurements spanning 5.4 rotation cycles were collected for GJ 846 (run #2) - too sparse a set for a reliable periodogram analysis. As a result, the following sections concentrate only on the 4 other stars of the sample, namely GJ 358, GJ 479, GJ 410 and GJ 205.

- GJ 358 : The $B_1$, RV, FWHM, Hα and $v_*$ curves as well
as the periodograms of \(B_r\), RV, FWHM and \(H_\alpha\) are presented in Fig. 6. The periodograms of both \(H_\alpha\) and FWHM show that the period \(P_{\text{rot}}\) previously identified with \(B_t\) has significantly more power than its harmonics (FAP < 1% for FWHM, < 15% for \(H_\alpha\)). It is a further confirmation that the observed RV modulation is mainly caused by activity. The periodogram of \(v_l\) indicates a period of \(P = 24.47 \pm 0.60\) d, in agreement with \(P_{\text{dr}}\), but with a FAP of only 10%. Moreover, we notice that \(v_l\) and \(B_r\) vary in quadrature: when \(B_r\) reaches its maximum value (of about +10 G), \(v_l\) is at mid-distance between its maximum and minimum (see, e.g., phases 0.70-0.75).

- **GJ 479**: \(H_\alpha\) and FWHM show variations with a period in the range 23-25 d, in agreement with the \(P_{\text{rot}}\) we previously derived from our \(B_t\) data. RVs allows to measure a period of 23.2 \pm 1.9 d, again fully compatible with \(P_{\text{rot}}\) (see Fig. E1). Moreover, the \(H_\alpha\) periodogram exhibits a similar harmonics spectrum (from \(P_{\text{rot}}\) to \(P_{\text{rot}}/4\)) as those of \(B_t\) and \(v_l\). Furthermore the shape of \(v_l\) and \(B_r\) curve are very similar, in particular \(v_l\) crosses its median value when \(B_r\) is close to zero (see, e.g., phase 0.45).

- **GJ 410**: Being the most active star of our sample, GJ 410 exhibits the largest temporal variations for all proxies (typically \(\times 1.5\), see Fig. 7). The periodogram of \(v_l\) indicates a period \(P = 14.20 \pm 0.20\) d, within the range of surface periods that differential rotation triggers (13.4-15.3 d, see Sec. 3.4). The period measured with \(v_l\) being higher than \(P_{\text{rot}}\) measured with \(B_t\), this suggests that the surface spots generating the observed RV variations are located at mid to high latitudes.

- **GJ 205**: The data and their periodograms are presented in Fig. E2. The \(H_\alpha\) periodogram shows a main peak at 33.46 d with \(\chi^2 = 0.37\) d, again fully compatible with \(P_{\text{rot}}\) (determined from the magnetic data), the FAP level drops down to 15%. This period is consistent with the differential rotation we measured from the magnetic data, see Sec. 3.2) and for which periodicity in the \(v_l\) signal is not really detected. However if we assume that DR is present at the surface of GJ 205 (at a level similar to that reported for GJ 410) and is responsible for modulating the RV data with a period of 39.70 \pm 0.35 d (rather than that of 33.61 \pm 0.19 d derived from the magnetic data), the FAP level drops down to 2%.

### 4.2.2 RV signal detection

The rms of the data (rms) is 2-3\(\times\) higher than the average noise \(\sigma_0\). The multiple sine fit (including the two first harmonics) to the RV data allows to improve \(\chi^2\) with respect to a fit with a constant RV, however we never reach \(\chi^2 = 1.0\) (see Table 6, 7 first columns). This suggests that the RV jitter, \(J_{\text{rot}}\), includes both a rotationally modulated component \(J_m\) (due, e.g., to long-lived spots at the stellar surface), as well as a randomly varying one \(J_p\) (of yet unclear origin, e.g., spots with lifetimes shorter than the rotation cycle). Their respective strengths vary from one star to the other. For example, the poorest fit to the data are that of GJ 205, whose period in the RV data significantly differs from \(P_{\text{rot}}\) (determined from the magnetic data, see Sec. 3.2) and for which periodicity in the \(v_l\) signal is not really detected.

Multiple sine fits and Doppler-imaging (see Sec. 5) can only succeed at modeling signals varying periodically with \(P_{\text{rot}}\). Our first task is thus to quantify the extent to which the observed RV signals are indeed mostly modulated by rotation. We thus compute the probability that a multiple sine fit provides a significantly better match to the observed RV variations than does a constant RV. 

We use the incomplete Gamma function to assess this probability \(p\), given both the number of degrees of freedom and the improvement in \(\chi^2\) that a multiple sine fit (including 2 harmonics) provides with respect to a constant RV. The closer \(p\) gets to 1.0 and the false alarm probability (FAP = 1-\(p\)) to 0, the more reliably the rotational modulation of the RV signal is detected and dominates the RV variations. We as test the ability of the model to fit the rotationally modulated component \(J_m\), we use a scaled \(\Delta\chi^2\) given by:

\[
\Delta\chi^2 = \frac{\chi^2_{J_m} - \chi^2_{\text{rot}}}{\chi^2_{1,1}} N,
\]

where \(N\) denotes the number of measurements. The resulting FAP are gathered in Table 6. We note that for GJ 358, JG 479 and GJ 410, \(J_m\) is dominant with a FAP level of < 1%, whereas for GJ 205 \(J_p\) largely dominates the signal (with a FAP level of \(\sim 73\%\)), so that for this star no coherently signal is detected at the rotation period measured from \(B_r\).

To quantify the strength of \(J_m\) and \(J_p\), we compute their rms, once having quadratically subtracted the noise (see Table 7). Whereas \(J_m\) is the major component for GJ 358 and, in a smaller extend for GJ 479, the trend is reversed for GJ 205 and GJ 410, where \(J_p\) becomes dominant. The Doppler imaging being able to model the rotational modulation only, we aim at reduce the activity jitter by a factor \(A_1\).

### 5 MODELING OF THE RV JITTER

The goal of this section is to consistently model the rotationally modulated component of the activity jitter (called \(J_m\) in Sec. 4.2.2).
Figure 6. Top: Temporal variations of $B_l$, $v_r$, FWHM, Hα and $v_s$ for GJ 358. Data and their error bars are in red. For all plots, the zero level is depicted by a dotted line. The green lines depict a multiple sine fit (including the fundamental at $P_{rot}$ and first harmonic at $P_{rot}/2$) to the data points. The vertical black lines outline the beginning of each rotation cycle. Bottom: Lomb-Scargle periodograms of $B_l$, $v_r$, FWHM and Hα for GJ 358. The blue vertical lines outline the rotation period $P_{rot}$ and its first 3 harmonics at $P_{rot}/2$, $P_{rot}/3$ and $P_{rot}/4$. The yellow and black horizontal lines respectively mark FAP levels of 10% and 1%.
Figure 7. As Figure E1 for GJ 410. The blue data are the $B_I$ values computed from NARVAL LSD profiles. The grey bands depict the range of periods at the surface of the star as a result of DR.
I served in Stokes studied - at least on a statistical point of view.

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tures can be found: hot
lation induced by spots. On the stellar surface, two kinds of fea-
v(Dumusque et al. 2014, Eq.10). In our sample,
RV variations is similar to or smaller than those of the bisector span
when the contribution of plages is dominant, the amplitude of the
component of the RV jitter,
1
2

Table 6. Table of the parameter that characterize the detection and the multiple sine fit of the RV activity jitter. The first column gives the name of the star, columns 2-4 give the observed average RV noise \( \sigma_0 \), the rms of the RV data \( \text{rms} \), and the associated \( \chi^2_0 \) to the fit \( \chi^2_1 \), Column 5 mentions the rms of the RV residual obtained after a multiple sine-fit (fundamental + 2 harmonics), the \( \chi^2_j \) associated to the fit \( \chi^2_{tot} \). Column 7 lists the estimate of the likelihood of the fit (FAP, see text). Columns 8-10 give the rms of the RV residuals after the DI modeling, the associated \( \chi^2_j \), and the FAP. Columns 11-13 list the initial and final \( \chi^2_j \) linked to the \( RI \) reconstruction, and the associated FAP.

| Star   | \( \sigma_0 \) (m s\(^{-1}\)) | \( \text{rms} \) (m s\(^{-1}\)) | \( \chi^2_0 \) (m s\(^{-1}\)) | \( \chi^2_1 \) (m s\(^{-1}\)) | FAP (%) | \( \chi^2_2 \) (m s\(^{-1}\)) | FAP (%) | \( \chi^2_3 \) (m s\(^{-1}\)) | FAP (%) |
|--------|-------------------------------|-------------------------------|-----------------------------|-------------------------------|---------|-----------------------------|---------|-----------------------------|---------|
| GJ 205 | 1.43                          | 3.52                          | 7.81                        | 3.05                          | 6.27    | 73                          | 3.17    | 6.31                        | 98      |
| GJ 410 | 3.28                          | 8.84                          | 7.85                        | 6.55                          | 3.96    | 0.04                        | 6.78    | 4.14                        | 2.89    |
| GJ 479 | 2.02                          | 5.29                          | 7.71                        | 3.65                          | 3.58    | 0.09                        | 3.93    | 4.05                        | 7.4     |
| GJ 358 | 2.08                          | 4.79                          | 5.59                        | 2.47                          | 1.69    | <0.01                      | 2.88    | 2.05                        | <0.01   |


and translate it into a distribution of surface features, whose relation to the parent magnetic topology (described in Sec. 3.4) can be studied - at least on a statistical point of view.

For this first approach, we assume that the distortions observed in Stokes I LSD profiles are only due to rotational modulation induced by spots. On the stellar surface, two kinds of features can be found: hot/bright plages and cool/dark spots. These features induce a RV activity jitter and variations of the bisector span. When the contribution of spots is dominant, the amplitude of the RV variations is higher than those of the bisector span, and when the contribution of plages is dominant, the amplitude of the RV variations is similar to or smaller than those of the bisector span (Dumusque et al. 2014, Eq.10). In our sample, \( v_t \) data do not exhibit a peak-to-peak amplitude higher than 15 m s\(^{-1}\) and we do not observe any clear \( v_t \) variations (see Sec.4.1), whereas the peak-to-peak amplitude of RV variations is always higher than 15 m s\(^{-1}\). Moreover, thanks to 3D-simulations of the near-surface convection of M dwarfs that take into account the small-scale magnetic field, Beeck et al. (2015) show that dark spots are much more abundant than plages. Thus, at first order, we consider dark spots only as the main origin of the observed rotationally modulated RV variations.

In the imaging procedure, we characterize a spot with its relative brightness \( b \), and its local profile \( I_i \). This two parameters being fixed, we adopt a simple two-temperature model (warm photosphere, cool spots) for the stellar surface and we choose the spot covering fraction as image parameter.

\[ I = C_1 J_0 + b(1 - C_2) J_1 \]

5.1 Method

As previously presented for the magnetic field reconstruction, the stellar surface is divided into 5000 cells, and the Stokes I profile at a given rotation phase is computed as the sum of all local Stokes I profiles from the different cells. With the spot description we chose, the parameter we reconstruct during the ZDI process is \( I_i \) with \( C_1 \) denoting the proportion of photosphere inside each cell \( (C_1 = 0) \) and \( C_2 = 1 \), respectively, corresponding to a spotted cell, and to an unspotted cell), and therefore, the local profile \( I_i \) of the cell \( j \) is given by:

\[ I_j = C_1 J_0 + b(1 - C_2) J_1 \]

where \( I_j \) is the local unpolarized profile within the photosphere, \( I_0 \) that within the spot, and \( b \) the relative spot to photosphere brightness contrast. To compute \( I_0 \), we use the profile given by UR’s analytical solution of the polarized radiative transfer equation in a Milne Eddington’s atmosphere (see Hébrard et al. 2014 for the values of the different parameters) and we adjust the average line-equivalent width to the observed value only. Following Dumusque et al. (2014), the local profile within the spot \( I_s \) is simply a broadened version (by a Gaussian of FWHM \( w = 2.3 \) km s\(^{-1}\), depending on the stars) of that in the photosphere \( I_0 \). We also have the option of red shifting \( I_s \) with respect to \( I_0 \) (to simulate the inhibition of the convective blue shift within the spot). However, we did not use this option for the present study given that convective blue shifts of M dwarfs are expected to be quite small.

As a result of their low \( v \sin i \), our sample stars feature spectral lines that mostly reflect their intrinsic profiles rather than their Doppler broadening (as opposed with most stars studied to date with conventional Doppler imaging, e.g., Collier Cameron 1992; Morin et al. 2008a). The consequence is that a direct modeling of the observed profiles would critically depend on our ability to achieve a detailed description of the local profile.

To overcome this limitation, we propose a novel technique, based on interpreting the residuals with respect to the average profile, rather than the profiles themselves. Practically speaking, we start the process by computing the average profile over the whole data set \( \langle I \rangle \). We then subtract \( \langle I \rangle \) from each individual Stokes I profile of the time series to derive the profile residuals \( RI \) that directly reflect the profile distortions and include most information about the spot distribution to be reconstructed. In parallel, we model \( \langle I \rangle \) by adjusting the parameters of the local profile \( I_0 \) until we obtain a good fit (including the Doppler broadening): we call
this model average profile \(<I'>\). We then sum the RI residuals to \(<I'>\) and obtain a new data set \(I'.\) Since \(<I'>\) is now perfectly known, the imaging code can concentrate its efforts on reproducing the RI residuals, i.e. the core material of our data set.

### 5.2 Simulations

We performed a set of simulations to test the performances of our novel reconstruction method. From an initial brightness map, we compute the associated Stokes \(I\) and \(RI\) data set for a given \(v\sin i\), stellar inclination \(i\), and spectral resolution. The objective is to retrieve both the brightness map and the quantities derived from the reconstructed profiles: the RV curve \(v_\text{r}\), FWHM and \(v_\text{c}\).

We present below the simulation results obtained in the case of slow rotators (\(v\sin i \leq 4 \text{ km s}^{-1}\)), and derived assuming a spectral resolving power of 10^5 (i.e., the resolution of HARPS-Pol). We further assume that the S/N of the LSD profile residuals \(RI\) is equal to 4,000 (value close to the observed S/N). Two different cases are studied: (i) a dense and regular sampling to test more specifically the use of the residuals (simulation A), and (ii) irregular sampling based on the observation of GJ 479, to mainly estimate the impact of a realistic phase coverage on the determination of the average profile (simulation B).

Dark spots are assumed to be circular with a relative size \(f^5\) with respect to the overall stellar surface. The total equivalent spot area, \(\epsilon\), is thus defined as \(\epsilon = f \times (1 - C) \times b\). For our simulation, we set \(b = 0.5\). We consider two dark spots: spot #1 has a relative area of \(f_1 = 3\%\) with \(C_1 = 0.4\) and thus \(\epsilon_1 = 0.9\%\), and is located at 20° of latitude, spot #2 is characterized by \(f_2 = 1.5\%\) with \(C_2 = 0.2\), and thus \(\epsilon_2 = 0.6\%\), and is at 50° of latitude. The full equivalent spot area \(\epsilon\) is equal to \(\epsilon_1 + \epsilon_2 = 1.5\%\). The \(v\sin i\) of the star ranges from 1 to 4 km s\(^{-1}\), and the stellar inclination is \(i = 60°\). The local profile within a spot is 15% larger than in the quiet photosphere.

#### 5.2.1 Reconstructed map

Figure 8 (top part) and Table 8 show, respectively, the maps and their associated reconstructed characteristics. To test the impact of using the profile residuals \(RI\) instead of Stokes \(I\), we compare the maps obtained using Stokes \(I\) profiles directly (called hereafter ‘the conventional method’) with those obtained from the \(I'\) replacement data set described above (called below ‘the residual method’).

We note that the global spot distribution is recovered, whatever the technique we used. With the conventional method, \(\chi^2\) of 1.0 is reached whatever the \(v\sin i\) and the phase coverage. However the spotted area is roughly under-estimated with decreasing \(v\sin i\). A similar but amplified behavior is observed with the residual method. The use of the average profile \(<I'>\) to compute the \(I'\) dataset mainly affects the reconstructed spotted equivalent spot coverage \(\epsilon\), which ends up being underestimated (1.25-1.45% instead of 1.5% depending on the \(v\sin i\)). This loss of accuracy when \(v\sin i\) decreases mainly reflects that information gets increasingly blurred in longitude as stellar rotation slows down, thus weakening profile distortions and making them harder to reconstruct for the code.

#### 5.2.2 Model of the RV jitter

The main parameter we aim at recovering is the RV curve shown in Figure 8 (3rd row, on the left) in the case of \(v\sin i = 1 \text{ km s}^{-1}\).

First, we note that RV variations are fitted down to the noise level, with both methods. For this spot configuration, the periodogram exhibits conspicuous peaks at \(P_{\text{rot}}\) and \(P_{\text{rot}}/2\). We find that both imaging methods provide similar results in the sense that they are quite successful at filtering the rotationally modulated activity jitter; we do not observe any strong peaks in the periodogram of the RV residuals O-C (= observed - computed, see periodograms Figure 8, right bottom panel).

To quantify the model efficiency, we compare the rms of O-C
Figure 8. Reconstructed map obtained for a simulated star with $v \sin i = 1 \text{ km s}^{-1}$ and $i = 60^\circ$ featuring an equivalent spot area $\epsilon$ of 1.5%. Top: Spot distribution to reconstruct. 2nd row, left: Reconstructed map from $I$ with the realistic sampling $B$. 2nd row, right: Same as left but reconstructed from RI residuals. The colour-scale depicts the photosphere filling factor of each cell $C_j$ (white corresponding to an unspotted cell). 3rd row, left: original $v_r$'s (red solid line) compared with those reconstructed using either the conventional (pink open squares) or residual (green crosses) imaging method respectively, and with those derived from the $v_r vs v_s$ anticorrelation (blue asterisks). The multiple sine fit to the data (cyan open diamonds) is also shown. The corresponding O-C residuals are presented on the bottom curve. The gray line depicts the 0 m s$^{-1}$ level. 3rd row, right: Same as 3rd row, left but for $v_s$. Bottom left: Same as 3rd row, left but for FWHM. Bottom right: Periodograms of $v_t$ (solid red line), of the $v_t$ computed from data set obtained with the conventional method (solid pink line), and with the residual method (solid green line). The periodograms of the filtered RVs (using either the conventional or the residual method) are respectively shown with the red and green dashed lines. The vertical lines outline the rotation period (in unit of $P_{\text{rot}}$) and its 3 first harmonics ($P_{\text{rot}}/4, P_{\text{rot}}/3, P_{\text{rot}}/2$). This figure is best viewed in colour.
data (see Table 9) using the two different imaging methods (based on $I$ and $I'$) with that derived from the multiple sine fits of $v_t$ (with fundamental + 1 to 3 harmonics), and from the usual anti-correlation observed between $v_t$ and $v_i$ (e.g., see Melo et al. 2007, for more details). From these results, we clearly see that the quality of the filtering based on Doppler imaging is similar to the one for more details). From these results, we clearly see that the quality of the filtering based on residual reconstruction (hereafter DI fit). The number of degrees of freedom associated with the imaging process is estimated from the number of parameters associated with the non-axisymmetric SH modes needed to describe the observed variations, i.e., $\sim 20$ for $l \leq 4$. Results are presented in Table 6.

5.3.1 GJ 358

From the $RI$ profiles (see Fig. 9), we reconstruct the map shown in Fig. 10, featuring an equivalent spot coverage $\epsilon$ of $\sim 1\%$ (with $b = 0.5$). The initial $\chi^2_s$ is 3.8 and corresponds to the fit to the $RI$ spectra with an unspotted star. Adding spots on the stellar surface allows the code to reduce $\chi^2_s$ down to 2.1, with a main spot at high latitude ($\sim 60^\circ$), and extending towards the equator.

Synthetic RV curve derived from this brightness map exhibits a full amplitude of 8.5 m s$^{-1}$, and matches the data down to $\chi^2_s = 2.05$. The rms of the RV residuals is 2.88 m s$^{-1}$ (whereas $\sigma_{\text{true}} = 2.08$ m s$^{-1}$). The low FAP ($< 0.01\%$) demonstrates that the imaging process provides a very significant improvement in the quality of the fit to the data. Moreover, in the $v_t$ periodograms we clearly see that (i) the signals at $P_\text{rot}$, $P_\text{rot}/2$ and $P_\text{rot}/3$ have been removed, and (ii) no major periodic signal remains.

5.3.2 GJ 479

The reconstructed spots have a equivalent surface of $\sim 1.4\%$, and are located at mid-latitude ($\sim 40^\circ$, see Fig. H1). It corresponds to a final $\chi^2_s$ of 2.9 (starting from $\chi^2_s = 5.0$).

The $J_s$ component of the RV jitter deduced from this map has a peak-to-peak amplitude of 11 m s$^{-1}$, and the rms of RV residuals is 3.93 m s$^{-1}$. Once $J_s$ is subtracted from RV data, the periodogram does not exhibit any strong peak anymore: the filtering allows to clean up the signals whose periods are $P_\text{rot}$, $P_\text{rot}/2$, $P_\text{rot}/3$.

5.3.3 GJ 410

For GJ 410, we collected observations over three months (i.e., six stellar rotations). We note that all the $RI$ spectra do not identically repeat from one rotation cycle to the next (see, e.g., phases 2.7 and 3.7, or phases 4.9 and 5.9 in Fig. 11). For this star, one of the most active of the studied sample, we first carried out a reconstruction for the whole data set (see Fig. H2). In a second step, we divided the data set into three sequential subsets to take into account the evolution of spot coverage on the stellar surface, respectively corresponding to rotation cycles 1.928-2.707 (epoch #1, 9 observations), 3.777-4.988 (epoch #2, 12 obs) and 5.058-6.199 (epoch #3, 7 obs). The results are given Fig. 12.

Dividing the data into multiple subsets allows us to improve the fit to the data, with a final $\chi^2$ decreased from 2.0 (for the complete set) to 1.2-1.7 (for the individual subsets). The reconstructed maps show that in epoch #1 a main dark spot at low latitude around phase 0.6 is visible at the stellar surface, with a fainter spot at phase 0.25 and 30° of latitude. This secondary spot grows and strengthens in epoch #2 and #3, and a new spot appears at phase 0.95 from epoch #2 onwards.

Moreover, the quality of the RV filtering increases within

with $\chi^2_{s1}$ and $\chi^2_{s2}$, respectively, corresponding to the $\chi^2$ of the multiple sine fit and of the fit obtained with the Doppler imaging based on residual reconstruction (hereafter DI fit). The number of degrees of freedom associated with the imaging process is estimated from the number of parameters associated with the non-axisymmetric SH modes needed to describe the observed variations, i.e., $\sim 20$ for $l \leq 4$. Results are presented in Table 6.

5.3 Application to M dwarfs

We apply the residual imaging method presented and tested in Sec. 5.1 & 5.2 to recover the parent spot distribution generating the observed RV activity jitter for the various stars of our sample.

To assess the likelihood of the RV fit we obtain from the map, we compute the FAP as presented in Sec. 4.2.2. We take the multiple sine fit of $v_t$ (fundamental + 2 first harmonics) as a reference to compute $\Delta \chi^2$: we then obtain (with a formula resembling Eq. 3):

$$\Delta \chi^2 = \frac{\chi^2_{s0} - \chi^2_{s2}}{\chi^2_{s1}} N$$

Figure 9. Temporal series of $RI$ of GJ 358. Data are in red, the modeled $RI$ are in black. On the right of each spectrum, we indicate the observation phase, on the left the 1-$\sigma$ error bars.
Figure 10. Top: Temporal evolution of $B_t$, $v_t$ and FWHM (with respect to the average value) of GJ 358. Data and their error bars are represented in red, blue and pink according the rotation cycle (cycle 1 in red, cycle 2 in blue and cycle 3 in pink). The green curves corresponds to the sine fit, and the brown curves represents the RVs computed from the DI map. Middle left: Maps of the filling factor of the photosphere (white means that there is only quiet photosphere, brown means there is only spot in the cell), and Middle right: Map of the radial large-scale magnetic field. Bottom: Periodograms of observed RVs (black), and of the RVs after the RV filtering from DI (blue). The FAP at 1% and 10% are represented in dotted lines and dot-dashed lines.
each of our subsets. The modeled RV curves we derive match the observed ones at a $\chi^2$ level of 1.0–1.9, to be compared with 4.1 when processing the whole data set. We conclude that in the case of GJ 410, the main variability observed in RV data likely comes from short-lived spots, inducing an evolution in the shape of the RV curve on a timescale of only 2 rotation cycles.

### 5.3.4 GJ 205

For GJ 205, the amplitude of the RI spectra is low ($\leq 0.05\%$, see Fig. G1). The DI reconstruction leads to an equivalent spotted area $\epsilon$ of $\sim 0.9\%$ that allows to decrease the $\chi^2$ to fit to the profiles from 4.3 to 3.8 only. The reconstructed features exhibit faint spot clusters, located at high and mid-latitude, however, this reconstruction is not reliable given the FAP of 75% associated with the Stokes I LSD fit. The RV jitter is not efficiently filtered (FAP $\sim 98\%$). These results validate that there is likely no signals at $P_{\text{rot}}$ and that DR might strongly affect the dark spot location at the surface of GJ 205 and thus the RV activity jitter of the star. Further work, taking explicitly into account differential rotation, is thus needed for this star. This would require in particular a high quality spectropolarimetric data set from which differential rotation can be reliably estimated.

### 5.3.5 Discussion

The efficiency of the RV filtering depends on the relative importance of the rotationally modulated RV component with respect to the random component. The importance of each component is re-minded in Table 11.

For the lowest mass star of this sample, GJ 358, the rotational modulated component $J_{\text{rot}}$ of the RV jitter have been divided by 2.8 (and $J_{\text{obs}}$ by 2.2). For the earliest M-dwarfs (GJ 205 and GJ 410), neither the DI modeling nor the multiple sine fit succeed at obtaining a decent match to the observed RV jitter (high FAP), because of a higher level of intrinsic variability of the RV curve. In the particular case of GJ 410, we observe that this higher level of intrinsic variability is directly related to the short spot lifetimes (1–2 rotation cycles), as evidenced by the significant improvement in the efficiency of the DI filtering when considering shorter time intervals (see Table 11). Contrary to a simple multiple sine fit, the use of the imaging techniques allows one to (i) to better constrain the origin of the activity jitter (dark spots and rotational modulation, DR or short spot lifetime), and (ii) to obtain a self-consistent physically-motivated, though still simple, description of the activity jitter rather than to perform a blind filtering of the RV data.

Our model is based on the assumption that the dominant contribution to the total RV signal in the M dwarfs should be the effect of dark spots. This assumption mainly relies on Sun-like stars studies, and on the low temperature of M dwarfs. However, we have to note that the current DI model does not yet allow us to faithfully reproduce the full amplitude of FWHM of the four studied stars. The phase of the variations are fitted, but the peak-to-peak amplitude is always underestimated in each case. This caveat may reflect inadequate assumptions/approximations in our modeling and will be further explored in forthcoming papers. The next step will be to add more physical realism in our model (e.g., use a more realistic line profile $I_0$ to characterize the spotted regions) to improve the modeling of the effects of the activity jitter in M dwarfs.

### 6 SUMMARY AND PERSPECTIVES

The magnetic analysis gives access to the large-scale magnetic field map of the observed weakly-active M dwarfs, as well as to a reliable and accurate estimate of $P_{\text{rot}}$. Fig. 13 summarizes the magnetic properties of our sample. These data allow us to add new observations in the $M_*$ - $P_{\text{rot}}$ diagram, covering a mostly unexplored domain so far. The magnetic fields detected for the early-M dwarfs exhibit strengths of a few tens of G, and are lower by a factor 5 than those of more active and rapidly rotating mid-M dwarfs (Morin et al. 2008b). We note that for the stars with a stellar mass larger than 0.5 $M_\odot$, the toroidal component is significant, except for GJ 205 whose large-scale magnetic field is dominated by a poloidal component. GJ 205 is the only observed star with a Rossby number $R_\ast^6$ higher than 1 (as the Sun). This is in agreement with the trends previously reported in Donati & Landstreet (2009), where stars with $R_\ast > 1$ tend to exhibit weak poloidal fields mostly aligned with the rotation axis.

For $M_* < 0.5 M_\odot$, the large-scale magnetic properties are diverse, with some stars featuring mainly poloidal and axisymmetric fields (GJ 358, GJ 674) and some others exhibiting more complex topologies (GJ 479, GJ 176). In particular, we note that 2 stars of our sample feature different types of fields while sharing the same location in the $M_*$ vs $P_{\text{rot}}$ plane. This is reminiscent of the bi-stable behavior of dynamo processes, as previously pointed out by, e.g., Morin et al. (2011) in the case of active very low-mass dwarfs. The theoretical models (e.g., Gastine et al. 2013) foresee a bistability around $R_\ast = 0.1$, with a transition between fields with a simple dipolar topology ($R_\ast < 0.1$) and fields with a complex topology.

![Figure 11. As Fig. 9, for GJ 410. The blue fit represents the fit from epochs #1 to #3, the red fit represents the fit from the full data set.](image-url)
Photosphere occupancy

Figure 12. Maps of the filling factor of the photosphere of GJ 410 (white means that there is only quiet photosphere, brown means there is only spot in the cell) at the three epochs (from (1) to (3), from left to right).

Table 10. Same as Table 6 for the three observation epochs of GJ 410. For the observation epochs (1) and (3) a single harmonics is sufficient to reach residual RVs lower than 3 m s\(^{-1}\). The RV jitter can by entirely modeled with rotational modulation (rms\(_J\), \(\sim\) 0 m s\(^{-1}\), and rms\(_J\), tot \(\sim\) rms\(_J\), m), and we choose \(\chi^2_r, 1 = 1.0\) and rms\(_J, 1 = \sigma_J\).

|          | \(J_m\) | \(J_m + J_I\) | \(J_m + J_I\) with DI | A1 | A2 | A3 |
|----------|---------|---------------|------------------------|----|----|----|
| GJ 205   | 3.12    | 1.75          | 2.68                   | 1.53 | 1.2 | 1.1 | 2.1 |
| GJ 410   | 8.21    | 5.67          | 5.93                   | 5.82 | 1.4 | 1.3 | 3.1 |
| epoch #1 | 9.01    | 9.01          | -                      | 8.43 | -  | 3.8 | 3.9 |
| epoch #2 | 6.37    | 6.02          | 2.07                   | 5.95 | 3.1 | 2.8 | 6.6 |
| epoch #3 | 5.10    | 5.10          | -                      | 5.04 | -  | 5.2 | 6.5 |
| full set | 4.89    | 3.83          | 3.04                   | 3.54 | 1.7 | 1.5 | 2.6 |
| GJ 358   | 4.31    | 4.10          | 1.33                   | 3.83 | 3.2 | 2.2 | 2.8 |

Table 11. Same as Table 7, with three additional columns: column 5 gives \(J_m\), the rms of the RV data modelled using the DI imaging, column 7 gives \(A_2\), quantifying how we can reduce the activity jitter thanks to DI imaging, and column 8 gives \(A_3 = J_m / \sqrt{P_m - P_{m,DI}}\), denoting the factor of decrease of the \(J_m\) component. The dash indicates that data can be reproduced down to the noise level, i.e., that the RV variations are due to rotational modulations only.

\(R_o > 1\). Our observations suggest that dynamo bi-stability may indeed be present at different places of the \(M_\ast\) vs \(P_{\text{rot}}\) diagram than previously identified by Morin et al. (2011) and whose relation with theoretical predictions is yet to be checked in more details. More spectropolarimetric observations of M dwarfs in this range of mass and rotation periods are necessary to investigate this result in more details.

To find an Earth-like planet (in terms of size, mass and ef-
fective stellar flux) thanks to the RV method, moderately active M dwarfs appear to be natural targets with their reduced effective temperature and their low-mass. However we still need to model and filter out the RV activity jitter to reveal these plausible low-mass planets RV signatures. To characterize the activity jitter of cool low-mass stars, we used the studies done for Sun-like stars (e.g., Dumusque et al. 2014), taking into account their reduced photospheric temperature. We then assumed the dominant contributor to the activity-modulated RV signal that plagues RV data is the rotational modulation caused by dark spot at the stellar surface (in agreement with theoretical studies as Béek et al. 2015). With this hypothesis, we were able to develop a technique, based on a tomographic imaging (ZDI), to model the spot distribution at the surface of the four weakly active early M dwarfs we observed.

The sampled stars being slow rotators ($v \sin i \leq 2 \text{ km} \text{s}^{-1}$), the observed spectral line width reflects directly intrinsic profiles rather than the Doppler broadening. To overcome this issue, we adapted the Doppler Imaging technique to reconstruct the profile residuals instead of the observed profiles themselves (see Sec. 5.1). Thanks to this approach, we are not dependent anymore on our ability at achieving a detailed description of the local profile, and the code is focussed on the profile distortion modeling only. Besides, this method relies on the knowledge of the rotational period $P_{\text{rot}}$, parameter previously estimated from the magnetic analysis.

The novel imaging method we devised is found to be reasonably successful at reconstructing the spot distribution at the surface of the early-type slowly-rotating stars that we studied. From this map and its associated set of spectra, we model the RV activity jitter whose period is commensurate to the magnetic analysis of the stellar activity. We achieve a detailed description of the local profile, and the code is focussed on the profile distortion modeling only. Besides, this method relies on the knowledge of the rotational period $P_{\text{rot}}$, parameter previously estimated from the magnetic analysis.

To disentangle stellar from planetary signals, a powerful analysis should be to carry out observations at both optical and IR wavelengths, particularly for M dwarfs emitting a large fraction of their flux in the IR. Several studies showed that the RV jitter will be divided by at least a factor of 2 due to the lower contrast between the dark spot regions and the quiet photosphere (Marchwinski et al. 2015) & Reiners et al. (2010; Rodler et al. 2011), respectively for Sun-like stars & late M dwarfs). In this context, the new generation of high resolution/precision velocimeters working in the nIR domain (e.g., CARMENES™, SPIRou™, CIRIRES+™) present a tremendous interest. Moreover, characterizing, modeling and filtering out the RV activity jitter of M dwarfs remain mandatory steps for all future velocimetric studies aiming at detecting small Earth-mass rocky planets. They allow to define the best adapted observational strategies, taking into account the specificities of the M dwarf activity that hampers RV measurements. Moreover, while the brightness contrast decreases in the IR, the impact of small scale-magnetic field on RVs strengthens through Zeeman effect. Therefore, the method we presented will be particularly adapted for SPIRou, which will be both a high-precision velocimeter and a spectropolarimeter. Spectropolarimetric surveys in nIR will give new options for filtering RV curves from the activity jitter using tomographic techniques like ZDI, and will efficiently further enhance the sensitivity to low-mass planets, as well as to the magnetic stellar activity RV signal itself.

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7 Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Echelle Spectrographs, a high-precision velocimeter at the 3.5m telescope at the Calar Alto Observatory.
8 SpectroPolarimeter in the near InfraRed, a spectropolarimeter/high-precision velocimeter for the 3.6m Canada-France-Hawaii Telescope. It will operate at near-infrared wavelengths (first light in 2017).
9 upgrade of the CRyogenic InfraRed Echelle Spectrograph at ESO/VLT (first light in 2018).
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Figure 14. The x-axis depicts the $C_j$, denoting the proportion of photosphere inside each cell, and the y-axis the absolute value of the radial component of the large-scale magnetic field. The colorscale represents the number of cells affected by both a radial magnetic field and a dark spot. The arrow indicates the absolute value of the radial polar magnetic field of the star. Top left: GJ 358 Top right: GJ 479 Bottom: GJ 410.
Modeling the RV jitter using tomographic imaging

| Star  | $p^{B_l}_{\text{rot}}$ | $p^{\text{RV}}_{\text{rot}}$ | $p^{\text{FWHM}}_{\text{rot}}$ | $p^{H\alpha}_{\text{rot}}$ |
|-------|------------------------|-------------------------------|-------------------------------|---------------------------|
| GJ 205 | 33.63±0.37             | 39.70±0.85                    | 41.9±1.9                      | 33.46±0.80                |
| GJ 410 | 13.83±0.10             | 14.20±0.10                    | 14.76±0.20                    | 15.15±0.30                |
| GJ 479 | 24.04±0.75             | 23.8±1.9                      | 25.48±0.81                    | 22.94±0.60                |
| GJ 358 | 25.37±0.32             | 24.47±0.60                    | 25.49±0.42                    | 23.8±2.7                  |

Table A1. Rotation periods derived from $B_l$, RV, FWHM and Hα measurements and the estimated error-bars at 1σ for the 4 stars of the sample.

APPENDIX A: ROTATION PERIODS DERIVED FROM $B_l$, RV, FWHM AND $H\alpha$.

APPENDIX B: OBSERVATIONS JOURNAL

Observations journal for the four M-dwarfs observed from October 2013 to August 2014 with HARPS-Pol@LaSilla and NARVAL@TBL.

This paper has been typeset from a TeX/LaTeX file prepared by the author.
## Table B1. Journal of observations for GJ 479. Columns 1 and 5, respectively, list the rotational cycle (computed with the rotation period mentioned in Table 1) according to ephemeris given by Eq 1, the date of the beginning of the night, the Barycentric Julian Date, the observation site, the peak S/N value bin. Column 6-7 give, respectively, the Cycle Date BJD instrument S/N B (G) RV (km s\(^{-1}\)).

| Cycle | Date      | BJD (+ 2,456,000) | Instrument | S/N | B (G) | RV (km s\(^{-1}\)) |
|-------|-----------|--------------------|------------|-----|-------|-------------------|
| 0.024 | 30apr14   | 778.5870           | HARPS-Pol  | 133 | 20.54 | 7.03  | 8.17e-03 ± 1.56e-03 |
| 0.069 | 01may14   | 779.6500           | HARPS-Pol  | 121 | 3.36  | 7.82  | 4.08e-03 ± 1.74e-03 |
| 0.151 | 03may14   | 781.6390           | HARPS-Pol  | 108 | 8.61  | 9.02  | 5.16e-03 ± 1.97e-03 |
| 0.190 | 04may14   | 782.5590           | HARPS-Pol  | 135 | 5.46  | 7.04  | 5.53e-03 ± 1.43e-03 |
| 0.231 | 05may14   | 783.5600           | HARPS-Pol  | 102 | 24.94 | 9.97  | 6.72e-03 ± 2.09e-03 |
| 0.272 | 06may14   | 784.5480           | HARPS-Pol  | 120 | 18.45 | 8.25  | 5.52e-03 ± 1.75e-03 |
| 0.356 | 08may14   | 786.5590           | HARPS-Pol  | 146 | 21.14 | 6.50  | 1.32e-02 ± 1.43e-03 |
| 1.314 | 31may14   | 809.5840           | HARPS-Pol  | 99  | 32.36 | 7.97  | 7.16e-04 ± 2.20e-03 |
| 1.397 | 02jun14   | 811.5850           | HARPS-Pol  | 120 | 16.67 | 7.65  | 9.20e-04 ± 1.69e-03 |
| 1.523 | 03jun14   | 814.6220           | HARPS-Pol  | 99  | -16.66| 9.66  | -4.61e-03 ± 2.14e-03|
| 1.607 | 07jun14   | 816.6220           | HARPS-Pol  | 95  | -34.92| 10.45 | -8.82e-03 ± 2.25e-03|
| 1.648 | 08jun14   | 817.6150           | HARPS-Pol  | 85  | -16.75| 11.69 | -4.24e-03 ± 2.31e-03|
| 1.689 | 09jun14   | 818.6140           | HARPS-Pol  | 75  | -16.33| 13.67 | -1.93e-03 ± 2.87e-03|
| 1.729 | 10jun14   | 819.5700           | HARPS-Pol  | 97  | 24.67 | 10.03 | -5.63e-03 ± 2.18e-03|
| 1.894 | 14jun14   | 823.5230           | HARPS-Pol  | 89  | 1.53  | 11.60 | 3.14e-03 ± 2.39e-03 |
| 1.935 | 15jun14   | 824.5230           | HARPS-Pol  | 106 | 15.89 | 9.20  | 5.63e-03 ± 1.96e-03 |
| 2.016 | 17jun14   | 826.4650           | HARPS-Pol  | 113 | 14.38 | 8.71  | 2.82e-03 ± 1.83e-03 |
| 2.099 | 19jun14   | 828.4620           | HARPS-Pol  | 129 | 22.29 | 7.44  | 2.27e-03 ± 1.60e-03 |
| 2.144 | 20jun14   | 829.5330           | HARPS-Pol  | 118 | 10.17 | 7.95  | 6.55e-03 ± 1.76e-03|
| 2.184 | 21jun14   | 830.5110           | HARPS-Pol  | 114 | 19.65 | 8.41  | 4.76e-03 ± 1.82e-03 |
| 2.352 | 25jun14   | 834.5360           | HARPS-Pol  | 101 | 40.06 | 9.60  | 3.41e-03 ± 2.12e-03 |
| 2.643 | 02jul14   | 841.5440           | HARPS-Pol  | 63  | 3.14  | 17.37 | 2.85e-03 ± 3.50e-03 |
| 2.684 | 03jul14   | 842.5310           | HARPS-Pol  | 101 | -18.62| 9.72  | -5.48e-03 ± 2.08e-03|

## Table B2. Same as Table B1 for GJ 358.
### Table B4.

| Cycle | Date       | BJD (+ 2 456 000) | instrument | S/N | B (G) | RV (km s\(^{-1}\)) |
|-------|------------|-------------------|------------|-----|-------|-------------------|
| 0.000 | 03oct13    | 569.8850          | HARPS-Pol  | 177 | 8.29  | ± 0.25           |
|       | 03oct13    | 570.9030          | HARPS-Pol  | 196 | 11.79 | ± 2.00           |
| 0.178 | 09oct13    | 575.8680          | HARPS-Pol  | 228 | 3.30  | ± 1.70           |
| 0.208 | 10oct13    | 576.8910          | HARPS-Pol  | 219 | 5.16  | ± 1.80           |
| 0.444 | 18oct13    | 584.8280          | HARPS-Pol  | 188 | 11.05 | ± 2.13           |
| 0.505 | 20oct13    | 586.8820          | HARPS-Pol  | 194 | 4.40  | ± 2.04           |
| 0.682 | 26oct13    | 592.8720          | HARPS-Pol  | 210 | -5.45 | ± 1.84           |
| 0.741 | 28oct13    | 594.8510          | HARPS-Pol  | 171 | -2.36 | ± 2.33           |
| 0.918 | 03nov13    | 600.8070          | HARPS-Pol  | 180 | 6.55  | ± 2.20           |
| 0.977 | 05nov13    | 602.8160          | HARPS-Pol  | 189 | 11.98 | ± 2.09           |
| 1.036 | 07nov13    | 604.7880          | HARPS-Pol  | 197 | 11.14 | ± 2.00           |
| 1.274 | 15nov13    | 612.7990          | HARPS-Pol  | 170 | 2.45  | ± 2.36           |
| 1.332 | 17nov13    | 614.7790          | HARPS-Pol  | 203 | 8.53  | ± 1.94           |
| 1.571 | 25nov13    | 622.8050          | HARPS-Pol  | 209 | 2.80  | ± 1.88           |
| 1.623 | 27nov13    | 624.5610          | NARVAL     | 313 | -1.60 | ± 1.31           |
| 1.630 | 27nov13    | 624.8090          | HARPS-Pol  | 174 | -2.16 | ± 2.32           |
| 1.688 | 29nov13    | 626.7720          | HARPS-Pol  | 185 | -4.40 | ± 2.13           |
| 1.745 | 01dec13    | 628.7000          | HARPS-Pol  | 138 | -5.52 | ± 3.04           |
| 1.864 | 05dec13    | 632.6810          | HARPS-Pol  | 171 | 5.87  | ± 2.39           |
| 2.006 | 10dec13    | 637.4830          | NARVAL     | 399 | 8.10  | ± 0.97           |
| 2.065 | 12dec13    | 639.4620          | NARVAL     | 454 | 6.75  | ± 0.83           |
| 2.186 | 16dec13    | 643.5400          | NARVAL     | 308 | 4.78  | ± 1.31           |
| 3.135 | 17jan14    | 675.5440          | HARPS-Pol  | 172 | 4.19  | ± 2.42           |
| 3.197 | 19jan14    | 677.6080          | HARPS-Pol  | 148 | 3.78  | ± 2.76           |
| 3.315 | 23jan14    | 681.5910          | HARPS-Pol  | 133 | 8.39  | ± 3.11           |
| 3.523 | 30jan14    | 688.5870          | HARPS-Pol  | 171 | 5.48  | ± 2.37           |

### Table B4.

| Cycle | Date       | BJD (+ 2 456 000) | instrument | S/N | B (G) | RV (km s\(^{-1}\)) |
|-------|------------|-------------------|------------|-----|-------|-------------------|
| 0.000 | 10sep13    | 546.4638          | NARVAL     | 301 | 2.71  | ± 1.43           |
| 0.637 | 17sep13    | 553.4688          | NARVAL     | 251 | 2.14  | ± 1.80           |
| 1.092 | 22sep13    | 558.4694          | NARVAL     | 282 | -1.07 | ± 1.57           |
| 1.269 | 24sep13    | 560.4200          | NARVAL     | 318 | -1.60 | ± 1.36           |
| 2.629 | 09oct13    | 575.3856          | NARVAL     | 278 | 3.12  | ± 1.57           |
| 2.821 | 11oct13    | 577.4947          | NARVAL     | 242 | 1.67  | ± 1.82           |
| 2.902 | 12oct13    | 578.3830          | NARVAL     | 297 | 1.19  | ± 1.41           |
| 2.993 | 13oct13    | 579.3876          | NARVAL     | 274 | -2.93 | ± 1.55           |
| 3.442 | 18oct13    | 584.3262          | NARVAL     | 209 | 4.21  | ± 2.21           |
| 4.622 | 31oct13    | 597.3060          | NARVAL     | 189 | 2.37  | ± 2.44           |
| 7.075 | 27nov13    | 624.2851          | NARVAL     | 194 | -6.40 | ± 2.41           |
| 8.252 | 10dec13    | 637.2351          | NARVAL     | 280 | 1.27  | ± 1.57           |
| 8.434 | 12dec13    | 639.2336          | NARVAL     | 305 | 1.98  | ± 1.42           |
| 8.615 | 14dec13    | 641.2530          | NARVAL     | 234 | 7.99  | ± 1.92           |
| 8.709 | 15dec13    | 642.2580          | NARVAL     | 291 | 4.24  | ± 1.52           |
| 25.764| 20jun14    | 829.8720          | HARPS-Pol  | 91  | 17.14 | ± 5.05           |
| 25.950| 22jun14    | 831.9170          | HARPS-Pol  | 158 | 7.85  | ± 2.62           |
| 26.132| 24jun14    | 833.9110          | HARPS-Pol  | 140 | 8.96  | ± 3.02           |
| 26.314| 26jun14    | 835.9120          | HARPS-Pol  | 100 | 2.19  | ± 4.55           |
| 28.311| 18jul14    | 857.8880          | HARPS-Pol  | 111 | 6.47  | ± 4.01           |
| 28.398| 19jul14    | 858.8430          | HARPS-Pol  | 141 | -0.08 | ± 2.96           |
| 28.493| 20jul14    | 859.8910          | HARPS-Pol  | 129 | 2.69  | ± 3.34           |
| 28.761| 23jul14    | 862.8310          | HARPS-Pol  | 107 | 6.86  | ± 7.38           |
| 28.850| 24jul14    | 863.8130          | HARPS-Pol  | 119 | 10.93 | ± 3.61           |
| 28.940| 25jul14    | 864.8020          | HARPS-Pol  | 131 | 4.41  | ± 3.28           |
| 31.849| 27aug14    | 896.8010          | HARPS-Pol  | 102 | -0.01 | ± 4.45           |

### Table B3.

Same as Table B1 for GJ 205.
| Cycle | Date      | BJD (+ 2 456 000) | Instrument | S/N | B (G) | RV (km s$^{-1}$) |
|-------|-----------|-------------------|------------|-----|-------|------------------|
| 0.558 | 09jan14   | 667.6948          | NARVAL     | 282 | -8.94 ± 1.50 | -         |
| 0.696 | 11jan14   | 669.6198          | NARVAL     | 255 | 5.28 ± 1.69  | -         |
| 1.000 | 15jan14   | 673.8840          | HARPS-Pol  | 90  | 16.52 ± 5.62 | 2.17e-02  |
| 1.928 | 28jan14   | 686.8660          | HARPS-Pol  | 84  | 27.53 ± 6.11 | 2.79e-03  |
| 1.996 | 29jan14   | 687.8170          | HARPS-Pol  | 79  | 8.28 ± 6.59  | 4.17e-03  |
| 2.067 | 30jan14   | 688.8200          | HARPS-Pol  | 108 | 4.11 ± 4.55  | -5.30e-04 |
| 2.228 | 01feb14   | 690.8100          | HARPS-Pol  | 112 | 3.32 ± 4.35  | 1.31e-02  |
| 2.281 | 02feb14   | 691.8190          | HARPS-Pol  | 103 | -1.09 ± 4.75 | 9.54e-04  |
| 2.423 | 04feb14   | 693.7960          | HARPS-Pol  | 110 | -15.13 ± 4.41| 2.79e-03  |
| 2.493 | 05feb14   | 694.7790          | HARPS-Pol  | 106 | -13.66 ± 4.66| 3.50e-03  |
| 2.565 | 06feb14   | 695.7870          | HARPS-Pol  | 109 | -8.80 ± 4.45 | 6.26e-03  |
| 2.707 | 08feb14   | 697.7710          | HARPS-Pol  | 100 | 10.94 ± 4.92 | -2.21e-02 |
| 3.777 | 23feb14   | 712.7580          | HARPS-Pol  | 123 | 34.21 ± 3.85 | -2.86e-03 |
| 3.849 | 24feb14   | 713.7600          | HARPS-Pol  | 107 | 30.37 ± 4.53 | 2.02e-03  |
| 3.992 | 26feb14   | 715.7630          | HARPS-Pol  | 122 | 19.46 ± 3.86 | -3.82e-03 |
| 4.133 | 28feb14   | 717.7440          | HARPS-Pol  | 101 | 3.45 ± 4.82  | 4.44e-03  |
| 4.278 | 02mar14   | 719.7690          | HARPS-Pol  | 125 | -2.65 ± 3.82 | 2.06e-02  |
| 4.347 | 03mar14   | 720.7430          | HARPS-Pol  | 118 | -7.61 ± 4.02 | 8.56e-03  |
| 4.418 | 04mar14   | 721.7260          | HARPS-Pol  | 103 | -1.61 ± 4.73 | 8.64e-03  |
| 4.630 | 07mar14   | 724.7060          | HARPS-Pol  | 98  | 9.48 ± 5.00  | 1.01e-03  |
| 4.703 | 08mar14   | 725.7160          | HARPS-Pol  | 94  | 24.12 ± 5.32 | 2.93e-03  |
| 4.776 | 09mar14   | 726.7450          | HARPS-Pol  | 108 | 16.25 ± 4.47 | 2.14e-03  |
| 4.845 | 10mar14   | 727.7130          | HARPS-Pol  | 113 | 22.17 ± 4.30 | -2.84e-03 |
| 4.988 | 12mar14   | 729.7070          | HARPS-Pol  | 112 | 9.37 ± 4.23  | -1.80e-04 |
| 5.058 | 13mar14   | 730.6860          | HARPS-Pol  | 89  | 6.96 ± 5.69  | -6.63e-03 |
| 5.130 | 14mar14   | 731.6960          | HARPS-Pol  | 83  | 7.69 ± 6.25  | -5.06e-03 |
| 5.769 | 23mar14   | 740.6520          | HARPS-Pol  | 103 | 16.34 ± 4.84 | -5.91e-03 |
| 5.913 | 25mar14   | 742.6630          | HARPS-Pol  | 113 | 11.95 ± 4.27 | 2.96e-03  |
| 6.036 | 27mar14   | 744.3780          | NARVAL     | 169 | 11.67 ± 2.85 |         |
| 6.055 | 27mar14   | 744.6480          | HARPS-Pol  | 97  | 5.46 ± 5.06  | -8.96e-03 |
| 6.127 | 28mar14   | 745.6580          | HARPS-Pol  | 110 | 6.51 ± 4.45  | -1.39e-02 |
| 6.199 | 29mar14   | 746.6660          | HARPS-Pol  | 124 | -3.10 ± 3.82 | 1.81e-03  |
| 6.753 | 06apr14   | 754.4280          | NARVAL     | 221 | 11.83 ± 2.09 |         |
| 6.899 | 08apr14   | 756.4720          | NARVAL     | 298 | 11.17 ± 1.43 |         |
| 6.969 | 09apr14   | 757.4440          | NARVAL     | 303 | 7.82 ± 1.42  |         |
| 7.119 | 11apr14   | 759.5440          | NARVAL     | 262 | 4.32 ± 1.73  |         |
| 7.184 | 12apr14   | 760.4620          | NARVAL     | 281 | 1.66 ± 1.53  |         |
| 7.255 | 13apr14   | 761.4560          | NARVAL     | 296 | -0.22 ± 1.47 |         |
| 7.323 | 14apr14   | 762.4040          | NARVAL     | 229 | -2.88 ± 1.91 |         |
| 7.399 | 15apr14   | 763.4680          | NARVAL     | 294 | -6.74 ± 1.47 |         |
| 7.468 | 16apr14   | 764.4370          | NARVAL     | 300 | -7.45 ± 1.45 |         |
| 7.542 | 17apr14   | 765.4620          | NARVAL     | 253 | -4.75 ± 1.76 |         |

Table B5. Same as Table B1 for GJ 410.
Figure C1. Same as Fig. 1 for GJ 479.

Figure C2. Same as Fig. 1 for GJ 205. HARPS-Pol data are in red, NARVAL data are blue.
Figure D1. Same as Fig. 3 for GJ 205. LSD Stokes $V$ profiles in the top left and top right panels correspond to HARPS-Pol and NARVAL observations respectively.
Figure D2. Same as Fig. 3 for GJ 479.
Figure D3. Same as Fig. 3 for GJ 846. LSD Stokes $V$ profiles in the top left and top right panels correspond to NARVAL and HARPS-Pol observations respectively.
Figure E1. As Figure 6 for GJ 479.
Figure E2. As Figure 7 for GJ 205. Note that for this star, the DR is supposed only, and not measured from the data set.
Figure F1. Reconstructed map obtained for a star with $v \sin i = 1 \text{ km s}^{-1}$ and $i = 60^\circ$ with 2 spots covering 1.5% of the stellar surface. Left: Reconstructed map from $I$ with the sampling A, Right: Reconstructed map from $RI$ with the sampling A. The colour-scale depicts the photosphere filling factor of each cell (white corresponding to an unspotted cell).

Figure G1. Same as Figure 9 for GJ 479 (left) and GJ 205 (right).
Figure H1. Same as Figure 10 for GJ 479
Figure H2. Same as Figure 10 for GJ 410, from the whole data set.
Figure H3. Same as Figure 10 for GJ 205