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IMPACT OF MAGNETIC FIELD ON RADIAL VELOCITY MEASUREMENTS.

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Abstract. Very low-mass stars are very promising targets for planet-search programs, in particular to discover super-Earths / Earths located in their habitable zone. Their detection is in principle accessible to the existing velocimeters of highest radial-velocity (RV) precision, but challenging due to activity (i.e., dark spots and magnetic regions at their surfaces) which generate a noise level in RV curves (RV jitter). It can severely limit our practical ability at detecting Earth-like planets. To overcome this intrinsic limitation, a promising option consists in modeling directly the stellar activity behind the activity jitter, and in particular the magnetic field that gives rise to it. To do this, simultaneous observations in velocimetry (for activity jitter) and in spectropolarimetry (for the Zeeman signatures in spectral lines tracing the presence of a large-scale field) are needed. We present here our first results both on the simulations on the impact of magnetic fields on line profiles (bisectors & RV data), and on the simultaneous observations done thanks to HARPSPol@LaSilla and NARVAL@TBL/SOPHIE@OHP on a small sample.

Keywords: magnetic fields, starspots, radial velocity, spectropolarimetry

1 Introduction

The first exoplanets were found nearly two decades ago. Since then, the attention has switched from simply looking for exoplanets to characterizing super-Earths / Earths within the habitable zones (HZs) of their host stars, i.e. in the orbital range where liquid water can be stable at the planetary surfaces. Despite the high precision of existing velocimeters, a major issue remains to detect them with radial velocity technique. We remain confronted with the interference of stellar noise. Stellar activity (e.g., spots, granulation, magnetic fields) can impact the shape of stellar spectral lines and thus induce apparent RV variations mimicking those induced by an orbiting planet (e.g., Queloz et al. 2001), called RV jitter. To improve the detection threshold with RV techniques, we need to efficiently diagnose the activity jitter to be able to filter out ultimately RV curves from stellar RV signals.

To diagnose the RV jitter and avoid misinterpreting RV data, it is crucial to accurately characterize the impact of stellar activity on usual proxies such as line bisectors. RV jitter results from the presence of inhomogeneities at the surface of the star, carried across the visible disk by rotation and impacting the position and shape of line profiles. By analyzing in detail the shape of spectral lines, one can distinguish planetary signals from activity jitters. Existing studies on RV jitters (such as Queloz et al. 2001; Desort et al. 2007; Boisse et al. 2011), mainly focus on the impact of cool/dark spots. They show that spots can impact in various ways RVs and line bisectors depending on the characteristics of the spot and the star. In particular, they find that in case of surface brightness inhomogeneities, there is an anti-correlation between the RV signal and the bisector slope. As most part of activity features is believed to be caused by magnetic areas, an investigation of the impact of the magnetic field on the spectral appearance is needed. The magnetic field may introduce significant distortions through the Zeeman effect. A recent study focuses on the impact of magnetic fields on RV measurements (Reiners et al. 2013). They conclude that magnetic regions can significantly distort near infra-red (nIR) stellar

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line profiles through Zeeman broadening and therefore affect RV measurements at the $\sim$1 m s^{-1} level, even in visible domain. In the first section, we extend this study to describe how Zeeman broadening distorts line positions and shapes.

To better characterize the activity jitter, a powerful option is to use simultaneous observations to combine different aspects of the activity impact. So far, the most common contemporaneous survey is RV & photometric survey to follow the brightness evolution due to spots and plages carried across the visible disk by rotation. Another possible survey consists in a simultaneous follow-up in spectropolarimetry to track in particular the large-scale magnetic field. The idea is thus to carry out a simultaneous monitoring of the activity jitter and of the magnetic topology in order to look for potential correlations between the two. Then, from this empirical relation and the underlying link between spot distributions and large-scale magnetic topologies, we will work out a way of filtering the activity jitter from RV data. In the second section, we present the preliminary result of this promising option.

2 Model of the impact of magnetic fields on line bisectors.

We investigate how magnetic regions affect the radial velocity V_r and the line shape depending on a number of key parameters (e.g., the projected rotation velocity $v \sin i$, the inhomogeneity latitude θ, the magnetic field strength B, the central wavelength of the study λ_0). To assess the line shape evolution, we calculate the velocity span (as introduced, e.g., by Gray 1982; Queloz et al. 2001) V_s, given by $V_\mathrm{t} - V_\mathrm{b}$, where V_t and V_b are respectively the average velocity at the top and bottom part of the bisector*. The distortion induced by a cool spot being mostly local, we find that V_b and V_t are correlated, for all stellar configurations and spot parameters.

If we look more precisely at the case of a magnetic field region at photospheric temperature, we find that magnetic regions have an effect on line profiles, especially at nIR wavelengths, showing both similarities and differences with the case of dark spots. In particular, although we always observe an anti-correlation between V_r and V_s, V_b and V_t can either be anti-correlated or correlated, depending on whether the Zeeman splitting is respectively smaller or larger than $v \sin i$. This anti-correlation is what differs most from the case of cool spots, and reflects that the Zeeman distortion affects simultaneously, but in opposite directions, V_b and V_t when the magnetic region crosses the center of the visible hemisphere (see Fig. 1). Looking at the correlation between V_b and V_t can bring further information, allowing to distinguish dark spots from magnetic regions in some specific cases especially in the nIR. To better emphasize this difference between line profile distortions caused by a magnetic region and a cool spot respectively, we show dynamic spectra of profile residuals for both cases (see Fig. 2) - residuals being computed as the difference between the distorted line profiles and the undistorted ones (corresponding to a quiet photosphere). Looking at dynamic spectra is an interesting option to diagnose the nature of the magnetic activity affecting RV curves. We clearly observe that a magnetic feature impacts the whole line profile, including wings and far wings. In the case of a cool magnetic spot, the impact of a magnetic field on the bisector is only visible at low photosphere-to-spot brightness contrasts, i.e., mostly for M dwarfs in the nIR. More details on the simulations and the results can be found in Hébrard et al. (2014).

3 Observations in spectropolarimetry.

As magnetic fields play an important role in the formation of the surface features inducing RV jitter, we performed a spectropolarimetric survey with HARPSPol@LaSilla and investigated how the collected data set can help to highlight the link between large scale magnetic field and RV jitter. With spectropolarimetry, we collect a set of circularly polarized spectra (or Stokes V signatures) at different observational phases. We can use them to infer the rotational period of the star. Moreover we can compute the longitudinal magnetic filed defined as the line of sight projected component of the magnetic field vector, which can help us to characterize stellar activity through the rotational modulations it usually exhibits. Finally, thanks to a tomographic technique like Zeeman-Doppler Imaging (ZDI), we can invert the sets of Stokes V signatures to reconstruct the parent large-scale magnetic field map (orientation & intensity).

We present here only the results obtained for Gl358, a moderately active M-dwarf. We gathered 23 measurements from january to march 2014 for this M3 star ($M_\star$= 0.41 M$_\odot$). The Stokes V signatures allow us to infer a rotational period of 25.4 ± 0.3 days, in good agreement with what we expect from the periodogram of velocities of Bonfils et al. (2012). Using ZDI technique, we recover the large scale magnetic field orientation and

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*The top and bottom parts include all points within 10-40% and 60-90% of the full line depth, respectively.

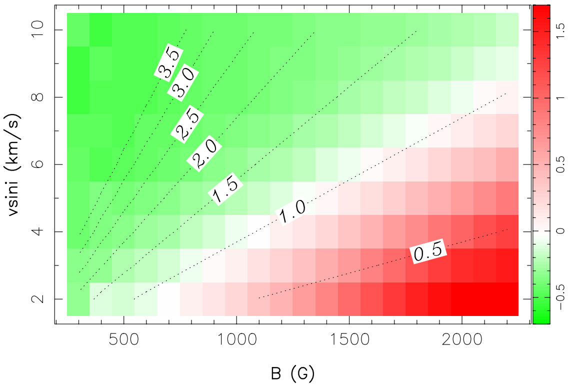

Fig. 1. Effect of $v\sin i$ and B on the average slope of V_t as a function of V_b. Red corresponds to a correlation, whereas green corresponds to an anti-correlation. Dotted lines trace contours of constant $\frac{v\sin i}{\Delta v_\mathrm{B}}$. Results are shown for a star with $i = 90°$ and $v\sin i = 5$ km s^{-1} and an equatorial magnetic area at photospheric temperature ($b = 0$) covering 1% of the stellar surface.

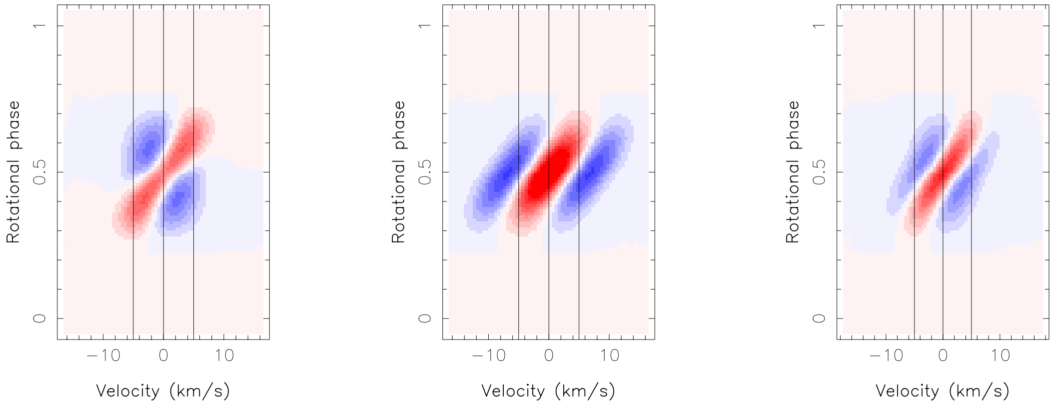

Fig. 2. Dynamic spectra of the line profile residuals in the case of a cool spot (contrast of 100% with the quiet photosphere & $B = 0$ kG left panel), of a magnetic region at photospheric temperature ($B = 1.8$ kG middle panel), and of a cool magnetic spot (contrast of 40% and $B = 1$ kG left panel). From left to right, the vertical lines correspond to velocity of -$v\sin i$, 0 and +$v\sin i$. Each horizontal strip corresponds to a color-coded difference spectrum at a given rotation phase, with blue and red respectively standing for differences of -10 and +10%. Results are shown for a star with $i = 90°$, $v\sin i = 5$ km s^{-1} and an equatorial surface feature covering 1% of the surface.

intensity (see top panel of Fig. 3). This star exhibits a rather simple large-scale magnetic structure. The field is a mostly axisymmetric poloidal field enclosing ~95 % of the reconstructed magnetic energy. This poloidal component can be approximated with a dominant dipole with a polar intensity of -110 G at 45° to the line of sight (towards phase ~ 0.2). Given the stellar inclination of $i \sim 60°$, the magnetic equator is clearly visible at phase ~ 0.75. Moreover, the preliminary analysis (see bottom panel of Fig. 3) shows that RVs and the full width at half maximum (FWHM) both exhibit rotational modulation with the same period as the longitudinal magnetic field B_l, with RV and B_l varying in quadrature. These two results suggest there is a cool spots cluster at phase ~ 0.75 (at mid-phase between RV maximum and minimum), i.e., close to the magnetic equator of the star ($B_l \sim 0$ G). This is observed on other stars (Hébrard et al. in prep.).

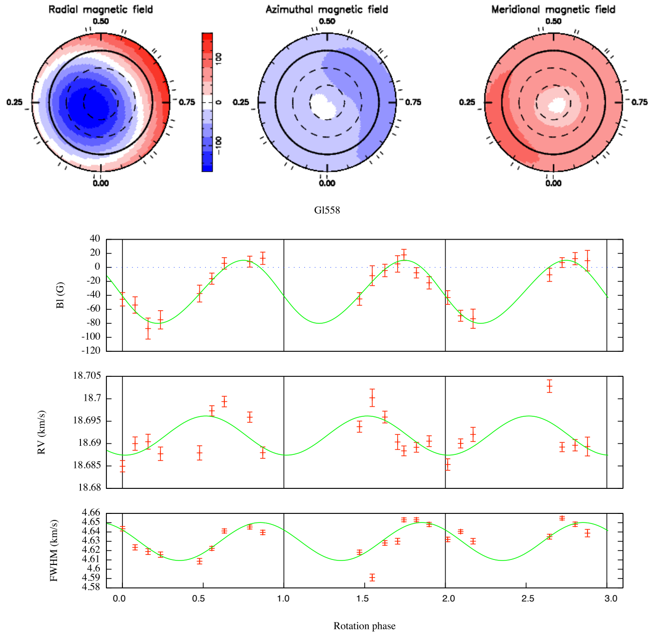

Fig. 3. Top: Large-scale magnetic field map of Gl358. The star is viewed in flattened polar projection. The pole is in the center, the bold circle depicts the stellar equator and the outer line represents the -30° latitude. We represent the three spherical components of the field. The radial ticks indicate the observational phases. **Bottom:** B_l (in G), RV (in $\mathrm{km\,s^{-1}}$) and FWHM (in $\mathrm{km\,s^{-1}}$) as a function of the rotation phase, collected with HARPSPol (red crosses with typical errors of resp. 6 G, 1.3 $\mathrm{m\,s^{-1}}$& 2 $\mathrm{m\,s^{-1}}$). The green curves represent an adjustment of a periodic wave (i.e sine+cosine at the stellar rotation period).

4 Conclusions

Impacting both RV and line profile shape, the magnetic field has to be taken into account to better understand, diagnose and filter the stellar activity jitter. Its impact is amplified in the nIR, so that new instruments like SPIRou@CFHT dedicated to simultaneous nIR high precision velocimetry / spectropolarimetry, will bring precious further information to characterize the RV jitter. Moreover, a spectropolarimetric survey provide key information to constrain the spots distribution on the stellar surface. Further studies are needed to get a brightness map and confirm our results (for instance inverting the Stokes I profile residuals). Ultimately we will obtain a valid filtering technique with which we can remove RV jitter from RV curves. It is done with success for young stars (such as T-Tauri stars, see Donati et al. (2014)). We are adapting and testing this method to slower and much less active stars.

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