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Simulating starspot activity jitter for spectral types F–M: Realistic estimates for a representative sample of known exoplanet hosts

Stefano Bellotti | Heidi Korhonen

1 Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, Toulouse, France
2 European Southern Observatory (ESO), Vitacura, Santiago, Chile
3 DARK, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

Abstract
Dark spots on the surface of active stars produce changes in the shapes of the spectral lines that mimic spurious Doppler shifts, compromising the detection of small planets by means of the radial velocity (RV) technique. Modeling the spot-driven RV variability (known as “jitter”) and how it affects the RV data sets is therefore crucial to design efficient activity-filtering techniques and inform observing strategies. Here, we characterize starspots and simulate the RV curves induced by them to determine typical jitter amplitudes for a representative sample of 15 known host stars spanning between F and M spectral types. We collect information on the log $R'_{HK}$ activity index from the literature for 205 stars and, due to a lack of data in the temperature range 4,000–4,500 K, we measure it for 10 stars using archival data. Additional stellar parameters required for the simulations are collected from the literature or constrained by observational data in order to derive realistic estimates. Our results can be used as reference to determine typical peak-to-peak spot-induced RV jitter in the visible domain that can be expected when targeting host stars with different properties.

KEYWORDS
techniques: radial velocities, stars: activity, stars: starspots, stars: planetary systems

1 INTRODUCTION
The radial velocity (RV) technique is the second most prolific exoplanet hunting method, counting 21% of the total confirmed discoveries. Central interest is given to the detection and characterization of habitable Earth-mass planets, which requires a precision on the order of m s$^{-1}$ or cm s$^{-1}$ for an M- or G-type star, respectively. Although instrumentation has witnessed significant advancements in this direction with ESPRESSO (Pepe et al. 2013), NEID (Schwab et al. 2016), and EXPRES (Jurgenson et al. 2016), stellar activity represents a serious limitation, as the associated RV jitter can completely swamp the planetary signal by several orders of magnitude (e.g., Donati et al. 2016; Meunier et al. 2010; Saar & Donahue 1997).

The activity-driven RV variability is caused by a diversity of phenomena taking place on different timescales (see Meunier 2021): oscillations and granulation induce RV signals on the order of m s$^{-1}$ over minutes and hours (Dumusque et al. 2011), whereas faculae, spots, and magnetic cycles lead to signals of m s$^{-1}$–km s$^{-1}$ over days and years (Hussain 2002; Lanza 2010). The common denominator for most of these phenomena with the largest

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Contributions resides in the magnetic field of the star (Schrijver & Zwaan 2008). Particular importance is given to faculae and spots, since their effects represent the main obstacle when searching for small planets. Faculae are responsible for the inhibition of convective motions, with consequent suppression of the blueshift arising from granulation (Haywood et al. 2014; Meunier et al. 2010; Miklos et al. 2020), while starspots distort the spectral line profiles when they cross the visible stellar disk (Saar & Donahue 1997), producing noise or mimicking RV variations due to a planet and therefore resulting in erroneous detections (e.g., Huélamo et al. 2008; Huerta et al. 2008; Queloz et al. 2001).

Modeling the starspot signature affecting RV data sets is therefore key to improve the precision of planet searches and inform observing strategies to minimize the impact of activity. To this aim, a number of tools have been developed such as SOAP (Boisse et al. 2012; Dumusque 2014), DEEMA (Korhonen et al. 2015), and STARSIM (Herrero et al. 2016).

In general, the impact of starspots on RV data sets and planet detectability has been simulated under different assumptions (Meunier 2021). For instance, Desort et al. (2007) studied the case of a single spot on the surface of different F–K stars and with different active latitudes, inclinations, and $\text{v} \sin \text{i}$; Lagrange et al. (2010) investigated planet detection limits for G-type stars using sun-like spot coverage; Santos et al. (2015) used an empirical model to reconstruct a synthetic solar sunspot cycle; Andersen & Korhonen (2015) explored the M-type regime and various activity levels; and Dumusque (2016) included instrumental, stellar, and planetary signals in simulated RV data sets for G–K stars to analyze different recovery techniques. These works studied the effects of different activity configurations or stellar parameters on the RV data sets. In comparison, we select a representative sample of known exoplanet hosts in the F–M spectral range, find or compute their stellar parameters, characterize their starspot properties, and simulate their spotted surface to obtain reasonable estimates of the spot-induced jitter. These can then be used to approximately predict peak-to-peak jitter values in the optical domain when targeting stars of analogous properties. We do not include faculae in our simulations because of their limited observational knowledge for other stars (e.g., filling factor). In addition, the facula–photosphere temperature contrast is predicted to be at most 3% and 10% of the spot–photosphere contrast for weak and strong magnetic fields, respectively (Johnson et al. 2021). This would imply that the jitter introduced by starspots would dominate over the contribution from the faculae.

This article is structured as follows. The list of magnetic activity for known host stars and the selection of a representative sample is detailed in Section 2. We then describe the estimates of the stellar parameters required for the simulations in Section 3. The parameters are used as input to produce synthetic spectra by means of the DEEMA code (Korhonen et al. 2015). Finally, we compute the spot-induced RV curves in Section 4 and discuss our results in Section 5.

2 | HOST STARS SAMPLE

We compile a list of magnetic activity for known host stars between M and F types, and the spectral range contains most of the planet hosts. The activity is quantified by the chromospheric activity index log $R'_{\text{HK}}$ representing the contribution of the CaII H and K lines to the bolometric luminosity of the star and corrected for the photospheric term (Noyes et al. 1984). This indicator was introduced by Middelkoop (1982) to substitute the color-dependent $S$ index, originally used in the Mount Wilson Observatory HK Project (Vaughan et al. 1978) to characterize stellar activity. Since log $R'_{\text{HK}}$ correlates with the presence of spots on the stellar surface, that is, sources of activity jitter, its temporal variation is often employed to discriminate between activity and genuine planetary signals (Bonfils et al. 2007).

Our list contains information on effective temperature ($T_{\text{eff}}$), $B − V$ color index, spectral type, and log $R'_{\text{HK}}$ index available either in the literature or on online databases. When the $S$ index is provided instead, we convert it to the log $R'_{\text{HK}}$ index by using the Rutten (1984) formula.

For all F, G, and some K stars, we extract data from the catalogue by Krejčová & Budaj (2012), who investigated the influence of an exoplanet on the magnetic activity of its host star. For later spectral types, we find known host stars via exoplanet.eu (Schneider et al. 2011) and exoplanet.org (Han et al. 2014) and we look for magnetic activity information in the literature. Moreover, we use the set of identifications measurements and bibliography for astronomical data (SIMBAD, Wenger et al. 2000) to obtain $B − V$ color indexes and as an auxiliary tool when the spectral type and evolutionary stage are uncertain.

The list obtained from these sources shows a dearth of targets with $T_{\text{eff}} = 4,000$–4,500 K and log $R'_{\text{HK}} < −5.0$ (Saikia et al. 2018). Therefore, we look for known host stars on exoplanet.eu in this temperature range, retrieve the corresponding spectra from the European Southern Observatory (ESO) archive, and measure the log $R'_{\text{HK}}$ index following Duncan et al. (1991).
2.1 Activity index measurements

We add 10 host stars to our list with $T_{\text{eff}} = 4,000$–$4,500$ K and with available ESO archive spectra. For each star, we select the spectrum with the highest signal-to-noise ratio collected with high-resolution spectrographs. This results in three spectra from HARPS, five from FEROS, and two from UVES. HARPS is the high-accuracy radial velocity planets searcher installed on the ESO 3.6 m telescope at La Silla observatory in Chile. It is a fiber-fed cross-dispersed echelle spectrograph covering the 3,800–6,900 Å spectral range with a resolving power of 115,000 (Mayor et al. 2003). FEROS is a fiber-fed extended range optical spectrograph operating at ESO La Silla as well. Its resolving power is 48,000 and it covers the wavelength range 3,600–9,200 Å over 39 orders (Kaufer et al. 1999). UVES is the ultraviolet and visible echelle spectrograph of the very large telescope (VLT). Its resolving power is about 40,000 when a 1 arcsec slit is used. The maximum (two-pixel) resolution is 80,000 and 110,000 in the blue arm and the red arm, respectively (Dekker et al. 2000).

Estimating the activity index consists of (a) measuring the $S$ index, (b) calibrating it to the Mount Wilson scale, and (c) converting it to $\log R'_{\text{HK}}$.  

1. The wavelength axis in the spectra is shifted to account for the RV of the star. We then reproduce the measurements of the $S$ index following Duncan et al. (1991): we define two triangular passbands with full width at half maximum $= 1.09$ Å centered on the cores of the K (3,933.661 Å) and H (3,968.470 Å) lines, and two 20 Å wide rectangular passbands centered on 3,901 Å (V band) and 4,001 Å (R band), respectively (Figure 1). The $S$ index is defined as

$$ S = \alpha \frac{N_{\text{H}} + N_{\text{K}}}{N_{\text{R}} + N_{\text{V}}}, \quad (1) $$

where $N_i$ are the counts in the corresponding ith passband and $\alpha$ is a calibration constant (Vaughan et al. 1978). $\alpha$ is used to relate the values obtained with HKP-2 to the HKP-1 scale (the first two spectrometers of the Mount Wilson project); it is set to 2.4 and, in turn, it is multiplied by 8, which is a correction factor due to the longer exposure times of the V and R passbands of the HKP-2 instrument relative to HKP-1.

2. For HARPS and FEROS, the calibration equations from the instrument scale to the Mount Wilson scale are given by Saikia et al. (2018) and Jeffers et al. (2018), respectively. They are as follows:

$$ S_{\text{MW}} = 1.1159 \cdot S_{\text{HARPS}} + 0.0343, \quad (2) $$

$$ S_{\text{MW}} = 1.1159 \cdot S_{\text{FEROS}} + 0.0343, \quad (3) $$

For UVES, the calibration equation is not present in the literature; we compute it taking the 20 stars we have in common with Wright et al. (2004) and comparing their $S$ index values (already converted to Mount Wilson scale) with ours. We perform a linear fit of the two $S$ index data sets (Figure 2), thus resulting in

$$ S_{\text{MW}} = 0.967 \pm 0.022 \cdot S_{\text{UVES}} + 0.017 \pm 0.004. \quad (4) $$

3. To convert the $S$ indexes in $\log R'_{\text{HK}}$, we use the color-dependent equation in Rutten (1984). The formula has a broad empirical validity in the $B-V$
range and distinguishes between main sequence and giant stars.

The measured activity indexes are summarized in Table 1. We extract the uncertainties on \( B - V \) from the works of Høg et al. (2000) and Zacharias et al. (2013) or SIMBAD when available, whereas we infer the uncertainties on \( S \) index and on \( \log R'_{\text{HK}} \) by error propagation. Contrarily to UVES, the uncertainty on the flux counts is not provided by HARPS and FEROS pipelines. In these cases, we infer the signal-to-noise ratio from a continuum region of the spectrum close to the H & K lines and use its reciprocal as an estimate of the error for all the bands that enter Equation (1).

The fact that some measurements present wide error bars could be attributed to the following: the choice of continuum region over which to estimate the signal-to-noise ratio, the propagation of large (\( \sim 0.1 \)) \( B - V \) errors, or a low signal-to-noise ratio of the spectrum. Typically the spectra have signal-to-noise ratio of at least 50, but in the case of HAT-P-54 only \( \sim 5 \).

### 2.2 Simulation sample

Adding the newly measured activity indices to the literature values results in a magnetic activity list composed of 218 stars of which 28 are F type, 90 G type, 69 K type, and 31 M type. The complete list is illustrated in Figure 3.

To simulate a representative sample of typical planet host stars, we select main sequence stars that are homogeneously distributed in the temperature–activity parameter space. The region \( T_{\text{eff}} = 4,000–4,500 \) K and \( \log R'_{\text{HK}} < -5.0 \) contains only stars that have evolved
We obtain a final simulation sample of 15 stars between 3,000 and 6,500 K, with the chromospheric activity index spanning between $-4.448$ (ε Eri) and $-5.283$ (GJ 180), as shown in Figure 4.

### 3 SIMULATION PARAMETERS

To generate synthetic stellar spectra, we require stellar mass, photospheric temperature, spot temperature, spot filling factor, stellar inclination, stellar rotation period, and active longitudes and latitudes. Stellar masses and temperatures are mainly retrieved from exoplanet.eu, while the remaining parameters are either computed using empirical relations or estimated based on data from previous works.

#### 3.1 Spot temperature and filling factor

Different methods can be applied to derive starspot properties, for example, Doppler and Zeeman–Doppler imaging, light curve modeling, molecular bands modeling, atomic line–depth ratios, and each with a different level of accuracy. Combining the results of these methods, Berdyugina (2005) argued that starspots can be 500–2,000 K cooler than the quiet photosphere and cover more than 30% of the stellar surface. The reported empirical fits have been recently implemented by Herbst et al. (2021) with an extension of the stellar sample over which the fit is computed.

For the spot temperature contrast, we use the stellar-temperature-dependent formula (equation 6 in Herbst et al. 2021) and we obtain values between 500 and 1,500 K for M- to F-type stars, in agreement with Berdyugina (2005) and Andersen & Korhonen (2015).

For the filling factor, the lack of an analytical expression relating it to the chromospheric activity level makes the estimation more complicated. There are empirical fits for G-type stars to determine the starspot size based on stellar radius, stellar temperature, and photometric variations (Maehara et al. 2017), but they are valid when large spot groups and long spot lifetimes can be both assumed. Knowing that starspots’ lifetimes span between few and several stellar rotations (Namekata et al. 2019) and that our simulations include M-type stars, which can be covered with small spots (Jackson & Jeffries 2012), we do not use these fits to predict the filling factor for our simulation stars.

Figure 5 clarifies the adopted procedure instead. For activity levels above $\log R'_{\text{HK}} = -4.5$, we identify three regions representing typical filling factors according to spectral type (Afram & Berdyugina 2015; Suárez Mascareño et al. 2018). To support the values in these regions, we also include observational filling factors for both active giants and main sequence stars (reported in Table A1). The $\log R'_{\text{HK}}$ value of $-4.5$ is reasonably consistent with the boundary between active and inactive stars in Henry et al. (1996).

At this point, we (a) extrapolate the three filling factor regions toward lower activity levels considering that the number of spots decreases with decreasing activity (Balmaceda et al. 2009) and (b) measure individual filling factors knowing that this quantity peaks for K stars (at ~4,500 K) and decreases quadratically toward both cooler and hotter stars (figure 10 in Berdyugina 2005). The latter feature is also used to obtain a filling factor region for F stars.

This filling factor estimate comes with important caveats. Because of the paucity of the data or contradicting values (e.g. EK Dra), some assumptions are necessary to constrain the filling factor regions and infer plausible values. Even though we expect the extrapolations to be neither the most accurate nor mathematically flawless, our estimates try to be as reasonable as possible. Further work, aimed at an improvement in the filling factor data sets, would most likely lead to better estimates.

Finally, our simulations allow the spots to be placed randomly on the stellar surface and use a lognormal spot size distribution (Korhonen et al. 2015 and references therein) peaking at $1^\circ$ in radius. This choice is motivated by the fact that larger spots are more easily modeled via tomographic imaging, so their effects can be efficiently filtered out, even though the spot jitter increases with the spot size.
FIGURE 5 Procedure adopted to constrain and estimate the spot filling factors for our simulation sample. Top: Known filling factor values. Observational data for giant (green squares) and main sequence (green circles) stars are shown. Multiple values for an individual star are connected, and both maximum and minimum are reported. The squared boxes represent the range of typical filling factor values over different spectral types, with associated values displayed on the top. Bottom: Our simulation sample. The squared boxes represent the extrapolated ranges of filling factors (given at the bottom of each box). These extrapolated regions are set to span between 0%, at \( \log R'_{\text{HK}} = -6.0 \), and a value that matches the observational boxes at \( \log R'_{\text{HK}} = -4.5 \) (Afram & Berdyugina 2015; Suárez Mascareño et al. 2018). The central extrapolated region (4,000–5,000 K) reaches 30%, which is approximately the average of observational values close to \( \log R'_{\text{HK}} = -4.5 \). The simulation sample is shown (red diamonds) along with the estimates of the filling factor. These values are obtained considering that the filling factor decreases toward lower activity levels, and toward hotter and cooler stars than K type.

3.2 Stellar rotation period

We compute the stellar rotation period (\( P_{\text{rot}} \)) employing activity–rotation relations available in the literature. Either derived using chromospheric activity (Noyes et al. 1984; Suárez Mascareño et al. 2018) or coronal activity indexes (West et al. 2008; Wright et al. 2013), the relations show that the activity level increases with decreasing rotation period until a saturation regime is reached.

For M-type stars, we use the formula provided by Suárez Mascareño et al. (2018), whereas for F-, G-, and K-type stars, we use the formalism given by Noyes et al. (1984). They obtained an empirical fit relating the magnetic activity to the Rossby number \( \text{Ro} = P_{\text{rot}} / \tau_{\text{conv}} \), where the convective turnover time \( \tau_{\text{conv}} \) is a function of spectral type. Therefore, inverting the fit yields an expression for \( P_{\text{rot}} \) as functions of \( \log R'_{\text{HK}} \) and \( B - V \) color index.

The computed periods for our sample are between 8 and 54 days (see Table 2), hence falling in the nonsaturated regime of the activity–rotation relation.

Our code computes the projected rotational velocity of the star (vsini) combining the rotation period and the stellar radius (obtained from the stellar mass, see Korhonen et al. 2015). Because we assume inclination of 90° (see Section 4.2), these values are equivalent to the equatorial velocity. We report the estimates in Table 2 for completeness. Note that the values of both \( P_{\text{rot}} \) and vsini are estimates from empirical relations, and as such cannot be considered to be analogous to the ones measured from observations. We also note that for some of the stars in our sample, there are estimates of the vsini and rotation period, but not for all, and the reported values are not always consistent.

3.3 Active latitudes

There is evidence that the latitude at which spots emerge shifts toward the poles as the rotation of the star increases (Granzer et al. 2000; İşık, Solanki, Krivova, & Shapiro, İşık et al. 2018; Schuessler et al. 1996). Schuessler & Solanki (1992) suggested that the Coriolis force affects the motion of the flux tubes as they rise to the surface: when the Coriolis force exceeds the buoyancy force, the flux tubes ascend parallel to the rotation axis and the star shows polar spots as a consequence.

Granzer et al. (2000) showed distributions of latitude emergence for rotation rates in range 0.25–63 \( \Omega_\odot \) or, equivalently, \( P_{\text{rot}} \approx 0.4–112 \) days, and for different stellar masses. In our simulation sample, the fastest rotator is HD 179949 with a period of 8 days, that is, \( \Omega = 3.5 \Omega_\odot \), and the slowest rotator is GJ 180 with a period of 54 days, that is, \( \Omega = 0.52 \Omega_\odot \). Considering both the stellar mass and the rotation period of our stars, we use the latitude distributions in Granzer et al. (2000) to infer values of the active latitude bands for our simulation sample (see Table 2).

4 SIMULATIONS

4.1 Setup

Using the collected parameters (Table 2), we compute stellar surface maps with SPOTSS and the associated synthetic spectra with DEEMA. A detailed explanation of these codes is found in Korhonen et al. (2015).
TABLE 2  Estimate properties of the simulated stars: chromospheric activity index, spectral type, stellar mass, effective temperature, spot temperature, filling factor, rotation period, projected rotational velocity, and active latitude band.

| ID     | \( \log R'_{HK} \) | Spectral type | \( M_\star (M_\odot) \) | \( T_{\text{eff}} (K) \) | \( T_{\text{spot}} (K) \) | \( \text{ff} (%) \) | \( P_{\text{rot}} (d) \) | \( \text{vsini} (\text{km s}^{-1}) \) | \( \pm \Delta \theta (\degree) \) |
|--------|--------------------|---------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| YZ Cet | -4.873\(^a\)      | M4.5 V        | 0.130           | 3,056           | 2,540           | 1              | 26             | 0.3            | \( \pm (35 - 60) \) |
| GJ 180 | -5.283\(^a\)      | M2 V          | 0.430           | 3,371           | 2,790           | 0.1            | 54             | 0.4            | \( \pm (30 - 55) \) |
| GJ 687 | -5.002\(^a\)      | M3.5 V        | 0.413           | 3,413           | 2,820           | 1              | 32             | 0.6            | \( \pm (35 - 60) \) |
| GJ 3634| -5.173\(^a\)      | M2.5 V\(^e\)  | 0.450           | 3,501\(^f\)    | 2,890           | 0.5            | 45             | 0.5            | \( \pm (30 - 55) \) |
| GJ 649 | -4.680\(^b\)      | M1.5 V\(^e\)  | 0.540           | 3,700           | 3,040           | 5              | 18             | 2.9            | \( \pm (20 - 65) \) |
| HIP 54373| -4.516\(^b\)    | K V           | 0.570           | 4,021           | 3,280           | 15             | 22             | 1.3            | \( \pm (20 - 65) \) |
| HIP 90979| -4.733\(^b\)     | K7 V          | 0.571           | 4,475           | 3,600           | 20             | 37             | 0.8            | \( \pm (15 - 60) \) |
| HD 156668| -5.010\(^b\)    | K3 V          | 0.772           | 4,851           | 3,860           | 10             | 49             | 0.8            | \( \pm (15 - 60) \) |
| HD 192263| -4.568\(^b\)     | K2 V          | 0.804           | 4,965           | 3,940           | 15             | 25             | 1.6            | \( \pm (10 - 60) \) |
| \( \varepsilon \) Eri | -4.448\(^d\)    | K2 V          | 0.830           | 5,116           | 4,035           | 20             | 13             | 3.1            | \( \pm (20 - 70) \) |
| HD 11964| -5.168\(^d\)     | G5            | 1.125           | 5,248           | 4,120           | 5              | 50             | 1.1            | \( \pm (0 - 65) \) |
| HD 49674| -4.800\(^d\)     | G5 V          | 1.015           | 5,482           | 4,270           | 5              | 27             | 2.0            | \( \pm (0 - 65) \) |
| HAT-P-5 | -5.061\(^b\)    | G1 V\(^f\)   | 1.163           | 5,960           | 4,560           | 0.5            | 51             | 1.0            | \( \pm (0 - 65) \) |
| WASP-1 | -5.114\(^d\)     | F7 V          | 1.240           | 6,200           | 4,700           | 0.1            | 40             | 1.3            | \( \pm (0 - 65) \) |
| HD 179949| -4.720\(^d\)     | F8 V          | 1.181           | 6,260           | 4,740           | 0.5            | 8              | 6.6            | \( \pm (10 - 65) \) |

Note: All spectral types, effective temperatures, and masses are taken from exoplanet.eu or from another otherwise specified reference.

\(^a\) Astudillo-Defru et al. (2017a).
\(^b\) Saikia et al. (2018).
\(^c\) This work.
\(^d\) Krejčová & Budaj (2012).
\(^e\) Houdebine et al. (2019)
\(^f\) Faedi et al. (2013).

Each surface map represents a certain spot configuration (including umbra and penumbra), which is assumed to change at every stellar rotation. Figure 6 illustrates an example for \( \varepsilon \) Eri. A map is accompanied by a number of synthetic spectra corresponding to the number of rotation phases.

The RV curve is obtained as illustrated in Figure 7. The synthetic spectra are cross-correlated using the spectrum corresponding to the first rotation phase as a template. The choice of which rotation-phase spectrum to take as template is rather arbitrary since it does not alter the results. We perform a Levenberg–Marquardt least squares fit of the maximum of the normalized cross correlation function (CCF) within \( \pm 10 \text{ km s}^{-1} \) and using a Gaussian function in order to find the value of the RV jitter.

We test the optimal number of simulated surface maps to ensure a reliable statistics of the jitter amplitude and a practical computation time. From Figure 8, we note that using 150 maps results in a reasonably symmetric distribution of the RV jitter amplitude, therefore satisfying our requirements. In addition, we set the number of synthetic spectra in each map equal to 20 to have a dense sampling of the RV curve.

4.2 Scaling of the jitter

We illustrate how our estimates of the activity jitter scale with parameters such as inclination, vsini, and wavelength coverage of the spectrum. These dependencies, which we display in Figure 9, have been previously investigated in several works (e.g., Desort et al. 2007; Korhonen et al. 2015; Lagrange et al. 2010).

For inclination and vsini, we reproduce the jitter values simulated by Korhonen et al. (2015) for a solar-like star (5,800 K) and a 5° equatorial spot (4,000 K). Changing the inclination from an equator-on view to the pole-on view leads to a reduced jitter, while stellar rotation correlates with the jitter. Note that for our simulation sample, we find an inclination of 60° for GJ 3634 (Bonfils et al. 2011) and 90° for HAT-P-5 and WASP-1 (Bakos et al. 2007, 2015; Simpson et al. 2011). However, to ensure that the comparison of the results is consistent, we set the inclination \( i \) to 90° for all our simulated stars.

For our simulations, we synthesize spectra covering between 8,202 and 8,248 Å and with an associated resolving power of \( R = 100,000 \). Although the wavelength range is rather narrow, which is not the case...
BELLOTTI and KORHONEN

FIGURE 6 Top: Example of stellar surface map for ε Er seen equator-on. Bottom: Mercator projection of the stellar surface. The x and y axes represent latitude and longitude, respectively, and are expressed in degrees. These maps are generated with $T_{\text{eff}} = 5,100$ K, $T_{\text{spot}} = 3,950$ K, $T_{\text{penumbra}} = 4,545$ K, $f_f = 20\%$, and $\Delta l = \pm (20 - 70)\circ$ for typical observations, no source of instrumental noise is included (ideal scenario). Thus, an extension of the wavelength interval would not reflect in an appreciable improvement of the CCF analysis. Moreover, Korhonen et al. (2015) showed that the jitter amplitude decreases when increasing the wavelength interval width up to 40 Å, and between 40 and 70 Å the jitter stays virtually constant.

Note also that this wavelength region has smaller intrinsic jitter than many bluer regions (Reiners et al. 2010). This is illustrated in Figure 9 for the following wavelength intervals: [3,700, 3,750], [4,350, 4,400], [5,500, 5,550], [6,400, 6,450], [6,900, 6,950], [7,300, 7,350], [8,200, 8,250], [9,100, 9,150] Å. We consider a G2 and a K2-type star with the temperature properties of the sun and ε Er, respectively, and a single 1° radius equatorial spot, resolution of 100,000, inclination of 90°, and vsini of 2.0 km s$^{-1}$. In this low activity scenario, the jitter amplitude ranges 70–44 and 59–42 cm s$^{-1}$ for the G2 and K2 star, respectively. The interval of our simulations leads to a jitter amplitude that is 10% and 25% lower than the bluest one for the G2 and K2 star.

FIGURE 7 From the top: synthetic spectrum of the first rotation phase, synthetic spectrum of the second rotation phase, normalized CCF between the first and second rotation phase spectra, Gaussian fit of the CCF around the peak, and spot-induced jitter for every rotation phase. In the bottom plot, the values are vertically shifted so that the jitter at the first rotation phase is zero. This example is for ε Er, the most active K-type star in our sample. CCF, cross correlation function

5 RESULTS AND DISCUSSION

From the RV curves of our simulations, we compute the mean peak-to-peak RV amplitude $\langle RV_{pp}\rangle$ and its minimum $\langle RV_{pp}\rangle_{\text{min}}$ and maximum $\langle RV_{pp}\rangle_{\text{max}}$ values over all the spot configurations for each star. The deema code produces the V-band light curves associated with the spots configurations as well, therefore we include information on the photometric variability: minimum ($\Delta I_{\text{min}}$), maximum ($\Delta I_{\text{max}}$), and mean amplitude ($\langle \Delta I \rangle$) of the light curve. This way we have a more complete view on the typical spot-driven jitter and photometric variability. The values are listed in Table 3.

5.1 Consistency with empirical relations

Figure 10 illustrates the RV results as a function of the stellar parameters collected in Section 3. The purpose of this plot is twofold: it allows a reasonable estimate of the RV jitter amplitude based on specific stellar parameters, hence informing observing strategies, and displays empirical relations between various quantities. Overall, we observe an increase of $\langle RV_{pp}\rangle$ with $\log R'_{\text{HK}}$, which is expected by construction since higher activity translates in higher noise in RV data sets. This is consistent with
belottii and korhonen

Figure 8: Test to determine the optimal number of surface maps to simulate, taking \( \varepsilon \) Eri as example. We consider a grid of 50, 100, 150, 200, 250, and 300 random surface maps and compute the mean RV jitter peak-to-peak amplitude in each case. From top to bottom, the distributions of the RV jitter amplitude for the 50, 150, and 300 cases are shown. Using 150 maps results in a symmetric distribution of the RV jitter amplitude, with a \( \leq 50 \text{ cm s}^{-1} \) difference relative to the 300 case. RV, radial velocity.

The empirical relation between the RV dispersion and \( \log R'_{\text{HK}} \), described in Hojjatpanah et al. (2020) and Saar et al. (1998). As can be observed by the color gradient, \( \langle \text{RV}_{\text{pp}} \rangle \) follows a parabolic trend over \( T_{\text{eff}} \) similarly to the filling factor (figure 10 in Berdyugina 2005), which stresses the importance of knowing the filling factor and determining robust empirical relations involving it, as it is a crucial factor in regulating the jitter amplitude.

The photometric amplitude shows a strong dependence of filling factor and spot-temperature contrast as well, in agreement with Johnson et al. (2021). Moreover, the fact that photometric and jitter amplitude follow similar trends is an indicator of their correlation (Hojjatpanah et al. 2020). In Figure 11, we note that for the most active stars in our sample, the clarity of the correlation diminishes (as indicated by the larger error bars as well). In particular, we observe that the largest \( \langle \text{RV}_{\text{pp}} \rangle \) is 21.6 m s\(^{-1}\) for \( \varepsilon \) Eri (the most active star in our sample), while the mean photometric amplitude peaks at 57.1 mmag for HIP 90979 (0.3 dex less active than \( \varepsilon \) Eri), whose estimated jitter is 7.0 m s\(^{-1}\). This can be explained by the different combination of the stellar parameters: the two stars share the same value of spot filling factor (20%), but the spot-photosphere temperature contrast is 200 K lower for HIP 90979, hence the spot configuration induces a smaller jitter (Lagrange et al. 2010; Reiners et al. 2010). At the same time, the estimated rotational velocity of \( \varepsilon \) Eri is higher than for HIP 90979, which leads to an enhanced
TABLE 3  Results of the simulations: minimum, maximum, and mean peak-to-peak RV amplitude, minimum, maximum, and mean amplitude of the photometric variations

| ID      | \(\langle RV_{\text{pp}}\rangle_{\text{min}}\) (m s\(^{-1}\)) | \(\langle RV_{\text{pp}}\rangle_{\text{max}}\) (m s\(^{-1}\)) | \(\langle RV_{\text{pp}}\rangle\) (m s\(^{-1}\)) | \(\Delta I_{\text{min}}\) (mmag) | \(\Delta I_{\text{max}}\) (mmag) | \(\langle \Delta I \rangle\) (mmag) |
|---------|-------------------------------------------------|-------------------------------------------------|---------------------------------|----------------|----------------|----------------|
| YZ Cet  | 0.2                                             | 2.0                                             | 0.6 ± 0.3                       | 2.4           | 24.4           | 7.7 ± 3.6      |
| GJ 180  | 0.04                                            | 1.8                                             | 0.3 ± 0.3                       | 0.3           | 15.1           | 2.6 ± 2.3      |
| GJ 687  | 0.2                                             | 2.8                                             | 0.8 ± 0.4                       | 1.6           | 20.9           | 6.4 ± 3.3      |
| GJ 3634 | 0.3                                             | 2.7                                             | 0.7 ± 0.3                       | 1.1           | 15.6           | 4.5 ± 1.8      |
| GJ 649  | 2.0                                             | 17.0                                            | 6.7 ± 2.7                       | 5.2           | 51.4           | 21.8 ± 9.0     |
| HIP 54373 | 4.0                                           | 19.7                                            | 9.8 ± 3.4                       | 10.9          | 63.2           | 30.5 ± 12.7    |
| HIP 90979 | 2.9                                           | 21.2                                            | 7.0 ± 2.6                       | 20.0          | 134.2          | 57.1 ± 20.3    |
| HD 156668 | 2.0                                          | 18.2                                            | 6.0 ± 2.1                       | 15.8          | 100.2          | 43.0 ± 14.6    |
| HD 192263 | 5.4                                           | 32.9                                            | 15.9 ± 5.5                      | 20.6          | 147.2          | 56.7 ± 21.5    |
| ε Eri   | 6.3                                             | 53.6                                            | 21.6 ± 7.5                      | 9.0           | 96.0           | 39.9 ± 14.7    |
| HD 11964 | 0.9                                             | 16.0                                            | 6.8 ± 2.9                       | 3.4           | 80.4           | 35.1 ± 15.4    |
| HD 49674 | 4.0                                             | 29.7                                            | 11.5 ± 4.5                      | 8.5           | 88.0           | 34.8 ± 13.6    |
| HAT-P-5  | 0.4                                             | 5.1                                             | 1.5 ± 0.8                       | 2.1           | 30.6           | 9.7 ± 4.7      |
| WASP-1   | 0.1                                             | 9.4                                             | 0.9 ± 1.0                       | 0.4           | 41.2           | 4.3 ± 4.6      |
| HD 179949 | 1.8                                           | 43.2                                            | 8.2 ± 6.5                       | 1.6           | 43.0           | 8.6 ± 5.9      |

Note: All quantities are computed using 150 different spot configurations and the error bars indicate the 1σ uncertainty.

FIGURE 10  Stellar parameter space of our simulations and corresponding spot-induced RV jitter. The sample of 15 simulated host stars is shown, with data point size and color encoding the spot filling factor and RV jitter amplitude, respectively. We include observational data (green) for three active stars (AU Mic, AB Dor, and V889 Her) for a comparison of activity level and jitter with respect to our sample. The size of these three data points does not scale with the filling factor, as this information is not always available. RV, radial velocity

We observe a large jitter amplitude (Desort et al. 2007; Korhonen et al. 2015). Furthermore, the active latitudes of HIP 90979 are \(\sim 10^\circ\) shifted toward the equator, implying a wider excursion of the spot impact on the light curve and therefore a larger photometric amplitude.

We observe a large jitter amplitude for HD 179949, the earliest star in our sample, reaching a value similar to active K dwarfs (HIP 54373, HIP 90979). The most likely explanation is not by the correspondingly large value of spot filling factor or spot-photosphere temperature contrast (as WASP-1 features an analogous value), but in a fast rotation. In fact, HD 179949 has the largest vsini in our sample (Table 2).

With the maximum and minimum of both RV jitter and photometric amplitude, we note that the range of plausible values correlates with the activity level of the star, as expected. These ranges also reflect different spot configurations: few and clustered big spots on one
side, and small numerous spots scattered over the surface on the other side. Taking GJ 180 as an example, these two extremes likely correspond to the simulated maximum and minimum photometric amplitudes of 0.3 and 15.1 mmag, respectively.

### 5.2 Comparison to observations

We compare some of our spot-induced jitter amplitudes to observed values. For ε Eri, our simulated value of $21.6 \pm 7.5$ m s$^{-1}$ is comparable (within error bars) to the reported values of $25-30$ m s$^{-1}$ (Giguere et al. 2016; Petit et al. 2021); for HD 156668, we estimate $6.0 \pm 2.1$ m s$^{-1}$, which is compatible with the 8 m s$^{-1}$ amplitude of the residuals of a Keplerian fit (Howard et al. 2011); for YZ Cet, an amplitude of $1.4$ m s$^{-1}$ was obtained via Gaussian Process modeling (Astudillo-Defru et al. 2017b), which is larger than our predicted value by a factor of 2.3, but it is within the range of maximum and minimum amplitudes we computed for the star; for HD 192263, we take the RV data set analyzed by Dragomir et al. (2012), apply a Keplerian fit with the parameters indicated by the authors, and find a $\sim 60$ m s$^{-1}$ RV amplitude of the residuals, which is two and four times larger than our simulated maximum and mean peak-to-peak amplitude, respectively.

Quantitative discrepancies between the simulated and observed values are expected since our computation considers starspots as the principal source of jitter, but other phenomena such as the inhibition of convective blueshift induced by faculae may dominate. Indeed, the impact of this effect becomes more relevant for G-type stars (Miklos et al. 2020), hence the derived amplitudes may be underestimated in these cases. In addition, the wavelength range we are considering is located on the red side ($8,200-8,245$ Å) of the optical spectrum for typical observations. Given that the jitter is expected to decrease with wavelength due to a lower contrast (Desort et al. 2007; Reiners et al. 2010), this may lead to underestimated values. Overall, the fact that some of our estimates are consistent with observations validates retroactively the assumptions on the stellar parameters (e.g. filling factor) we made in Section 3.

We also investigate whether the choice of latitude bands has a significant impact on the jitter and photometric variability estimates. Indeed, restricting the spot appearance within latitude bands increases their uniformity, thus leading to a reduced jitter. We simulate the spotted surface of GJ 649 (our most active M dwarf) without latitude constraints and compare the new estimates. We find $\langle RV_{pp}\rangle_{\text{min}} = 2.4$ m s$^{-1}$, $\langle RV_{pp}\rangle_{\text{max}} = 16.5$ m s$^{-1}$, and $\langle RV_{pp}\rangle = 7.9 \pm 3.2$ m s$^{-1}$, which are only slightly larger (<1 m s$^{-1}$) than the values computed with the latitude bands. Likewise, we obtain $\Delta I_{\text{min}} = 3.8$ mmag, $\Delta I_{\text{max}} = 47.2$ mmag, and $\langle \Delta I \rangle = 23.9 \pm 9.6$ mmag, which are at most 4 mmag greater than the constrained latitudes case. Therefore, for both jitter and photometric amplitudes and for a given star, we observe only a marginal effect of latitude bands.

In Figure 10, we also locate the position of AU Mic, AB Dor, and V889 Her. These are three very active stars, whose reported $\log R'_{HK}$ is between $-3.8$ and $-3.9$ (Saikia et al. 2018; Strassmeier et al. 2000), that is, 0.7 dex greater than the most active star in our sample. Such values reflect in a jitter amplitude of $400$ m s$^{-1}$ for AU Mic (Plavchan et al. 2020) and $600$ m s$^{-1}$ for AB Dor and V889 Her (Jeffers et al. 2014; Korhonen et al. 2015), at least one order of magnitude greater than for ε Eri. This approximate upper limit defined by AU Mic, AB Dor, and V889 Her gives a better sense of the low and moderate activity level of our simulation sample and helps locating a preferential region in which the spot-induced jitter is below 50 m s$^{-1}$.

### 6 CONCLUSIONS

In this article, we have carried out simulations of the spotted surface for a sample of 15 known host stars representative of the M–F spectral type range and provided their typical spot-induced jitter amplitudes (see Figure 10). The peak-to-peak RV jitter in the visible domain for stars with similar properties can then be estimated from these reference values.

Prior information on the activity level was collected from the literature or measured by us: the simulation sample is characterized by $\log R'_{HK}$ intermediate between $-4.5$ and $-5.3$, that is, belonging to the moderately active and inactive regime. This range originates directly from the fact that the planet searches have primarily targeted inactive stars. The activity index was used to characterize the starspot activity on these stars as accurately as possible. Finally, the stellar parameters required to simulate the spotted surfaces were also retrieved from other works or estimated from empirical relations.

We can draw the following conclusions from our simulations:

- We observe a positive correlation between the RV and photometric amplitude, as well as with $\log R'_{HK}$, in accordance with (Hojjatpanah et al. 2020). The departure from a tight correlation for some stars can be explained by their different activity levels and by a certain combination of stellar properties, consistently with known empirical trends (e.g. increased jitter with vsini or spot-photosphere temperature contrast).
- When compared to observational values, our estimates of RV$_{pp}$ show a reasonable agreement. Discrepancies are
a direct consequence of our stellar parameter approximations and of our limited model. Knowledge about, for example, the spot filling factor is scarce and restricted to more active stars than our simulation sample, hence our estimates rely inexorably on extrapolations. At the same time, the exclusion of faculae (and their effect on the suppression of convective blueshift) may contribute to the discrepancy of few m s$^{-1}$ (Milbourne et al. 2019).

- Even for the low activity levels characterizing our sample, the RV signal induced by spots only is once again demonstrated to be a nuisance for small planet searches. It is indeed comparable to or greater than the signature induced by an Earth-mass planet, which is on the order of cm s$^{-1}$ and m s$^{-1}$ for G- and M-type stars, respectively. This emphasizes the importance of an appropriate target selection for RV surveys aimed at finding Earth’s siblings. In this sense, Figure 10 can be used as reference to estimate the expected RV$_{pp}$ of targets for RV searches.

In this work, we have provided means to characterize starspot properties for moderately active and inactive stars spanning spectral types M–F. We also provide estimates of the jitter caused by these starspot to help plan future planet searches using RV method. Additional constraints of the stellar surfaces over different spectral types from observations are required to proceed further in this work. In fact, our simulations would benefit from more precise star spot properties and from the additional modeling of stellar faculae, overall leading to more realistic estimates of the activity jitter.

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ORCID
Stefano Bellotti https://orcid.org/0000-0002-2558-6920
Heidi Korhonen https://orcid.org/0000-0003-0529-1161
APPENDIX A. STELLAR DATA FROM OBSERVATIONS

TABLE A1 Activity levels for main sequence and giant stars used as references in Figure 5

| ID     | $T_{\text{eff}}$ (K) | Spectral type | ff (%) | $\log R'_{\text{HK}}$ |
|--------|----------------------|---------------|--------|-----------------------|
| Giants |                      |               |        |                       |
| HD 199178 | 5,350          | G5 III       | 29     | −4.056$^a$            |
| $\lambda$ And | 4,750        | G8 III       | 23     | −4.476$^f$            |
| $\lambda$ And | 4,780        | G8 III       | 17     | −4.476                |
| $\sigma$ Gem | 4,600       | K1 III       | 33     | −4.360$^d$            |
| $\sigma$ Gem | 4,440       | K1 III       | 8      | −4.360                |
| HR 1099 | 4,700          | K1 IV        | 40     | −3.841$^b$            |
| IM Peg  | 4,450          | K2 III       | 20     | −4.208$^i$            |
| IM Peg  | 4,400          | K2 III       | 15     | −4.208$^i$            |
| IM Peg  | 4,666          | K2 III       | 11     | −4.208$^i$            |
| IM Peg  | 4,666          | K2 III       | 12     | −4.208$^i$            |
| IM Peg  | 4,666          | K2 III       | 15     | −4.208$^i$            |
| IM Peg  | 4,666          | K2 III       | 15     | −4.208$^i$            |
| VY Ari  | 4,916          | K3 IV        | 41     | −3.894$^d$            |
| VY Ari  | 4,600          | K3 IV        | 15     | −3.894$^d$            |
| VY Ari  | 4,600          | K3 IV        | 12     | −3.894                |
| VY Ari  | 4,600          | K3 IV        | 15     | −3.894$^d$            |
| VY Ari  | 4,916          | K3 IV        | 15     | −3.894$^d$            |
| VY Ari  | 4,916          | K3 IV        | 16     | −3.894                |
| Main sequence |            |               |        |                       |
| Sun min | 5,870          | G2 V         | 0.02   | −4.981$^m$            |
| Sun max | 5,870          | G2 V         | 0.50   | −4.931$^m$            |
| EK Dra  | 5,930          | G2 V         | 6      | −4.103$^n$            |
| EK Dra  | 5,850          | G2 V         | 11     | −4.103$^n$            |
| EK Dra  | 5,830          | G2 V         | 40     | −4.103$^n$            |

AUTHOR BIOGRAPHY

**S. Bellotti** (born 1994 in Italy) graduated in physics in 2017 at the University of Pavia, Italy and obtained a MSc degree in astrophysics in 2019 at the Niels Böhr Institute, Copenhagen, Denmark. Currently he is a Ph. D. student in the Physique du Soleil, des Étoiles et des Exoplanètes (PS2E) group at the Institut de Recherche en Astrophysique et Planétologie (IRAP) in Toulouse, France.

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TABLE A1 (Continued)

| ID       | $T_{\text{eff}}$ (K) | Spectral type | ff (%) | $\log R_{\text{HK}}'$ |
|----------|----------------------|---------------|--------|-----------------------|
| HD 130322$^a$ | 5,330                | K0 V          | 1$^c$  | −4.552                |
| AB Dor   | 5,200                | K0 V          | 5      | −3.877$^b$            |
| AB Dor   | 5,200                | K0 V          | 12     | −3.877                |
| LQ Hya   | 5,175                | K2 V          | 45     | −3.967$^b$            |
| OU Gem   | 4,925                | K3 V          | 35     | −4.490$^b$            |
| V833 Tau | 4,500                | K4 V          | 45     | −4.060$^b$            |
| EQ Vir   | 4,380                | K5 V          | 45     | −3.864$^b$            |
| BY Dra   | 4,100                | M0 V          | 34     | −3.811$^b$            |
| BY Dra   | 4,100                | M0 V          | 60     | −3.811                |
| AU Mic   | 3,500                | M2 V          | 10     | −3.883$^b$            |
| EV Lac   | 3,300                | M4 V          | 7      | −3.749$^b$            |
| HU Del$^b$ | 3,200               | M4 V          | 3$^d$  | −4.498$^b$            |

Note: All values of surface temperature and filling factor are taken from Berdyugina (2005) and Andersen & Korhonen (2015), unless specified differently. Multiple entries for the same star correspond to different techniques with which the filling factor was measured. The $\log R_{\text{HK}}'$ index is extracted from the indicated reference or computed by us when only the $S$ index is provided (similarly to Section 2.1).

$^a$Krejčová & Budaj (2012).
$^b$Houdebine et al. (2019).
$^c$Hinkel et al. (2015).
$^d$Barnes et al. (2015)
$^e$S index from Duncan et al. (1991) and $B - V$ from Panov & Dimitrov (2007).
$^f$Gray et al. (2003).
$^g$S index from Duncan et al. (1991) and $B - V$ from Ducati (2002).
$^h$Gray et al. (2006).
$^i$Isaacson & Fischer (2010).
$^j$S index from Duncan et al. (1991) and $B - V$ from Rutten (1987).
$^k$S index from Pace (2013) and $B - V$ from Strassmeier et al. (2000).
$^l$Wright et al. (2004).
$^m$Egeland et al. (2017).
$^n$Saikia et al. (2018).
$^o$Mishenina et al. (2012).
$^p$Houdebine et al. (2017)