SOAP 2.0: A TOOL TO ESTIMATE THE PHOTOMETRIC AND RADIAL VELOCITY VARIATIONS INDUCED BY STELLAR SPOTS AND PLAGES

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ABSTRACT

This paper presents SOAP 2.0, a new version of the Spot Oscillation And Planet (SOAP) code that estimates in a simple way the photometric and radial velocity (RV) variations induced by active regions. The inhibition of the convective blueshift (CB) inside active regions is considered, as well as the limb brightening effect of plages, a quadratic limb darkening law, and a realistic spot and plage contrast ratio. SOAP 2.0 shows that the activity-induced variation of plages is dominated by the inhibition of the CB effect. For spots, this effect becomes significant only for slow rotators. In addition, in the case of a major active region dominating the activity-induced signal, the ratio between the FWHM and the RV peak-to-peak amplitudes of the cross correlation function can be used to infer the type of active region responsible for the signal for stars with \( \sin i \lesssim 8\, \text{km\,s}^{-1} \). A ratio smaller than three implies a spot, while a larger ratio implies a plage. Using the observation of HD 189733, we show that SOAP 2.0 manages to reproduce the activity variation as well as previous simulations when a spot is dominating the activity-induced variation. In addition, SOAP 2.0 also reproduces the activity variation induced by a plage on the slowly rotating star α Cen B, which is not possible using previous simulations. Following these results, SOAP 2.0 can be used to estimate the signal induced by spots and plages, but also to correct for it when a major active region is dominating the RV variation.

Key words: planetary systems – stars: activity – stars: individual (alpha Cen B) – stars: individual (HD 189733) – techniques: radial velocities

Online-only material: color figures

1. INTRODUCTION

The radial velocity (RV) technique is an indirect method that does not allow us to directly detect a planet: it measures the stellar wobble induced by a planet orbiting its host star. The technique is sensitive not only to possible companions, but also to signals induced by the host star. At the meter-per-second level, RV measurements are affected by solar-type oscillations (Arentoft et al. 2008; Kjeldsen et al. 2005; Bouchy et al. 2005; Mayor et al. 2003), granulation phenomena (Dumusque et al. 2011c; Lindegren & Dravins 2003; Dravins 1982), and activity signals (Robertson et al. 2014; Jeffers et al. 2013; Meunier & Lagrange 2013; Lovis et al. 2011; Dumusque et al. 2011b; Boisse et al. 2011, 2009; Saar 2009; Huelamo et al. 2008; Desort et al. 2007; Queloz et al. 2001; Santos et al. 2000; Saar & Donahue 1997). The recent confirmation of Kepler-78 with HIRES@KECK and HARPS-N@TNG (Sanchis-Ojeda et al. 2013; Howard et al. 2013; Pepe et al. 2013), and the characterization of the 17 Earth-mass planet Kepler-10c (Dumusque et al. 2014) show that breakthrough results can be obtained with RV measurements. It is therefore extremely important to understand the different type of stellar signals affecting RV measurements to be able to correct them if we want the RV technique to be efficient in the future.

Optimal observational strategies can be used to mitigate the effect of oscillations and granulation phenomena when observing solar-type stars (Dumusque et al. 2011b), which enables the detection of tiny planetary signals (Dumusque et al. 2012; Pepe et al. 2011). However, activity signals are more difficult to average out. Among the different types of activity signals affecting RV measurements, one should distinguish between short-term variations, with a timescale similar to the rotational period of the star (Saar & Donahue 1997), and long-term perturbations induced by solar-like magnetic cycles (Meunier & Lagrange 2013; Gomes da Silva et al. 2013; Lovis et al. 2011; Dumusque et al. 2011a).

This paper focuses on the short-term variation that is induced by stellar rotation in the presence of active regions, i.e., regions like spots and plages that are the result of strong local magnetic fields. When the star is rotating, these active regions will induce an RV variation by two different physical processes. Because these regions will have temperatures that differ from the average surface temperature, their flux will be different, which shall be referred to as the flux effect throughout this paper. The second effect is induced by the inhibition of the convective blueshift (CB) inside active regions because of the strong local magnetic field (Cavallini et al. 1985a; Dravins et al. 1981). An active region will therefore have a different RV than the average stellar surface, which will induce what is referred to as the CB effect throughout this paper.

A spot will induce an RV variation due to its small flux compared to the average stellar surface. Sunspots, being ∼700 K cooler than the effective temperature of the Sun (Meunier et al. 2011),...
have a much lower flux than the quiet solar photosphere regions.\textsuperscript{6} A spot will therefore break the flux balance between the blueshifted approaching limb and the redshifted receding limb of a rotating star, and will induce an RV variation as it passes on the visible stellar disk. A plage at the disk center is only slightly hotter than the average effective temperature and will induce a small flux effect. A plage on the limb will be brighter due to a center-to-limb brightness dependence (e.g., Meunier et al. 2010a; Unruh et al. 1999; Frazier 1971); however, at this location, the star emits less light due to limb darkening. Independently of its location, a plage will therefore induce a small flux effect compared to a spot, even if plages tend to be an order of magnitude more extended than spots (Chapman et al. 2001).

A plage or a spot is a region affected by strong local magnetic fields. These magnetic fields will inhibit locally the convection, which will suppress the CB effect inside active regions ($\sim 300 \text{ m s}^{-1}$ for the Sun; e.g., Dravins et al. 1981). These regions therefore appear redshifted in comparison to the quiet photosphere (see Figure 3 in Cavallini et al. 1985a for a plage and Figure 2 of this work for a spot), which induces an RV variation as active regions appear and disappear from the visible part of the stellar disk due to rotation. The CB effect for spots and plages of the same size will be similar.

Several simulations estimating the RV variation induced by active regions already exist. However, most of them only consider the flux effect (Oshagh et al. 2013; Boisse et al. 2012; Barnes et al. 2011; Desort et al. 2007; Hatzes 2002; Saar & Donahue 1997). The ones that include the CB effect do it in a simple way by assuming Gaussian spectral lines that are redshifted by a fixed amount to consider the convection inhibition inside active regions (Aigrain et al. 2012; Lanza et al. 2010; Meunier et al. 2010a). As we will see in this paper, considering observed spectral line shape is essential in reproducing the variation of the bisector span (BIS SPAN) and the FWHM of the cross correlation function (CCF) used to derive precise RV measurements.\textsuperscript{7} Saar (2009, 2003) estimated the CB effect using the observed bisector of a solar spectral line in and outside of an active region. However, the use of only a single spectral line makes it difficult to extrapolate this work to stars other than the Sun. For other stars, the signal-to-noise ratio required to detect activity signal in the spectrum can only be obtained on the CCF that is an average profile of all the spectral lines in the visible, and therefore only reflects partially the behavior of individual spectral lines.

Considering only the flux effect was justified a decade ago when the precision of the best RV instruments was only able to detect the flux effect induced by spots on rapid rotators. With the meter-per-second precision reached nowadays, the inhibition of the CB effect inside active regions is measurable and should be accounted for to reproduce the activity-related RV, BIS SPAN, and FWHM variations.

This paper presents a new code to estimate the activity-induced RV variation. The CB effect is accounted for by using observed spectra of the quiet solar photosphere and of a sunspot, which is the natural way to include all the physics related to stellar atmosphere. After a presentation of the new code in Section 2 and a comparison between the different effects induced by spots, plages and stellar parameters in Sections 3 and 4, the result of this activity simulation is confronted with observations of solar-type stars in Section 5.

The SOAP 2.0 software is available for use along with a brief manual and some example data at the following Web site: http://www.astro.up.pt/soap. When using SOAP 2.0 in publications, it is appropriate to cite this paper.

2. SIMULATING THE EFFECT INDUCED BY ACTIVE REGIONS

In this section, we first describe briefly the code Spot Oscillation And Planet (SOAP; Boisse et al. 2012), a code designed to estimate the flux effect of active regions on the photometric and spectroscopic measurements. We then discuss the improvements made to this code to include the CB effect, the limb brightening effect of plage, a quadratic limb darkening law, a realistic active region contrast, and the resolution of the spectrograph used for the observations.

2.1. The SOAP Tool

Different tools to estimate the photometric and RV contribution of active regions have been published (Aigrain et al. 2012; Lanza et al. 2010; Meunier et al. 2010a; Saar & Donahue 1997), and we decided here to focus on SOAP (Boisse et al. 2012). This code only considers the flux effect of active regions (see Section 1) to estimate the activity-induced variation on the photometry, RV, BIS SPAN, and FWHM. In this section, only a general presentation of SOAP is done and defines the material that will be used in the next sections. For a complete and more detailed description of the tool, the reader is referred to the original SOAP paper (Boisse et al. 2012).

In SOAP, and as a first step, the non-spotted emission of the star is computed. The visible stellar surface is divided in cells having the same projected area (whose number is defined by the user, generally more than 10,000). Each cell presents a different RV depending on the rotational period and radius of the star, and a different weight depending on a linear limb darkening law. In each cell, the emerging stellar spectrum is represented by a Gaussian line profile equivalent to the spectrum CCF of a solar-type star with zero rotation. The velocity of this Gaussian line profile is shifted to the projected velocity of the cell (dependent on its position on the disk, the geometry of the system, and the rotational velocity of the star), and its contrast is weighted by a linear limb darkening law. Therefore, the integrated CCF of the quiet stellar disk, $\text{CCF}_{\text{tot, quiet}}$, is defined by

$$\text{CCF}_{\text{tot, quiet}} = \sum_{x,y} I_{ld}(x, y) \text{CCF}(x, y).$$

(1)

where $x$ and $y$ scan the stellar grid that has a size $N \times N$, and $I_{ld}(x, y)$ represents the limb darkening law and CCF is in the case of SOAP a Gaussian line profile. The non-spotted emission of the star, $\text{Flux}_{\text{tot, quiet}}$, is simply the integration of the limb darkening law over the entire stellar disk:

$$\text{Flux}_{\text{tot, quiet}} = \sum_{x,y} I_{ld}(x, y).$$

(2)

Then, an active region of a given size is added at a given longitude and latitude. The Gaussian CCF considered for this
region is the same as the one for the stellar disk, but its weight depends on the region brightness: \([0:1]\) for a dark spot, \(>1\) for a plage. In each cell affected by the active region, defined by \((x_a, y_a)\), SOAP estimates the difference between the quiet CCF at this location and the CCF of the active region, CCF\(_a\), which gives

\[
\Delta \text{CCF}(x_a, y_a) = \sum_{x, y} I_{ld}(x_a, y_a) \times \left[ \text{CCF}(x_a, y_a) - I_a \text{CCF}_a(x_a, y_a) \right].
\]

where \(I_a = \text{Planck}(\lambda_0, T_{\text{active region}})/\text{Planck}(\lambda_0, T_{\text{eff}})\) is the relative brightness of the active region, \(\lambda_0\) being the wavelength at which the Planck function is estimated, \(T_{\text{active region}}\) the temperature of the active region, and \(T_{\text{eff}}\) the effective temperature of the star.

Finally, the difference between the quiet CCF at the active region location (if the active region does not exist) and the CCF of the active region is subtracted from the quiet integrated CCF, which gives us the integrated CCF, taking into account the effect of the active region:

\[
\text{CCF}_{\text{tot, active}} = \text{CCF}_{\text{tot, quiet}} - \Delta \text{CCF}(x_a, y_a) = \sum_{x, y} I_{ld} \text{CCF} - \sum_{x_a, y_a} I_{ld} \left[ \text{CCF} - I_a \text{CCF}_a \right] = \sum_{x, y} I_{ld} \text{CCF} - \sum_{x, y} \sum_{x_a, y_a} I_{ld} \left[ \text{CCF}(1 - 1) - I_a \text{CCF}_a \right] = \sum_{x, y} I_{ld} \text{CCF} + \sum_{x_a, y_a} I_{ld} I_a \text{CCF}_a.
\]

This approach of first estimating the integrated CCF of the quiet star and then assuming only the contribution of the active region, \(I_a\), which is Doppler shifted to account for rotation. The rotational speed \(v \sin i\), in the case of the Sun is given as the horizontal bar at the bottom of the figure. The intensity of each cell is weighted by a limb darkening law, and the intensity is reduced (or increased) in presence of a dark spot (or a bright plage). Here dark spots with no emitting flux are considered. The integrated CCF over the stellar disk is obtained by summing up all the cells. Note that here all the Gaussian have the same depth. On the limb, the Gaussians appear shallower because they are weighted by the limb darkening.

(Figure explaining how SOAP simulates the effect of active regions. The star is divided in a grid of \(N \times N\) cells, each of them having its own Gaussian corresponding to the stellar disk. Depending on the cell position, the Gaussian is Doppler shifted to account for rotation. The rotational speed \(v \sin i\) in the case of the Sun is given as the horizontal bar at the bottom of the figure.)

The total integrated CCF, \(\text{CCF}_{\text{tot, active}}\), can be modified in two ways. On the one hand, we can change the intensity of the active region, \(I_a\), assuming that the CCF inside the quiet photosphere and inside the active region is the same (\(\text{CCF} = \text{CCF}_a\)). This is what is done in SOAP because the CCF of solar-type stars inside the photosphere or inside an active region can be approximated at first order by the same Gaussian. Because in this case only the active region intensity is affecting the total integrated CCF, this corresponds to the flux (\(F\)) effect. On the other hand, we can fix the intensity of the active region and consider a different CCF inside the active region from inside the quiet photosphere (\(\text{CCF} \neq \text{CCF}_a\)). This is what will be done in the next sections to include the CB effect. These two ways of modifying the total integrated CCF can be written as

\[
\text{CCF}_{\text{tot, active, F effect}} = \sum_{x, y} I_{ld} \text{CCF} + \sum_{x_a, y_a} I_{ld} I_a \text{CCF}_a \\
\text{CCF}_{\text{tot, active, CB effect}} = \sum_{x, y} I_{ld} \text{CCF} + \sum_{x_a, y_a} I_{ld} \text{CCF}_a.
\]

\(\text{The BIS SPAN is defined here as the difference between the top of the bisector ranging from 10\% to 40\% of the depth and the bottom of the bisector ranging from 60\% to 90\% of the depth. This is the definition adopted for HARPS measurements.}\)
extended than spots (Chapman et al. 2001), increasing even more their activity-induced RV effect. Some authors have tried to include the CB effect and its inhibition inside active regions. Saar (2009, 2003) derived the activity-related RV variation for a plage, using solar observations of an iron line measured inside the quiet photosphere and inside a plage. In solar spectra, the “C” shape of spectral lines that formed inside a quiet photosphere region reflects the presence of the CB effect (Dravins et al. 1981). Therefore, using solar observations of the quiet photosphere and of a plage naturally includes the CB effect and its inhibition in plages. However, only one single spectral line has been used in these studies. Nowadays, the most precise spectrographs use the information of the entire visible spectrum to reach a high precision in RV. This RV is measured on the CCF obtained by the cross correlation of the stellar spectrum with a synthetic stellar template (Pepe et al. 2002; Baranne et al. 1996). Because each spectral line is affected in a different way by convection, it is not straightforward from one spectral line to estimate the variation of the entire visible spectrum. The most reliable way to include the effect of CB, as well as its inhibition inside active regions due to strong magnetic fields, is to use observed spectra of the quiet solar photosphere and of a solar active region. Because our goal is to simulate the RV effect of active regions as seen with a high-resolution instrument like HARPS, we require some high-resolution solar spectra covering the visible spectral range. The Fourier Transform Spectrograph (FTS) at the Kitt Peak Observatory has obtained such spectra. In the archive of the instrument, we were able to obtain a spectrum for the quiet photosphere (Wallace et al. 1998) in the disk

\[ \text{RV} \approx \text{rms} \times \frac{\Delta \lambda}{\lambda} \]
center, and one for a sunspot (Wallace et al. 2005). We then computed the CCFs of these two spectra using the G2 HARPS template (Pepe et al. 2002) and associated these CCFs to the non-active region and active region of the star, respectively. The same spectrum will be used for a spot and a plage, because no spectrum for a plage with the required properties could be found in the literature. It is clear that the differences in temperature for a spot and a plage will influence the emerging spectrum and modify the CCF bisector; however, at first order, the inhibition of convection, shifting spectral lines by $\sim 300 \text{ m s}^{-1}$, will be the dominant effect. The CCFs for the quiet photosphere and the active region that we use, with their respective bisectors, are displayed in Figure 2. As we can see, the inhibition of CB inside an active region induce a CCF redshift of $350 \text{ m s}^{-1}$ and changes the shape of the bisector considerably.

The choice of using the CCFs here rather than the spectra is for computational efficiency. Indeed, with only a few hundred data points, the CCF carries the averaged information of the entire spectrum (500,000 points for the FTS spectra compared to 201 points in our case for the CCF). In Appendix A, we show analytically that the integrated CCF over the stellar disk and therefore the contrast is dependent on the position of the active region on the stellar disk. Meunier et al. (2010a) show that the temperature difference between a plage and the quiet photosphere is given by the law

$$\Delta T_p = 250.9 - 407.7 \cos \theta + 190.9 \cos^2 \theta,$$

where $\theta$ is the angle between the normal to the stellar surface and the observer ($\theta = 0$ at the stellar disk center and $\pi/2$ at the limb). A plage is therefore brighter on the solar limb than on the solar disk center, with a contrast ranging from 1.22 to 1.03 at 5293 Å, respectively.

We also modified the linear limb darkening law originally present in SOAP by a more realistic quadratic model (Mandel & Agol 2002), as was done in SOAP-T (Oshagh et al. 2013):

$$I_{\ell}(\cos \theta) = 1 - \gamma_1 (1 - \cos \theta) - \gamma_2 (1 - \cos \theta)^2 \quad \gamma_1 + \gamma_2 < 1. \quad (9)$$

For a stellar effective temperature close to that of the Sun (5778 K), we choose $\gamma_1 = 0.29$ and $\gamma_2 = 0.34$ (Oshagh et al. 2013; Claret & Bloemen 2011; Sing 2010). In the following sections, these values will be used unless specified otherwise.

Finally, to compare the results of this simulation to observations, the resolution of the spectrograph has to be considered as it might influence the estimation of the RV, BIS SPAN, and FWHM (Boisse et al. 2012; Desort et al. 2007). The spectra obtained with the FTS have a resolution higher than 700,000, and therefore the resolution of the disk integrated CCF has to be reduced to match observations made with HARPS or other instruments. This step is done by convolving to the CCF an instrumental profile that can be approximated by a Gaussian for fiber-fed spectrographs like HARPS, HARPS-N, SOPHIE, CORALIE, and TRES. The FWHM of this Gaussian is equal to the velocity resolution $\Delta v$ given by the formula $\Delta v = c/R$, where $R$ is the instrumental resolution and $c$ the speed of light in vacuum. For example, this gives us an FWHM of 2.6 and 5.5 km s$^{-1}$ for HARPS ($R = 115,000$) and CORALIE ($R = 55,000$), respectively.

### 3. Modifications Brought by the Convective Blueshift Effect and Additional Stellar Physics

In the previous section, we listed the different improvements implemented into SOAP to include more stellar atmospheric physics based on solar observations. Here, to investigate the effect brought by each improvement, we simulate an active region on a rotating star and estimate the variations seen in photometry, RV, BIS SPAN, and FWHM. Note that we will use the differential value for the variation of all these observables, which explains why the FWHM variation is sometimes equals to zero or smaller. We will first study the variation brought by different limb darkening laws and by different instrumental resolutions. We will then study the effect induced by the use of the observed solar spectra. In our simulation, the star has a radius and a projected rotational velocity fixed to the solar value ($v \sin i = 2 \text{ km s}^{-1}$), and is seen equator-on. The active region is set on the equator and has a size of $S = 1\%$. This size is defined as the fraction of the surface of the visible hemisphere covered by the active region. The results of this section are obtained considering observed CCFs in each of the 300 $\times$ 300 cells (except for Section 3.3 and Figure 5 where we compare the use of Gaussian and observed CCFs).

#### 3.1. Modifications Brought by the Limb Darkening

In SOAP, as we can see in Equations (4) and (5), the limb darkening law affects quiet regions as well as active ones. Using different limb darkening laws will therefore affect all regions of the star. Figure 3 displays the variations induced by a spot or a plage, assuming a linear limb darkening law with parameter value 0.6 and a quadratic one with $\gamma_1 = 0.29$ and $\gamma_2 = 0.34$ (see Equation (9)). As we can see in Table 1, the RV and BIS SPAN peak-to-peak differences for the variation induced by an active region when comparing a linear and quadratic law are at the detection limit of future spectrographs designed to reach the 0.1 m s$^{-1}$ precision level (e.g., ESPRESSO@VLT, G-CLEF@GMT). The impact of the limb-darkening law on the RV and BIS SPAN measurements is therefore very small, which implies that limb-darkening laws more precise than quadratic are not useful for estimating the variation of these observables. The photometry is, however, significantly affected when assuming a quadratic rather than a linear limb darkening law for a spot. An effect of 600 ppm is easily detected by a space-based instruments like Kepler and therefore a quadratic limb darkening law should be used to properly estimate the photometric effect of spots. Finally, the FWHM is also significantly influenced.

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9 The photometric effect is only dependent on the active region contrast compared to the quiet photosphere in our simulation (see Equation (5)). This contrast is estimated at 5293 Å, and therefore the photometric effect that will be derived in this paper is for Sun-like active regions observed in a narrow filter centered on 5293 Å.

10 $S = \pi R_{\text{eq}}^2 / 2 \pi R_s^2$, where $R_{\text{eq}}$ is the radius of the spot and $R_s$ the radius of the star.
Figure 3. Photometric, RV BIS SPAN, and FWHM variations induced by an equatorial spot or plage on an equator-on star when assuming a linear limb darkening law (green dotted line) and a quadratic one (red continuous line). The size of the active region is 1%. The contrast of the active region is 0.54 in the case of a spot (663 K cooler than the effective temperature of the Sun, at 5293 Å), and is given by Equation (8) in the case of a plage. The active region is on the stellar disk center when $\theta = 0$ and on the limb when $\theta = \pm \pi/2$.

(A color version of this figure is available in the online journal.)

### Table 1

Peak-to-peak Differences in Photometry and in the CCF Parameters when Comparing Different Limb Darkening Laws

| Spot | Flux (ppm) | RV (m s$^{-1}$) | BIS SPAN (m s$^{-1}$) | FWHM (m s$^{-1}$) |
|------|------------|-----------------|-----------------------|------------------|
| Lin-quad | 613 (5%) | 0.1 (0%) | <0.1 (0%) | 0.9 (4%) |
| Plage | Flux (%) | RV (m s$^{-1}$) | BIS SPAN (m s$^{-1}$) | FWHM (m s$^{-1}$) |
| Lin-quad | 22 (3%) | 0.4 (4%) | <0.1 (0%) | 1.5 (5%) |

**Note.** In brackets, the fraction of the difference is shown in percent. The spot and the plage have the same properties as in Figure 3.

3.2. Modifications Brought by the Spectrograph Resolution

When observing with different instrumental resolutions, the integrated CCF over the stellar disk will be modified because the star is a point source, and thus the integrated light over the stellar disk is fed into the spectrograph. This integrated CCF will be convolved with a Gaussian instrumental profile that has an FWHM that depends on the instrumental resolution.

As we can see in the last paragraph of Section 2.3, the lower the resolution, the larger will be the FWHM of the instrumental profile. Figure 4 displays the photometric, RV, BIS SPAN, and FWHM variations when assuming the instrumental resolutions of the FTS ($R > 700,000$), HARPS ($R = 115,000$), and CORALIE ($R = 55,000$). As we can see in Figure 4 and Table 2, the photometry is not affected because this observable only depends on the intensity of the active region and the limb darkening law used (Equation (5)), which are not modified here. The difference in RV variation is small, $\sim$10%, because convolving with a Gaussian will not significantly modify the center of the CCF. However, the peak-to-peak amplitudes seen in the BIS SPAN and the FWHM will be strongly reduced by lower resolutions because convolving with wider instrument profiles will average out any asymmetry or intrinsic width of the CCF. In Table 2, we can see that the BIS SPAN peak-to-peak amplitude obtained with the FTS resolution is nearly twice that obtained with the CORALIE resolution. The differences between the FTS and HARPS resolutions are smaller but still approximatively 20% of the BIS SPAN peak-to-peak amplitude (see Table 2). As already demonstrated by other authors (Boisse et al. 2012; Desort et al. 2007), a high resolution will therefore
Figure 4. Photometric, RV BIS SPAN, and FWHM variations induced by an equatorial spot or plage on an equator-on star when assuming different instrument resolutions: $R > 700,000$ (FTS, blue dashed line), $R = 115,000$ (HARPS, green dotted line), and $R = 55,000$ (CORALIE, red continuous line). The size of the active region is 1%. The contrast of the active region is 0.54 in the case of a spot (663 K cooler than the effective temperature of the Sun, at 5293 Å), and is given by Equation (8) in the case of a plage. The active region is on the stellar disk center when $\theta = 0$ and on the limb when $\theta = \pm \pi/2$.

(A color version of this figure is available in the online journal.)

| Activity | Flux (ppm) | RV (m s$^{-1}$) | BIS SPAN (m s$^{-1}$) | FWHM (m s$^{-1}$) |
|----------|-----------|----------------|----------------------|------------------|
| Spot     |           |                |                      |                  |
| $R_{\text{FTS}} - R_{\text{HARPS}}$ | 0 (0%) | 1.0 (4%) | 2.2 (23%) | 1.9 (9%) |
| $R_{\text{FTS}} - R_{\text{CORALIE}}$ | 0 (0%) | 2.8 (12%) | 5.5 (88%) | 5.7 (32%) |
| $R_{\text{HARPS}} - R_{\text{CORALIE}}$ | 0 (0%) | 1.9 (8%) | 3.3 (52%) | 3.8 (21%) |
| Plage    |           |                |                      |                  |
| $R_{\text{FTS}} - R_{\text{HARPS}}$ | 0 (0%) | 0.4 (4%) | 3.4 (22%) | 2.0 (7%) |
| $R_{\text{FTS}} - R_{\text{CORALIE}}$ | 0 (0%) | 1.1 (12%) | 8.4 (85%) | 6.1 (25%) |
| $R_{\text{HARPS}} - R_{\text{CORALIE}}$ | 0 (0%) | 0.7 (8%) | 5.0 (50%) | 4.0 (16%) |

Note. Different resolution: $R_{\text{FTS}} > 700,000$, $R_{\text{HARPS}} = 115,000$ and $R_{\text{CORALIE}} = 55,000$. In brackets, the fraction of the difference is shown in percent. Values higher than 10% are highlighted in bold face. The spot and the plage have the same properties as in Figure 4.

strengthen the correlation between the RV and the BIS SPAN or the FWHM variations. These correlations are often a powerful diagnostic to determine whether the observed RV signal is of activity or planetary origin (e.g., Boisse et al. 2009; Bonfils et al. 2007; Queloz et al. 2001).

3.3. Modifications Brought by the Convective Blueshift

We now consider the effect on the photometry, RV, BIS SPAN, and FWHM induced by the use of different CCFs. We will compute the differences among the following three cases: (1) assuming the same Gaussian CCF in the quiet photosphere and in the active region, (2) assuming the same Gaussian CCF but shifted by 350 m s$^{-1}$ inside an active region, and (3) assuming CCFs of observed solar spectra of the quiet photosphere and of an active region. We use the quadratic limb darkening law and the HARPS resolution ($R = 115,000$) to derive the results of these three different assumptions, which can be seen in Figure 5 and Table 3. As in the previous case when comparing different resolutions, the photometry is not affected because this observable only depends on the intensity of the active region and the limb darkening law used (Equation (5)), which are not modified here. The RV induced effect of a spot is not very different when assuming Gaussian CCFs or observed CCFs. This is because the spot intensity is 54% of the quiet photosphere brightness (663 K cooler than the effective temperature of the
Figure 5. Photometric, RV BIS SPAN, and FWHM variations induced by an equatorial spot or plage on an equator-on star when assuming different CCFs in SOAP: same Gaussian CCF in the quiet photosphere and in the active region (blue dashed line), same Gaussian CCF but shifted by 350 m s$^{-1}$ in the active region (green dotted line) and observed solar CCFs (red continuous line). The size of the active region is 1%. The contrast of the active region is 0.54 in the case of a spot (663 K cooler than the effective temperature of the Sun, at 5293 Å), and is given by Equation (8) in the case of a plage. The active region is on the stellar disk center when $\theta = 0$ and on the limb when $\theta = \pm \pi/2$.

(A color version of this figure is available in the online journal.)

| Spot | Flux (ppm) | RV (m s$^{-1}$) | BIS SPAN (m s$^{-1}$) | FWHM (m s$^{-1}$) |
|------|------------|-----------------|------------------------|-------------------|
| G-G shift | 0 (0%) | 0.7 (3%) | 0.8 (29%) | 4.2 (33%) |
| G-CCF | 0 (0%) | 3.6 (15%) | 7.6 (80%) | 13.0 (60%) |
| G shift-CCF | 0 (0%) | 2.9 (12%) | 6.8 (72%) | 8.8 (40%) |
| Plage | Flux (%) | RV (m s$^{-1}$) | BIS SPAN (m s$^{-1}$) | FWHM (m s$^{-1}$) |
| G-G shift | 0 (0%) | 6.8 (73%) | 2.7 (95%) | 12.5 (92%) |
| G-CCF | 0 (0%) | 6.6 (72%) | 14.8 (99%) | 27.4 (96%) |
| G shift-CCF | 0 (0%) | 0.2 (2%) | 12.1 (81%) | 14.9 (52%) |

Table 3: Peak-to-peak Differences in Photometry and in the CCF Parameters when Comparing Different CCFs Injected in each Cell

Note. Three cases are considered: the same Gaussian CCF is used for the quiet photosphere and for the active region (G), a Gaussian CCF is used for the quiet photosphere and the same Gaussian CCF, but shifted by 350 m s$^{-1}$, is used for the active region (G shift), and CCFs of observed solar spectra of the quiet photosphere and of a spot are used. In brackets, the fraction of the difference is shown in percent. Values higher than 10% are highlighted in bold face. The spot and the plage have the same properties as in Figure 5.

Sun, at 5293 Å, and therefore the flux effect of the spot is more important than the effect induced by the CB and its inhibition in active regions. A plage is, however, only 3%–22% brighter than the quiet photosphere and in this case the CB effect becomes $\sim$10 times more important than the flux effect. We see in Figure 5 that there is only a small difference between the RV peak-to-peak amplitudes when using the same Gaussian CCF but shifted by 350 m s$^{-1}$ inside the active region, or when using observed CCFs (compare the green and red curves). Therefore, the main parameter influencing the RV effect of a plage is the $\sim$350 m s$^{-1}$ shift difference in velocity between the CCF in the quiet photosphere and the one in the active region, due to the inhibition of the CB (compare the green and red curves to the blue curve). Another important point is that the flux effect on RVs is anti-symmetric compared to the center of the star (see the RV variation of the spot), while the CB RV effect is symmetric$^{11}$ (see the RV variation of the plage). This can be explained because the spot-induced RV variation, dominated by the flux effect, is sensitive to the stellar projected rotational velocity that is anti-symmetric, being blueshifted on one half of the star and redshifted on the other half. The plage-induced RV variation, dominated by the CB effect, will be sensitive to the limb darkening and the plage intensity variation, which are both symmetric effects with respect to the disk center.

$^{11}$ The effect is not totally symmetric because the bisector of the CCF inside the quiet photosphere is different from the one inside the active region (see Figure 6 and related text).
Looking at the variations of the BIS SPAN and the FWHM, we see that using observed CCFs, which are not symmetric, induces a much higher peak-to-peak amplitude for both the spot and the plage than when assuming symmetric CCFs (compare the red curve to the blue and green curves). Therefore, the use of observed CCFs significantly modify the BIS SPAN and FWHM amplitude, without influencing the RV amplitude. By studying the RV data of a few active stars, we could test if using observed CCFs rather than Gaussian CCFs gives a better description of the induced effect of active regions. This will be the topic of Section 5.

We can also study the correction $\Delta$CCF (see Equation (3)) applied to the quiet Sun integrated CCF, $\text{CCF}_{\text{tot, quiet}}$, to estimate the effect induced by a spot and a plage. On the left plot of Figure 6, we can see the flux effect (see Equation (6)) for a spot and a plage. The contribution of a spot is negative and increases close to the disk center, due to limb darkening. The contribution of a plage is always positive and is maximum in the region between the limb and the center of the disk. This can be explained by a balance between two opposite effects: the limb darkening of the star and the limb brightening of plages.

On the right plot of Figure 6, we compare the CB effect (see Equation (7)) when assuming the use of the same Gaussian CCF for all stars but shifted by 350 m s$^{-1}$ inside the active region (top plot), and when assuming the use of observed CCFs (bottom plot). Because the CCF that we use for the spot and the plage are the same, we will have the same CB effect for both type of active region. When assuming a Gaussian CCF, the effect is anti-symmetric with respect to the disk center. This is no longer the case when assuming observed CCFs because the bisector in the quiet photosphere is different from the one in the active region. This explains the important differences in the BIS SPAN and the FWHM variations that we see when using Gaussian CCFs or observed CCFs in our simulation (see Figure 5).

4. TESTING DIFFERENT STELLAR AND SPOT PARAMETERS

In this section, we use a quadratic limb darkening law and observed CCFs of the quiet solar photosphere and of a solar active region. From all the tested configurations in the preceding section, this one, that we call from hereon SOAP 2.0, is the most similar to what is observed on the Sun. In the present section, after fixing the instrumental resolution to that of HARPS ($R = 115,000$), we investigate the effect of different projected stellar rotational velocities, different active region sizes, different stellar inclinations compared to the line of sight, and different latitudes of active regions. If not specified in the text, the star will be seen equator-on and its radius and projected rotational velocity will be fixed to the solar value ($v \sin i = 2$ km s$^{-1}$). The active region will be on the equator and will have a size of $S = 1\%$. The results of this section are obtained for a star divided in $300 \times 300$ cells.

In Figure 7, we show the RV, BIS SPAN, and FWHM peak-to-peak amplitudes induced by an active region as a function of the projected rotational velocity. We compare the variation induced by the flux effect only (see Equation (6)), with the variation induced by the total effect, which includes the flux and the CB effects (see Equation (4)). When comparing our results for the flux effect only with the ones obtained with SOAP (see Figure 5 in Boisse et al. 2012), we notice that our estimates of the peak-to-peak amplitudes for the RV and the BIS SPAN are twice as small. In Boisse et al. (2012), the spot inducing the RV and the BIS SPAN variations is totally black, while in our case the spot emits 54% of the flux of a non-active region, explaining this factor of two difference.

For a spot, the RV peak-to-peak amplitude that we obtain from the flux effect and from the total effect are very similar, independently of the projected stellar rotational velocity. This implies that the flux effect dominates the RV variation for any $v \sin i$. For the BIS SPAN and the FWHM peak-to-peak amplitudes, the flux effect dominates for rapid rotators. However, for small $v \sin i$ similar to the solar value, the flux effect vanishes and the CB effect becomes dominant (see the zoom in the left plot of Figure 7). Therefore, simulations like the original SOAP, which only includes the flux effect, manages to reproduce well the small $v \sin i$ similar to the solar value, the flux effect vanishes and the CB effect becomes dominant (see the zoom in the left plot of Figure 7). Therefore, simulations like the original SOAP, which only includes the flux effect, manages to reproduce well the

\[ \Delta v \text{RV} = \Delta v \text{flux} \]

\[ \Delta v \text{BIS SPAN} = \Delta v \text{CB} + \Delta v \text{flux} \]

\[ \Delta v \text{FWHM} = \Delta v \text{CB} + \Delta v \text{flux} \]

We arrive to similar values than Figure 5 in Boisse et al. (2012); however, we show the peak-to-peak amplitudes, while Boisse et al. (2012) show the semi-amplitudes.
variations induced by a spot in rapid rotators. For slow rotators like the Sun, SOAP 2.0 predicts that the BIS SPAN and the FWHM peak-to-peak variations are larger than when considering the flux effect only.

For a plage, the RV, BIS SPAN, and FWHM peak-to-peak amplitudes are dominated by the CB effect for any projected stellar rotational velocity. This can be explained by the small contrast difference between a plage and the quiet photosphere, which implies a small flux effect. For a plage, SOAP 2.0 yields much higher RV, BIS SPAN, and FWHM peak-to-peak amplitudes than simulations considering only the flux effect predict.

The introduction of the inhibition of the CB effect causes the FWHM peak-to-peak amplitude of a plage to be always three times greater than the RV peak-to-peak amplitude, for every stellar rotational velocities smaller than 8 km s\(^{-1}\). For spots, on the contrary, this is never the case. Therefore, the ratio between the FWHM peak-to-peak amplitude and the RV peak-to-peak amplitude informs us of the type of active regions at the origin of the activity-induced variation: spot or plage. For \(v \sin i \leq 8\) km s\(^{-1}\), a ratio smaller than three implies the presence of a spot, while a ratio larger than three indicates the presence of a plage.

In Figure 8, we show the RV, BIS SPAN, and FWHM peak-to-peak amplitudes as a function of active region size. As we can see, these parameters are proportional to the active region size, which is the case because we stay in the small active region regime where the geometry of these regions does not change. As discussed in the preceding paragraphs, the faster a star rotates, the higher will be the activity-induced effect on the RV, the BIS SPAN, and the FWHM. The photometry is the only observable independent of the stellar projected rotational velocity.

Using the results of Figures 7 and 8, we can estimate the photometric, RV, BIS SPAN, and FWHM peak-to-peak amplitudes as a function of \(v \sin i\) and the active region size. These results are obtained assuming an equatorial spot on a star seen equator-on, which is the configuration leading to the maximum effect. The following equations thus give us the maximum photometric, RV, BIS SPAN, and FWHM peak-to-peak amplitudes that a spot Sp or a plage Pl with a size \(S\) (in percent) can induce considering a stellar projected rotational velocity in the range \(0.5 \leq v \sin i \leq 12\) km s\(^{-1}\):

\[
\Delta_{\text{FLUX,SP}} = S \cdot 10819 \\
\Delta_{\text{RV,SP}} = S \cdot [1.83 + 9.52 v \sin i + 0.79 v \sin i^2 - 0.04 v \sin i^3] \\
\Delta_{\text{BIS,SP}} = S \cdot [1.84 + 2.21 v \sin i - 0.46 v \sin i^2 + 0.57 v \sin i^3 - 0.03 v \sin i^4] \\
\Delta_{\text{FWHM,SP}} = S \cdot [16.66 - 6.06 v \sin i + 4.88 v \sin i^2 - 0.21 v \sin i^3] \\
\Delta_{\text{FLUX,PL}} = S \cdot 728 \\
\Delta_{\text{RV,PL}} = S \cdot [7.66 + 0.25 v \sin i + 0.20 v \sin i^2] \\
\Delta_{\text{BIS,PL}} = S \cdot [4.38 + 1.10 v \sin i + 1.98 v \sin i^2 - 0.12 v \sin i^3] \\
\Delta_{\text{FWHM,PL}} = S \cdot [31.93 - 7.35 v \sin i + 3.92 v \sin i^2 - 0.41 v \sin i^3 + 0.01 v \sin i^4]. \quad (10)
\]

The flux peak-to-peak amplitude is expressed in ppm and the RV, BIS SPAN, and FWHM peak-to-peak amplitudes in m s\(^{-1}\).

The parameters or these polynomials have been estimated by fitting the results of the simulation.

In Figure 9, we display the photometric, RV, BIS SPAN, and FWHM peak-to-peak amplitudes as a function of stellar rotational velocity \(v\) (the absolute value) and as a function of active region latitude \(\phi\) (the star being equator-on, i.e., \(i = 90^\circ\)). The maximum peak-to-peak amplitude for all the different observables are obtained for an equatorial active region on a star observed equator-on. For both the spot and the plage, the photometric, RV, BIS SPAN, and FWHM peak-to-peak amplitudes vary in a similar way when modifying the stellar inclination or the active region latitude. The amplitudes of the induced variations vary roughly as \(\sin^2 i\) or \(\cos^2 \phi\). These formulae give us an indication of how the peak-to-peak variations change but should not be used to get precise values.
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Figure 8. Peak-to-peak (p2p) amplitudes of the photometry, RV, BIS SPAN, and FWHM induced by a spot (left) and a plage (right) as a function of the active region size. Two different values for $v \sin i$ are considered: 2 and 5 km s$^{-1}$ (blue lines and red lines, respectively). The RV, BIS SPAN, and FWHM are represented by continuous, dashed, and dotted lines, respectively. As we can see, the photometric effect is independent of the stellar projected rotational velocity. Note that in the right plot, the red continuous line corresponding to the RV effect for a $v \sin i = 5$ km s$^{-1}$ is overplotted on top of the blue dashed line corresponding to the BIS SPAN effect for $v \sin i = 2$ km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 9. Peak-to-peak (p2p) amplitudes of the photometry, RV, BIS SPAN, and FWHM induced by a spot (left) and a plage (right) as a function of the stellar inclination (the active region being at the equator, red lines) and of the active region latitude (the star being equator on, blue lines). The RV, BIS SPAN, and FWHM are represented by continuous, dashed, and dotted lines, respectively. The photometric variation is shown as green lines with triangle markers. Note that the photometric variation (green line with triangle markers) is the same when the inclination or the latitude is modified.

(A color version of this figure is available in the online journal.)

5. OBSERVATIONAL TEST

In the preceding sections, we presented SOAP 2.0, a new simulation of stellar activity that estimates the impact of spots and plages on the photometry, RV, BIS SPAN, and FWHM. In this section, we compare the result of this simulation with observations of HD 189733 and α Centauri B. The full description of the method using SOAP 2.0 to fit the data of both stars is described in another paper (Dumusque et al. 2014). We however show the results here to demonstrate that the results of SOAP 2.0 reproduce the stellar activity observed in solar-type stars.

5.1. HD 189733

HD 189733 will be used as a first example. This star is rather active because its photometric variability in the visible reaches the percent level (Winn et al. 2007; Croll et al. 2007). In addition, signs of stellar activity have also been detected in the X-ray (Poppenhaeger et al. 2013) and in the calcium H and K activity index (Boisse et al. 2009; Moutou et al. 2007), which is compatible with a star rotating moderately fast, with a $v \sin i$ of $\sim 3$ km s$^{-1}$ (e.g., Triaud et al. 2009) and a rotational period of 11.95 days (Henry & Winn 2008). All these indicators favor a star for which the activity should be dominated by the effect of the plage, the limb darkening is competing with the increase of the active region intensity when approaching the limb, which induces a nearly constant flux from $i = 90$ to 30 or from $\phi = 0$ to 60°.

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Figure 10. Photometric, RV, and BIS SPAN variations and best fit (black continuous line) of the activity-induced signal observed on HD 189733. Our best fit to the data corresponds to a 0.8% spot that can be found at a latitude of 61°. The star rotates in 10.27 days and is seen nearly equator-on with an inclination of 80°. Note that the planetary signal has been removed using the planetary solution of Boisse et al. (2009) and that the residual RVs and the BIS SPAN have been centered on zero using a weighted mean.

(A color version of this figure is available in the online journal.)

spots on the stellar surface (Shapiro et al. 2014; Lockwood et al. 2007). In that case, the flux effect should explain the major part of the photometric, RV, BIS SPAN, and FWHM activity-induced variations.

HD 189733 has been observed in 2007 July simultaneously in spectroscopy with SOPHIE at the Observatoire de Haute Provence in France and in photometry with the MOST satellite. These data have been used to test other activity simulations (Boisse et al. 2012; Aigrain et al. 2012; Lanza et al. 2011) that could reproduce the photometric and RV activity-induced variations fairly well. Here we will use the same data set to check if the SOAP 2.0 code manages to also reproduce the variations seen in photometry and RV, in addition to the variation observed in BIS SPAN. The FWHM of HD 189733 for the same period exhibits a peak-to-peak amplitude of 135 m s$^{-1}$, which is unlikely to be due to activity variations. We therefore decided not to include the FWHM in our fitting procedure.

Given the regular photometric variation over two rotational periods (see Figure 10), it is justified to consider that one main active region is present on the stellar surface. We therefore try to reproduce the activity-induced variation using only one active region. If a plage was at the origin of the photometric variation, the RV and BIS SPAN variations would be much larger in amplitude, and thus we decided to use a spot to fit the data.

After binning the MOST and SOPHIE measurements over 1 day and running a Markov Chain Monte Carlo (MCMC) to fit the results of SOAP 2.0 to the photometric, RV, and BIS SPAN data (see X. Dumusque 2014), we obtain our best fitted solution represented by the black curve in Figure 10. The reduced $\chi^2$ of this model is 1.18 compared to 20.31 for a flat model.

The fit does not match the RV data around BJD = 2454308.5 (10 days in the abscissa of Figure 10). In the studies by Aigrain et al. (2012) and Lanza et al. (2011), the same anomaly was reported using a spot model taking into account the flux effect and in some way the CB effect. The results of SOAP 2.0 show that the CB effect is not dominating the activity-induced RV variation when spots are present on the stellar surface (see Section 4). Therefore the flux effect is dominating in this case, and because this effect is estimated in SOAP 2.0 in a similar way to the works published by Aigrain et al. (2012) and Lanza et al. (2011), it is not surprising that we find the same anomaly. The RV data around BJD = 2454308.5 were obtained near the full Moon (BJD = 2454311.5), which can contaminate some spectra in case of clouds. Boisse et al. (2009) removed strongly contaminated spectra from the observations; however, without simultaneous observation of the sky, it is possible that some of the remaining spectra are slightly contaminated. Note that this contamination could be at the origin of the large peak-to-peak amplitude observed in the FWHM. In addition, as already discussed by Lanza et al. (2011), flares could also be the cause of this anomaly, because the calcium activity index of HD 189733 can sometimes vary on a very short timescale (Fares et al. 2010; Moutou et al. 2007).

Removing the two bad points of the anomaly and considering only the spectroscopic data (RV and BIS SPAN), the reduced $\chi^2$ is 1.18 compared to 20.31 for a flat model.

A linear trend was fitted to the MOST photometric data to account for an instrumental drift or a long-term activity variation not related to rotational modulation.

\footnote{A linear trend was fitted to the MOST photometric data to account for an instrumental drift or a long-term activity variation not related to rotational modulation.}

\footnote{The second fiber was illuminated by a thorium lamp for cross calibration, and not by the nearby sky.}
Figure 11. RV, BIS SPAN, and FWHM variations and best fit (black continuous line) of the activity-induced signal observed on α Cen B. The best-fitted solution corresponds to a plage of size 2.4% that can be found at a latitude of 44°. The star rotates in 36.65 days and is seen with an inclination of 22°. Note that the binary contribution of α Cen A has been removed from the raw RVs published in Dumusque et al. (2012) and that the residual RVs, the BIS SPAN, and the FWHM have been centered on zero using a weighted mean.

(A color version of this figure is available in the online journal.)

χ² of the fit is 1.17 compared to 1.26 for a flat model, and the standard deviation of the RV residuals is 5.57 m s⁻¹ compared to 7.53 m s⁻¹, which is an improvement of 5.06 m s⁻¹. Although the improvement in χ² only considering the spectroscopy is not very significant when comparing our best fit model to a flat model, we have to note that photometry and spectroscopy are both fitted together and that photometry constrains the fit much more than spectroscopy in this case. With this slight improvement in χ² and the improvement in standard deviation, we are confident that our best fit reproduces the data better than a flat model.

To fit the data of HD 189733, we used the observed CCF in our simulation. The result would have been similar using the same Gaussian CCFs in the quiet photosphere and the active region, or Gaussian CCFs shifted by 350 m s⁻¹, because the three different prescriptions predict a similar RV effect (see Figure 5). The prescription using the observed CCF predicts a larger BIS SPAN amplitude; however, the precision on the BIS SPAN for HD 189733 is not good enough to be able to differentiate between either of the prescriptions.

The stellar inclination obtained from the marginalized posterior of our MCMC, \( i = 84°^{+6}_{-20} \), as well as the latitude of the spot found, \( 67°^{+12}_{-36} \), are compatible with previous measurements of the spin–orbit angle close to zero degrees\(^{15} \) (Collier Cameron et al. 2010; Triaud et al. 2009; Winn et al. 2006), and

\(^{15} \) Because the spin–orbit alignment of HD 189733b is close to zero degrees, the stellar inclination can be different from 90° only in the plane perpendicular to the planetary orbit that contains the line of sight. The probability of the stellar spin being in this plane is very small compared to all the possible orientations and therefore there is a high probability that the stellar inclination is close to 90°.

\( Hubble Space Telescope \) observation of the transiting planet HD 189733b occulting stellar spots at \( \sim 30° \) in latitude (Pont et al. 2007). More information about confronting our results with previous measurements can be found in X. Dumusque (2014). This compatibility with previous observations brings us confidence that the results of SOAP 2.0 manages to reproduce the activity-induced variation of stars that are spot-dominated and rotate moderately fast, like HD 189733.

5.2. \( \alpha \) Cen B

As a second example, we want to see if SOAP 2.0 can reproduce the activity-induced variation of slow rotators, for which the effect of plages should dominate the activity-induced variation (Shapiro et al. 2014; Lockwood et al. 2007). Many slow rotators have been observed with HARPS, HARPS-N, and HIRES to search for planets with the sufficient RV precision and evidence to study stellar activity. However, RV surveys are biased toward non-active stars, or stars at the minimum of their activity cycle, for which the RV activity-induced signature is at the level of the instrumental precision. Nevertheless, a few RV observations of slow rotators during their high-activity phase exist, and the best RV measurements to study stellar activity are probably the ones used to detect the closest planet to our solar system orbiting \( \alpha \) Cen B (Dumusque et al. 2012). The data for 2010 exhibit an important and extremely regular activity index variation (in Ca II H and K, Dumusque et al. 2012) that can be modeled by a single major active region present on the stellar surface. Looking at the spectroscopic measurements of \( \alpha \) Cen B in Figure 11, we notice that the FWHM peak-to-peak amplitude is nearly four times larger than the RV
peak-to-peak amplitude. Using the results of Section 4, this ratio can be explained if a plage is responsible for the activity-induced variation.

The results of SOAP 2.0 can be used to predict the projected rotational velocity of $\alpha$ Cen B. The ratio among the RV, the BIS SPAN, and the FWHM peak-to-peak amplitudes implies a $v \sin i$ of $\sim 1$ km s$^{-1}$ (see Figure 7). This is compatible with the projected rotational velocity calculated using the rotational period of $\alpha$ Cen B, i.e., $v \sin i \sim 1.15$ km s$^{-1}$ (rotational period of 37.8 days; Dumusque et al. 2012).

As for HD 189733, we used the results of SOAP 2.0 and run an MCMC to fit the data of $\alpha$ Cen B. The details of the fit can be found in X. Dumusque (2014). Our best fit to the data, shown by the black curve in Figure 11, matches well the observed variations. The reduced $\chi^2$ of this fit is 1.00 compared to 11.17 for a flat model. When only considering the RVs, the reduced $\chi^2$ of the fit is 1.85 compared to 4.90 for a flat model, and the standard deviation of the RV residuals is 1.58 m s$^{-1}$ compared to 2.73 m s$^{-1}$, which is an improvement of 2.22 m s$^{-1}$. Our best-fitted model is therefore a better representation of the observed RV variations than a flat model and it can be used to correct the RVs from activity variations.

To fit the data of $\alpha$ Cen B, we used the observed CCF in our simulation. Looking at Figure 5 and comparing with the significant variation in BIS SPAN and in FWHM, we need peak-to-peak amplitude. Using the results of Section 4, this ratio

6. DISCUSSION AND CONCLUSION

This paper presents SOAP 2.0, a new version of SOAP (Boisse et al. 2012), which estimates the activity-induced variations seen in photometry and spectroscopy. The convective blueshift (CB) effect and its inhibition inside active regions is included in the simulation by using spectra of the Sun taken in the quiet photosphere and inside an active region. This inhibition is one of the major causes of activity-induced variation for slow rotators (Meunier et al. 2010a). Limb-brightening of plages, i.e., plages that are brighter on the limb than on the disk center (Meunier et al. 2010a), is also taken into account, as well as a quadratic limb darkening law. Finally, SOAP 2.0 is optimized to estimate the activity-induced variation as seen by high-resolution fiber-fed spectrographs like HARPS, HARPS-N, SOPHIE, and CORALIE.

An important result obtained with SOAP 2.0 is that for slow rotators, the CB effect and its inhibition in active regions plays an important role in the activity-induced variation. For stars with $v \sin i$ smaller than 8 km s$^{-1}$, the CB effect dominates the activity-induced FWHM variation, regardless of the type of active region considered, spot or plage. This is different for the RV variation that is dominated by the flux effect in the presence of a spot, or by the CB effect in the presence of a plage. This difference has a direct impact on the ratio between the FWHM and the RV peak-to-peak variations, which can be used to characterize the type of the active region responsible for the activity-induced signal. When a major active region is dominating the activity-induced signal, this active region is a spot if this ratio is smaller than three, while it is associated with a plage for larger ratios. Note that this result should be the same when several active regions are present on the star because the total activity variation will just be the sum of the variation of each individual active region.

For fast rotators, the results of SOAP 2.0 show that the flux effect dominates the activity-induced RV, BIS SPAN, and FWHM variations when spots are at the origin of the activity-induced signal, while it is the CB effect that dominates when plages are present on the stellar surface.

When the Sun is at its maximum activity level, it is not uncommon to see one long-lived main active region on the stellar surface. The data presented here for HD 189733 and $\alpha$ Cen B show a similar behavior, which therefore seems to be common among solar-type stars. In the case where only one active region dominates the activity-induced variation and if this active region evolves slowly in comparison with the stellar rotation period, SOAP 2.0 can be used to fit the observed data. Accounting for the CB effect in SOAP 2.0 allows us to better reproduce the variations seen in photometry, RV, BIS SPAN, and FWHM. Fitting all these observables simultaneously allows us to lift the degeneracy between active region size, active region latitude, and stellar inclination. For more information, readers are referred to the paper from Dumusque (2014), where the author shows how the stellar inclination can be obtained using the results of SOAP 2.0, even in the case of stellar projected rotational velocity smaller than 2 km s$^{-1}$.

When several active regions are present on the stellar surface, it is more difficult to fit the activity signal due to degeneracy between the active region latitudes and sizes, and the stellar inclination. However, if the stellar inclination can be measured on a small subset of the data that shows only one dominant active region, the posterior of the stellar inclination estimated on that subset can then be used as a prior to fit the other parts of the data. Once the stellar inclination is fixed, fitting several active regions becomes less degenerate and computationally more efficient. This will be tested in forthcoming papers. In the case of HD 189733 and $\alpha$ Cen B, fitting the stellar activity signal and correcting the RV measurements from it reduces the standard deviation by 5.06 and 2.22 m s$^{-1}$, respectively.

The results of this paper are obtained for active regions with a temperature fixed to the solar value. When fitting stellar activity on stars other than the Sun, like the K1 dwarfs HD 189733 and $\alpha$ Cen B, the temperature difference between the active region and photosphere could be different. The active region temperature is always degenerate with the active region size to first order, because the signal of a big active region with a small contrast can be reproduced by a smaller active region with a higher contrast. However, if we study in detail the activity-induced signal of a spot as a function of the spot temperature difference (see Figure 12), the ratios between the photometric, RV, BIS SPAN, and FWHM peak-to-peak variations change as a function of spot temperature. It is therefore possible that precise spectroscopic measurements can lift some degeneracy between spot temperature and spot size. Another possibility for measuring the spot temperature would be multi-band photometry, which has been obtained in the case of HD 189733. In Pont et al. (2013), the temperature difference of a spot occulted during the transit of HD 189733b is estimated to be $-750 \pm 250$ K, compatible with our value of $-663$ K adopted in SOAP 2.0.

Although SOAP 2.0 includes some additional solar physics compared to previous activity codes, the simulation is still simple compared to the complexity of the stellar atmosphere.
and further improvements can be made. In SOAP 2.0, the spectrum of a plage is considered the same as that of a spot. At first order, this can be done because the most important effect is the inhibition of convection inside a spot or a plage due to strong magnetic fields. This inhibition shifts toward the red the bisectors of the spectral lines, which has an influence on the RV, BIS SPAN, and FHWM. The temperature inside a plage is however hundreds of kelvin higher than inside a spot, which will modify the emerging spectrum of the active region and thus modify the bisector shape. Therefore, an observed spectrum of a solar plage should be used in order to include the correct bisector shape of a plage in SOAP 2.0. Furthermore, the convection seen inside a quiet photosphere region depends on the position of this region on the stellar disk, as different depths inside the star are probed. This difference induces a decrease of the granulation contrast when going toward the limb (Sánchez Cuberes et al. 2003; Beckers & Taylor 1980; Beckers & Nelson 1978), and consequently the amount of CB decreases as well. This limb-shift effect influences the shape of the stellar integrated CCF and therefore on the RV, BIS SPAN, and FHWM variations is however of the second order because of limb darkening.

To conclude, we would like to make it clear that the results of SOAP 2.0 are based on one solar observation of the quiet photosphere and one of a spot. We make the assumption that these two spectra are representative of all quiet photosphere regions and active regions. These spectra will be different if we consider different localization on the stellar surface, different magnetic field strengths and configuration, or a star with a different spectral type. However, our test including the limb-shift effect shows that if these differences are small, we think that they will induce a second order effect because the inhibition of the convection inside the active region will dominate and because limb effects will be averaged out by limb darkening. The fact that SOAP 2.0 manages to reproduce the activity-induced variation of the early-K dwarfs HD 189733 and α Cen B shows that we have some margins; however, we have to be cautious when using SOAP 2.0 on stars with a different spectral type from the Sun.

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APPENDIX A

EQUIVALENCE IN INTEGRATED CCF WHEN USING A SPECTRUM OR ITS CCF IN EACH CELL OF THE SOAP SIMULATION

To obtain the quiet Sun CCF of the integrated disk, several linear processes are used:

1. calculation of the CCF of the quiet Sun spectrum. According to Pepe et al. (2002), the value of the CCF at velocity $v_R$ is given by:

$$\text{CCF}(v_R) = \int S(\lambda)M(\lambda, \nu_R) d\lambda, \quad (A1)$$

where $\nu_{\text{eq}} = \lambda \sqrt{1 + v_R/c} / (1 - v_R/c)$, $S$ is the spectrum, and $M(\lambda, \nu_{\text{eq}})$ represents the Doppler-shifted numerical mask used for the correlation;

2. shift of the CCF according to the projected stellar velocity $v_j$ of cell $j$:

$$\text{CCF}(v_R) = \text{CCF}(v_R + v_j); \quad (A2)$$
3. Summation of the CCFs present in every cell to obtain the integrated CCF, $\text{CCF}(v_R)_{\text{tot, quiet}}$:

$$\text{CCF}(v_R)_{\text{tot, quiet}} = \sum_j \text{CCF}(v_R).$$  \hfill (A3)

Therefore, the integrated CCF over the stellar disk is given by

$$\text{CCF}(v_R)_{\text{tot, quiet}} = \sum_j \int S(\lambda) M(\lambda v_j + v_j) d\lambda.$$  \hfill (A4)

One can also consider the quiet Sun spectrum in each cell and shift it to the corresponding projected stellar velocity $v_j$ of each cell. The integrated spectrum over the entire disk is obtained by summing all the spectra in the cells and the CCF can then be calculated. In this case:

$$\text{CCF}(v_R)_{\text{tot, quiet}} = \int \sum_j S(\lambda) M(\lambda v_j + \lambda v_j) d\lambda,$$  \hfill (A5)

where $\lambda v_j = \lambda \sqrt{1 + v_j/c} / (1 - v_j/c)$. By doing the change of variable $\lambda \rightarrow \lambda' = \lambda v_j$, we have $d\lambda \rightarrow$
Figure 15. Photometric, RV BIS SPAN, and FWHM variations induced by an equatorial spot or plage on an equator-on star when considering the limb-shift effect (green dotted line) or not considering it (red continuous line). The size of the active region is 1%. The contrast of the active region is 0.54 in the case of a spot (663 K cooler than the effective temperature of the Sun, at 5293 Å), and is given by Equation (8) in the case of a plage. The active region is on the stellar disk center when $\theta = 0$ and on the limb when $\theta = \pm \pi/2$.

(A color version of this figure is available in the online journal.)

$$\sqrt{1 - v_j/c}/1 + v_j/c d\lambda',$$

and therefore Equation (A5) can be rewritten:

$$CCF(v_R)_{hot, quiet} = \sum_j \sqrt{1 - v_j/c}/1 + v_j/c \int S(\lambda') M(\lambda v_R + v_j) d\lambda',$$

where we used

$$M(\lambda v_R) = \frac{1 + v_R/c}{1 - v_R/c} \rightarrow \lambda' \sqrt{\frac{1 + v_R/c}{1 - v_R/c}} \rightarrow \lambda \sqrt{\frac{(1 + v_j/c)(1 + v_R/c)}{(1 - v_j/c)(1 - v_R/c)}}$$

$$\rightarrow \lambda \sqrt{\frac{1 + (v_R + v_j)/c + v_R \cdot v_j/c^2}{1 - (v_R + v_j)/c + v_R \cdot v_j/c^2}}$$

$$\rightarrow \lambda \sqrt{\frac{1 + (v_R + v_j)/c + v_R \cdot v_j/c^2}{1 - (v_R + v_j)/c + v_R \cdot v_j/c^2}}$$

$$\rightarrow M(\lambda v_R + v_j)$$

where the last equivalence can be obtained for small velocities compared to the speed of light, $v_R \cdot v_j \ll c^2$, which is the case here.

Considering a CCF in each cell and obtaining the integrated CCF by summing all the cells together is therefore equivalent to considering a spectrum in each cell, obtaining the integrated spectrum, and finally calculating the CCF of this integrated spectrum. Figure 13 illustrates this analytical result using our simulation. By injecting spectra or CCFs in each cell of SOAP 2.0, it was possible numerically to retrieve the same CCF and bisector, proving that the simulation is returning coherent results.

APPENDIX B

WARPING THE CCFs TO ACCOUNT FOR THE LIMB SHIFT OF SPECTRAL LINES

On the Sun, the contrast of the granulation pattern decreases when going toward the limb (Sánchez Cuberes et al. 2003; Beckers & Taylor 1980; Beckers & Nelson 1978), and consequently the amount of CB decreases as well. This limb-shift effect will affect the shape of the spectral lines, being a “C”
shape on the stellar disk center and a “D” shape on the stellar limb. The variation of a few spectral lines from the solar disk center to the limb have been measured on the Sun (e.g., Cavallini et al. 1985b); however, these observations do not help us in modeling this limb-shift effect because we are working with CCFs. A CCF is a weighted average of nearly all the spectral lines in the visible, and because different spectral lines are affected differently by convection, the bisector of a CCF is different from the bisector of a given spectral line (see the left plot of Figure 13).

To account for the limb-shift effect of spectral lines, we decided to warp the CCFs depending on the stellar disk position. The CCF for the quiet photosphere that we use throughout the paper have been extracted from an FTS spectrum taken at the disk center. We therefore have the correct CCF for the stellar disk center. On the limb, the granulation contrast decreases and therefore the amount of CB as well. The quiet photosphere CCF on the limb should therefore not include any CB, which implies that the CCF should be redshifted by $\sim$350 km s$^{-1}$ and its bisector should be straight. For regions between the disk center and the limb, we interpolated linearly in $\cos \theta$ between the two bisectors of these extreme regions. The left plot of Figure 14 shows the CCF bisectors for $\cos \theta = 1, 0.8, 0.6, 0.4, 0.2,$ and 0. The CCF at any position on the disk is obtained by warping the quiet photosphere CCF taken at the disk center to reproduce the desired bisector.

To test whether our empirical way of considering the limb-shift effect is realistic, we selected two solar twins observed with HARPS during their minimum of activity: $\alpha$ Cen A and 18 Scorpii. If the limb-shift effect is accounted for in a realistic way, the bisector of the integrated CCF estimated with our model without any active region should be similar to the CCF bisectors of these two stars. The result of this test is shown in the right plot of Figure 14. We can see that the bisector derived when considering the limb-shift effect does not match the observations, and that the bisector obtained without this extra effect is a better match.

Following these results, we can conclude that our empirical way to include the limb-shift effect cannot reproduce the observations, and we decided not to include this effect at this stage. Further developments to include this limb-shift effect using either solar observation at different $\cos \theta$ angles, or MHD simulations that can reproduce realistic bisector shape for different positions on the stellar disk are required. Nevertheless, comparing the photometric, RV, BIS SPAN, and FWHM activity-induced variations derived with and without considering the limb-shift effect (Figure 15), we see that this effect, even if it is accounted for in a realistic way in the future, does not significantly modify the activity-induced variations. This is because the limb-shift effect only influences the limb of the star that has a small weight in the disk-integrated CCF because of limb darkening.

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