DERIVING STELLAR INCLINATION OF SLOW ROTATORS USING STELLAR ACTIVITY*

X. DUMUSQUE

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; xdumusque@cfa.harvard.edu

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ABSTRACT

Stellar inclination is an important parameter for many astrophysical studies. Although different techniques allow us to estimate stellar inclination for fast rotators, it becomes much more difficult when stars are rotating slower than ~2–2.5 km s⁻¹. By using the new activity simulation SOAP 2.0 which can reproduce the photometric and spectroscopic variations induced by stellar activity, we are able to fit observations of solar-type stars and derive their inclination. For HD 189733, we estimate the stellar inclination to be $i = 84^\circ_6^{+5}_{-20}$ deg, which implies a star–planet obliquity of $\psi = 4^\circ_{+18}^{+4}$ considering previous measurements of the spin–orbit angle. For $\alpha$ Cen B, we derive an inclination of $i = 45^\circ_{+9}^{+19}$, which implies that the rotational spin of the star is not aligned with the orbital spin of the $\alpha$ Cen binary system. In addition, assuming that $\alpha$ Cen Bb is aligned with its host star, no transit would occur. The inclination of $\alpha$ Cen B can be measured using 40 radial-velocity measurements, which is remarkable given that the projected rotational velocity of the star is smaller than 1.15 km s⁻¹.

Key words: stars: activity – stars: individual (HD 189733, a Cen B) – starspots – techniques: radial velocities

Online-only material: color figures

1. INTRODUCTION

In many different fields of astrophysics, obtaining stellar inclination is often a critical step for further modeling. Reconstructing spots maps from Doppler imaging requires stellar inclination to recover the latitude of spots on the stellar surface (e.g., Vogt et al. 1987). This inclination can however be constrained during the Doppler imaging fitting process itself if the signal-to-noise ratio of the data is sufficient because a wrong inclination produces systematic errors in the spot map (Rice & Strassmeier 2000). When studying the large-scale topology of magnetic fields using Zeeman–Doppler imaging (ZDI) measurements, the stellar inclination must also be chosen to lift the degeneracy between magnetic field configuration and inclination of the star (e.g., Donati et al. 2006). Last but not least, stellar inclination is required to get the true obliquity of a transiting planet orbiting its host star, i.e., the angle between the orbital angular momentum and the stellar rotation axis (e.g., Fabrycky & Winn 2009). The obliquity can be obtained from the stellar inclination if a measurement of the sky-projected obliquity angle, most commonly called spin–orbit angle, can be performed (e.g., Lund et al. 2014). This sky-projected obliquity angle is generally measured using the Rossiter–McLaughlin effect (Queloz et al. 2000; Rossiter 1924; McLaughlin 1924). Obtaining the obliquity is of prime importance to distinguish between the various migration scenarios that have been proposed to explain the existence of close-in giant-like hot Jupiters or hot Neptunes. Indeed, theories like disk migration predict a rather small misalignment between stellar spin and planetary orbital axes (e.g., Lin et al. 1996), while theories like planet–planet scattering or migration produced by Kozai cycles in combination with tidal circularization predict a very wide range of obliquity angles (e.g., Nagasawa & Ida 2011; Fabrycky & Tremaine 2007; Wu & Murray 2003). Note however that stellar magnetic fields can induce an obliquity between the stellar spin and the planetary orbital angular momentum even in the disk migration scenario (see Lai et al. 2011).

2. DERIVING STELLAR INCLINATION AND OBLIQUITY

2.1. Measuring the Projected Rotational Velocity with Spectroscopy

The most common technique to derive stellar inclination is first to estimate the stellar projected rotational velocity $v \sin i$, where $v$ is the equatorial rotational velocity of the star, and $i$ its inclination. This can be done by matching an observed stellar spectrum to a grid of synthetic model spectra (e.g., SPC and SME codes; Buchhave et al. 2012; Valenti & Fischer 2005; Valenti & Piskunov 1996). Then an estimation of the rotational period of the star $P_{\text{rot}}$, using the photometric light curve (Hirano et al. 2012, 2014), rotation–age mass correlations (Schlaufman 2010) or the chromospheric calcium index modulation (e.g., Lendl et al. 2014), gives us $v$ and thus the stellar inclination.

Another possibility to obtain $v \sin i$ is to study the width of the cross correlated function (CCF) obtained after cross-correlating a stellar spectrum with a synthetic template (Pepe et al. 2002; Baranne et al. 1996). The CCF can be considered as the average line of the target spectrum, and therefore carries information on the stellar atmospheric parameters (like the global abundances, thermal broadening, pressure broadening, or micro-turbulence), the macroturbulence, the projected rotational velocity (Gray 2008), and the instrumental profile.

The Gaussian width of a weak spectral line of a “non-rotating” star depends mostly on its spectral type and luminosity class. Therefore by observing with the same instrument, i.e., same instrumental profile, for dwarfs that have a similar B – V color, the only parameter affecting the width of the CCF is the projected rotational velocity of the stars. Stars that have the minimum width will be associated with “non-rotators,” i.e., stars that are seen pole-on, and all excess width will be associated with non-zero projected rotational velocity (Boisse et al. 2010; Santos et al. 2002; Queloz et al. 1998; Benz & Mayor 1981).

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2 Using the formula $v = 2 \pi R_*/P_{\text{rot}}$, where $R_*$ is the stellar radius generally derived from evolutionary tracks or asteroseismology.
Deriving stellar inclination from a \( v\sin i \) measurement obtained either by matching stellar spectra or using the width of the CCF is limited by the instrumental resolution of the spectrograph used. Even for high-resolution instruments like HARPS, HARPS-N, and HIRES, it is difficult to measure precise \( v\sin i \) for stars rotating slower than 2–2.5 km s\(^{-1}\).

If the star is hosting a transiting planet, the \( v\sin i \) can be obtained by measuring the Rossiter–McLaughlin effect. By masking part of the stellar disk in rotation, the transiting planet creates an anomaly in the radial velocity (RV) curve that is proportional to \( v\sin i \) (Winn 2010; Triaud et al. 2009; Queloz et al. 2000). However, the use of different models estimating the Rossiter–McLaughlin effect can lead to different results for the shape of the RV anomaly and therefore different \( v\sin i \) determinations (Boué et al. 2013). In the special case when the spin–orbit angle measured using the Rossiter–McLaughlin effect is close to zero, there is a high probability that the star is seen equator-on, and thus the obliquity of the planet is close to zero. Indeed, if the spin–orbit angle is close to zero, the stellar inclination can be different from 90 deg 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 deg.

### 2.2. Measuring Rotational Splitting Using Asteroseismology

Another possible way to measure stellar inclination is by observing rotational splitting of the oscillation modes of the star. Detailed descriptions of the principles of this method based on asteroseismology may be found in Ballot et al. (2006, 2008) and Gizon & Solanki (2003).

In the absence of rotation, the frequency of a mode depends only on its radial spherical harmonic order \( n \) and its degree \( l \). Modes are \((2l+1)\) times degenerate among the azimuthal spherical harmonic order \( m \). This degeneracy is removed by breaking the spherical symmetry, especially by rotation. For geometrical reasons, only modes with an \( l \leq 3 \) have sufficient amplitude to be visible in an oscillation spectrum due to the integration of the signal over the entire stellar disk. For \( l = 1 \), each multiplet \((n, l)\) will have three peaks in the power spectrum and the relative heights between them allows us to constrain the stellar inclination (Huber et al. 2013).

An asteroseismic analysis requires bright targets and long-duration, high-cadence space-based photometric time series to give the requisite signal-to-noise and frequency resolution for extracting clear signatures of rotation from the oscillation spectrum, and hence the stellar inclination angle. Up to now only a few inclination studies with asteroseismology were carried out on solar-type stars observed with *Kepler* as signals are faint for these type of targets (Van Eylen et al. 2014; Chaplin et al. 2013; Huber et al. 2013).

#### 2.3. Spot Occultation During Transit

The passage of a transiting planet in front of a star can map spots on its surface, which can be used to infer the stellar inclination depending on whether or not the planet masks the same spot in consecutive transits (e.g., Sanchis-Ojeda et al. 2012; Désert et al. 2011; Sanchis-Ojeda & Winn 2011; Nutzman et al. 2011). This technique requires space-based photometry in high-cadence mode during several consecutive transits, active stars presenting big spots, and relatively big planets to map sufficiently the stellar surface. In addition, the period of the transiting planet must be much shorter than the rotational period of the star and the spot lifetime so that the occultation signal stays in phase for a few consecutive transits.

#### 2.4. Other Methods to Derive Stellar Inclination

For extremely fast rotators, the obliquity of the system can be obtained using the gravity darkening signature. This has been done so far for the KOI-13 and KOI-368 systems (Ahlers et al. 2014; Szabó et al. 2011; Barnes et al. 2011; Barnes 2009).

Stellar inclination can also be obtained in special cases using the beaming effect (Shporer et al. 2012; Groot 2012).

### 3. FITTING STELLAR ACTIVITY TO DERIVE STELLAR INCLINATION

In this section, we present a new technique to derive stellar inclination using the photometric and spectroscopic variation induced by short-term activity, i.e., modulations induced by the presence of active regions on the stellar surface. In principle, the inclination of the stellar spin axis can be extracted from photometric and spectroscopic measurements when one major active region, spot or plage, is dominating the activity signal. With the photometry alone, it is possible to study the amplitude of the light modulation and the duration of the flux anomaly produced by an active region that is in view only for a fraction of the rotational phase. This provides information on a combination of the stellar spin inclination, the active region latitude, and its area. These three parameters cannot be characterized individually and a third observable is required to lift the degeneracy between them. This third observable can come from spectroscopy measurements, for which the amplitude of the RV signal can be used. Estimating the stellar inclination that way requires us to know the equatorial rotational velocity of the star, which is often derived from the stellar radius and the rotational modulation seen in photometry. In conclusion, if the temperature of the active region is fixed and the equatorial velocity is known, we can extract information on the stellar spin axis and the active region latitude and area.

Several preceding attempts have tried to derive the stellar inclination by using the photometric and RV information (Boisse et al. 2012; Lanza et al. 2011); however, a model that estimates in a proper way the photometric and spectroscopic variations of active region is required. In this paper, we use the recently published results of the SOAP 2.0 code (X. Dumusque et al. 2014, in press) which estimates the effect of spots and plages based on spectroscopic observations of the Sun. This code allows us to reproduce the activity-induced variation seen in photometry, RV, bisector span (BIS SPAN), and FWHM of the CCF. We show in the following two examples that fitting simultaneously all these observables lifts the degeneracy between stellar inclination, active region size, and latitude, and in the end the stellar inclination can be inferred.

#### 3.1. HD 189733

To illustrate how we can derive the stellar inclination of a star from fitting its stellar activity variations, we will first use a rather active star that rotates moderately fast, for which spots should be the dominant active regions (Shapiro et al. 2014; Lockwood et al. 2007). In that case, the flux effect should explain the

5 The active region size is degenerate with the active region contrast if the active region temperature is not fixed (see Section 4).
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Table 1
Parameters of HD 189733 and α Cen B

| Parameter                  | HD 189733 Value | Ref.          | α Cen B Value  | Ref.          |
|----------------------------|-----------------|---------------|----------------|---------------|
| Radius ($R_\odot$)         | 0.766 ± 0.01    | Triaud et al. (2009) | 0.863 ± 0.005 | Kervella et al. (2003) |
| $T_{\text{eff}}$ (K)       | 5040 ± 50       | Torres et al. (2008) | 5214 ± 33     | Dumusque et al. (2012) |
| [Fe/H]                    | −0.03 ± 0.08    | Torres et al. (2008) | 0.19 ± 0.09   | Santos et al. (2005)  |
| log g                      | 4.59 ± 0.02     | Torres et al. (2008) | 4.37 ± 0.12   | Santos et al. (2005)  |
| Limb darkening $g_1$       | 0.7787          | Claret (2004)    | 0.7207         | Claret (2004)        |
| Limb darkening $g_2$       | 0.0549          | Claret (2004)    | 0.1054         | Claret (2004)        |
| Active region type         | Spot            | X. Dumusque et al. (2014, submitted) | Plage          | X. Dumusque et al. (2014, submitted) |
| $\Delta T$ active region (K) | −663            | Meunier et al. (2010) | 250.9–407.7 cos $\theta$ + 190.9 cos$^2$ $\theta$ | Meunier et al. (2010) |
| Instrument resolution      | 75000           | SOPHIE (high res. mode) | 115000        | HARPS |

Notes. Parameters of HD 189733 and α Cen B used when fitting the observed data. The effective temperature, metallicity, and gravity are only used to derive the limb darkening parameters. $\theta$ 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 limbs).

major part of the photometric, RV, BIS SPAN, and FWHM activity-induced variations (X. Dumusque et al. 2014, in press.). As done in the original SOAP paper (Boisse et al. 2012), we use HD 189733 as a benchmark. This star hosts a hot Jupiter (Bouchy et al. 2005) and is an active star variable at the percent level. Activity has been detected photometrically (Winn et al. 2007; Croll et al. 2007), but also in X-ray (Poppenhaeger et al. 2013) and in calcium activity index (Boisse et al. 2009; Moutou et al. 2010) the observed variations in photometry, RV, and BIS SPAN. The FWHM of HD 189733 for the same period exhibits due only to activity-induced variations and could be induced by instrumental drift or a long-term activity variation not related to rotational origin of the photometric variation, the RV and BIS SPAN variations would be much larger, and thus we decided to use a spot to fit the data (X. Dumusque et al. 2014, in press.). Pont et al. (2013) also found the presence of spots on HD 189733 and tried to estimate the temperature difference compared to the photosphere of the spots occulted during the transit of HD 18973b. They arrived at the conclusion that this temperature difference is $−750 ± 250$ K, which is compatible with the $−663$ K (Meunier et al. 2010) used in SOAP 2.0. We therefore decided to use this later value.

The free parameters fitted with the MCMC are the active region longitude, latitude $\phi$ and $\beta$, the stellar rotational period, and inclination $i$, in addition to a stellar jitter term for the photometry and another one for the spectroscopy. The size $S$ is defined as the fraction of the surface of the visible hemisphere covered by the active region. Because $S, \phi, \beta$, and $i$ are correlated due to geometrical symmetries and projections, the following empirical change of variables,

$$\alpha = \sqrt{S} \sin(\phi) \sin(\theta), \quad S = \alpha^2 + \beta^2 + \gamma^2,$$
$$\beta = \sqrt{S} \sin(\phi) \cos(\theta) \cos(\psi), \quad i = \cos^{-1}\left(\frac{\gamma}{\sqrt{S}}\right),$$
$$\gamma = \sqrt{S} \cos(\phi) \sin(\phi), \quad \phi = \tan^{-1}\left(\frac{\alpha}{\beta}\right). \quad (1)$$

is performed to reduce the correlation between these parameters, and therefore improves the efficiency of the MCMC. The photometric and spectroscopic jitter terms are quadratically added to the flux and the RV and BIS SPAN error bars$^5$ when maximizing the log likelihood, respectively.

Seven MCMC chains of $2 \times 10^6$ steps each is obtained to fit the observed data of HD 189733 starting with random initial values within the following uniform priors:

$$\alpha = [-\sqrt{S_{\text{max}}}, \sqrt{S_{\text{max}}}]$$
$$\beta = [0, \sqrt{S_{\text{max}}}]$$
$$\gamma = [0, \sqrt{S_{\text{max}}}]$$
$$\gamma = [0, \sqrt{S_{\text{max}}}]$$

$$P_{\text{rot}} = [9, 14]$$

Longitude = $[-50, 100]$

Jitter Flux = $[0, 50 \times \text{med}(\sigma_{\text{Flux}})]$

Jitter RV = $[0, 10 \times \text{med}(\sigma_{\text{RV}})]$. \quad (3)

$^4$ 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.

$^5$ The error bars on the BIS SPAN is considered here to be the same as the ones on the RVs.
Figure 1. 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 deg. The star rotates in 10.27 days and is seen nearly equator-on with an inclination of 80 deg.

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

where $S_{\text{max}}$ is the maximum size allowed for the active region, fixed here at 50%, and $\text{med}(\sigma_{\text{flux}})$ and $\text{med}(\sigma_{\text{RV}})$ are the median of the flux and the RV error bars, respectively. To prevent symmetries, the inclination of the star is allowed to vary from 0 to 90 deg and the latitude can take any value between $-90$ and 90 deg, which implies that $\beta > 0$ and $\gamma > 0$. Because $\alpha$, $\beta$, and $\gamma$ are still correlated with each other, despite the change of variable (see Equation (1)), an adaptive Metropolis–Hasting step method is used to explore better the full parameter space (Haario et al. 2001).

A Gelman–Rubin test (Gelman et al. 2004) on these seven chains gives a potential scale reduction better than 1.0049 for all parameters, proving the convergence and the proper mixing of the chains. With the first $2 \times 10^5$ steps rejected removing the burn-in period, and without any constrains on $\alpha$, the correlation between the posterior distributions of the fitted parameters in Figure 2 show that the data are compatible with a stellar inclination angle above 50 deg, for which we can have either a big spot near the southern pole, or a smaller one in the northern hemisphere. These two solution are equivalent because it is not possible to differentiate between a northern and a southern spot at the same latitude when the star is close to equator-on. The solution with the spot on the southern hemisphere is more likely, because in this case, the spot can grow to very large sizes as part of it will be out of view to the observer and therefore will not contribute to the signal. This can be seen when studying the inclination–size correlation plot. Note also that when the spot grows to very large sizes, the RV jitter goes to non-realistic values higher than 10 m s$^{-1}$. To lift this degeneracy between a southern or a northern spot, and to prevent the spot from growing on the invisible part of the star, we selected the northern solution by imposing the following priors on $\alpha$ and $\gamma$:

$$\alpha = [-0.1, \sqrt{S_{\text{max}}}]$$
$$\gamma = [0, 0.2].$$

where $\alpha = -0.1$ is the delimitation between the southern and northern solutions (see the top row correlation plots for $\alpha$ in Figure 2), and $\gamma = 0.2$ constrains the spot size to be smaller than 10% for stellar inclination higher than 50 deg.

We run a new MCMC chain with $2 \times 10^6$ steps with this new constrain on $\alpha$ and $\gamma$ and removed the first $2 \times 10^5$ to reject the burn-in period. Figure 3 shows the posterior correlations between the different fitted parameters and Figure 4 shows the marginalized posterior distributions of the parameters including the obliquity of the star–planet system. The best-fitted solution maximizing the log likelihood is represented by the black curve in Figure 1, and corresponds to a $\chi^2$ of 1.18 compared to 20.31 for a flat model.

The fit does not match the two RV measurements near BJD = 2454308.5 (10 days in the abscissa of Figure 1). 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 convective blueshift effect. These two RV measurements 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
\( \chi^2 \) 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 \( \chi^2 \) only considering the spectroscopy is not very significant comparing our best fit model to a flat model, we have to note that photometry and spectroscopy are both fitted together and that photometry is much more constraining the fit than spectroscopy in this case. With this slight improvement in \( \chi^2 \) and the improvement in standard deviation, we are confident that our best fit reproduces the data better than a flat model.

The marginalized posteriors for the rotational period converges to 11.95 days, which is smaller than the previous estimate of 13.4 days (Winn et al. 2007). One year before the simultaneous observations, the Hubble Space Telescope (HST) observed three

\[
\cos \psi = \sin i \cos \lambda \sin i_p + \cos i \cos i_p, \quad (5)
\]

where \( \lambda \) is the spin–orbit angle, which can be measured by the Rossiter–McLaughlin effect (Rossiter 1924; McLaughlin 1924). With our stellar inclination posterior for HD 189733, the spin–orbit angle and orbital plane of the planet found by Triaud et al. (2009), \( \lambda = -0.85 \pm 0.32 \) deg and \( i_p = 85.5 \pm 0.1 \) deg, we estimate the obliquity of the system to be \( \psi = 4^{18}_{-4} \) deg (see Figure 4). The alignment of HD 189733b with its host star is expected given the effective temperature of HD 189733 (Winn et al. 2010).

One year before the simultaneous MOST and SOPHIE observations, the Hubble Space Telescope (HST) observed three
transits of HD 189733b (in 2006 May and July), and the data revealed that the planet was masking stellar spots during its passage in front of the stellar disk (Pont et al. 2007). Given the impact parameter of the planet $b = 0.671 R_*$, and the planet to star radius ratio of 0.16 inferred at the time, plus the stellar inclination found here, the latitude of the spots observed by *HST* are estimated to be at $36\pm15$ deg in latitude. This value is compatible with the latitude of the spot fitted in this paper, although we have large uncertainties. Note that the planet is also occulting spots in another study using a different data set (Pont et al. 2013).

The *HST* and *MOST* data have been taken with a separation of one year; therefore, the spot seen on the *MOST* data is not necessarily one of the spots observed with *HST*, as spots evolve and disappear with time. On the Sun, spots appear at a preferred latitude, which varies with the magnetic cycle phase. During an 11 yr magnetic cycle, spots drift from ~40 deg in latitude to the equator. Assuming that the activity of HD 189733 can be compared to the Sun, which seems reasonable given the results of Reiners (2006), we expect only a small change in the preferred latitude of spots during a one-year timescale. It is therefore not surprising that a spot latitude compatible with the *HST* observations is found.

### 3.2. α Cen B

The next step is to derive the stellar inclination for a slow rotator, for which the effect of plages is dominating the activity-induced variation (Shapiro et al. 2014; Lockwood et al. 2007). Slow rotators are the main targets of RV surveys searching for small mass planets because they tend to be less active, and therefore to exhibit a smaller activity-induced RV variation than rapid rotators. Many slow rotators have been observed using HARPS, HARPS-N, and HIRES with the sufficient RV precision and cadence to study activity. However, to reduce at maximum the impact of activity when searching for planets, the observations are generally taken when these stars are at the minimum of their magnetic cycle, when only small active regions are present on the stellar surface. In this case, the activity-induced RV signal is at the level of the instrumental noise, and these data cannot be used to study the effect of activity on slow rotators. Nevertheless, a few data sets exist, and one of the best is the RV measurements that have been used to detect the closest planet to our solar system orbiting α Cen B (Dumusque et al. 2012). This star has been observed between 2008 and 2011, during which the stellar activity level changed from minimum to maximum due to a solar-like magnetic cycle. In 2010, the data 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. To fit the activity-induced variation, the binary contribution of α Cen A has been removed from the raw RVs published in Dumusque et al. (2012), and the residual RVs, the BIS SPAN, and the FWHM have been centered on zero using a weighted mean.

Looking at the data in Figure 5, we can see 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 in X. Dumusque et al. (2014, submitted), this ratio between the amplitudes of the RV and the FWHM of the observed signal can be explained if a plage is dominating the activity-induced variations. The ratio between the RV, BIS SPAN, and FWHM peak-to-peak amplitudes for $\alpha$ Cen B implies a $v \sin i \sim 1$ km s$^{-1}$ according to the SOAP 2.0 results for a plage (see Figure 7 in X. Dumusque et al. 2014, submitted). With a rotational period of 37.8 days for $\alpha$ Cen B (Dumusque et al. 2012) and a radius of 0.863 $R_\odot$ (Kervella et al. 2003), the stellar project rotational velocity is less than 1.15 km s$^{-1}$, which is consistent with our small $v \sin i$ estimate.

Seven MCMC chains of $5 \times 10^5$ steps each are obtained to fit the observed data of $\alpha$ Cen B starting with random initial values within the following uniform priors:

$$\alpha = [-\sqrt{S_{\text{max}}}, \sqrt{S_{\text{max}}}]$$

$$\beta = [0, \sqrt{S_{\text{max}}}]$$

$$\gamma = [0, \sqrt{S_{\text{max}}}]$$

$$P_{\text{rot}} = [35, 40]$$

$$\text{Jitter RV} = [0, 10 \times \text{med}(\sigma_{\text{RV}})]$$

where $S_{\text{max}}$ is the maximum size allowed for the active region, fixed here at 20%, and $\text{med}(\sigma_{\text{RV}})$ is the median of the RV error bars. Everything is similar to the fit done for HD 189733, except that the RV, BIS SPAN, and FWHM variations are fitted here and that the stellar radius, the limb darkening coefficients and the active region temperature are fixed to the values shown in Table 1. In addition, only one jitter term is quadratically added to the RV, BIS SPAN, and FWHM error bars when maximizing the log likelihood.\(^7\) A Gelman–Rubin test (Gelman et al. 2004)

\(^7\) For HARPS data, the error bars on the BIS SPAN and the FWHM are 2 and 2.35 times more than the ones for the RVs.

Figure 4. Marginalized posterior distributions returned by our MCMC fit to the data of HD 189733. The mode (black thick line) of the distribution for each parameter, with its 1σ uncertainty (purple shaded regions delimited by red dashed lines) and 2σ uncertainty (delimited by green thin lines), can be found on each plot. The title of each plot gives the value for the mode of the distribution and its 1σ uncertainty. (A color version of this figure is available in the online journal.)
Figure 5. 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 deg. The star rotates in 36.65 days and is seen with an inclination of 22 deg.

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

on the seven chains gives a potential scale reduction better than 1.0042 for all parameters, proving the convergence and the proper mixing of the chains. Following the positive result of the Gelman–Rubin test, we decided to run a long chain with \(2 \times 10^6\) steps starting with initial values close to where the seven chains converged, and removed the first \(2 \times 10^5\) steps to reject the burn-in period. The correlation between the posterior distributions of the MCMC parameters are shown in Figure 6.

Figure 7 shows the marginalized posterior distributions for the size \(S\), the latitude \(\phi\) and the longitude of the active region, and the stellar rotational period and inclination \(i\). The best-fitted model maximizing the log likelihood is shown by the black curve in Figure 5, and corresponds to a configuration where the plage is at a latitude of 44 deg and has a size of 2.4%, on a star that have a stellar inclination of 22 deg. The reduced \(\chi^2\) of this model is 1.00 compared to 11.17 for a flat model. Considering only 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\(^{-1}\), respectively.

Our best-fitted model is therefore a better representation of the observed RV variations than a flat model. When comparing the stellar inclination and the active region latitude of the best fit (see Figure 5) with the marginalized posterior distributions (see Figure 7), we note that the best-fitted solution is outside of the 1\(\sigma\) uncertainty interval. This is not the case when looking at the correlation between the stellar inclination and the active region latitude in Figure 6, where the best-fitted solution is within 1\(\sigma\). This discrepancy is induced by the marginalization of the posterior distribution on parameters that are correlated between each other.

α Cen B is one of the components of the α Cen binary system that has a nearly edge-on orbit relative to the line of sight with an angle of 79.20 ± 0.04 deg (Pourbaix et al. 2002). Our measurement of the stellar inclination for α Cen B derived from the marginalized posterior 45\(^{+9}_{-19}\) excludes the spin–orbit of the star to be aligned with the binary orbital spin, with a difference greater than 20 deg at 2\(\sigma\). This misalignment is expected for wide separation binaries like the α Cen system (Jensen & Akeson 2014; Hale 1994; Gillett 1988). In addition, we also exclude the star to be pole on or equator on. Assuming a spin–orbit alignment for the close-in planet α Cen B b, our measurement of the stellar inclination implies that the planet is not transiting its host star.

Simultaneous photometric measurements could constrain better the size of the active region, and therefore could improve the precision on each parameters. Unfortunately, such data with the required precision do not exist for α Cen B, and would be difficult to obtain because of the brightness of the star and therefore the lack of reference star to perform differential photometry.\(^8\)

The rotational period of the star is estimated at 36.66\(^{+0.28}_{-0.30}\) days, which is one day faster than the value fitted in the discovery paper of α Cen B b (37.80 ± 0.16; Dumusque et al. 2012). In this discovery paper, the activity was modeled by fitting sine waves at the rotational period of the star and its harmonics (\(P_{\text{rot}}/2, P_{\text{rot}}/3, P_{\text{rot}}/4\)), which does not always give the correct rotational period estimate (see Section 2.4 in Dumusque et al. 2011).

4. DISCUSSION AND CONCLUSION

In this paper, we estimate the stellar inclination for a moderate and a slow rotator: HD 189733 with \(v\sin i \sim 3\) km s\(^{-1}\) and α Cen B with \(v\sin i \lesssim 1.15\) km s\(^{-1}\), respectively. This stellar inclination is derived with a new approach that uses the results of α Cen A could be used; however, one reference star is often not enough for high photometric precision.
the SOAP 2.0 activity simulation to fit the photometric, RV, BIS SPAN, and FWHM variations induced by stellar activity. In the two examples shown in this study, on average, 40 photometric and/or spectroscopic measurements covering two rotational period of the star are enough to recover the stellar inclination. This is much less that the number of measurements required to derive stellar inclination using asteroseismology, which is the only other technique to be able to measure inclinations for rotators slower than 2–2.5 km s\(^{-1}\). In our analysis, the stellar inclination can be obtained when rotators slower than 2–2.5 km s\(^{-1}\), as is the case for \(\alpha\) Cen B.

In the case of HD 189733, our estimate of the stellar inclination \(i = 84^{+16}_{-26}\) deg can be used with a measurement of the spin–orbit angle to obtain the obliquity of the star–planet system. We confirm that the obliquity is small, \(\psi = 4^{+13}_{-5}\) deg, which was highly probable given the spin–orbit measurement that was very close to zero degrees (e.g., Triaud et al. 2009). In addition, we find that the active region responsible for the variation is a spot at a latitude of \(67^{+12}_{-8}\) deg, compatible with previous HST observations showing the occultation of spots by the transiting planet orbiting HD 189733 (Pont et al. 2007).

For \(\alpha\) Cen B, we find a stellar inclination of \(45^{+8}_{-19}\) deg, which excludes the rotational spin of \(\alpha\) Cen B from being aligned with the orbital spin of the \(\alpha\) Cen binary system. In addition, assuming that the close-in planet \(\alpha\) Cen Bb is aligned with its host star, this estimate also excludes the transit of the planet.

In the two examples shown in this paper, either we analyze good photometric measurements and poor spectroscopic observations, or precise spectroscopic data but without photometry. The combination of photometric measurements at the tens of ppm precision and spectroscopic data at the meter per second level would allow us to better constrain the different stellar and active region parameters. The extended Kepler mission (K2), as well as CHEOPS (Broeg et al. 2013), TESS (Ricker et al. 2014), and PLATO (Rauer et al. 2013) will be able to deliver such data. Another alternative to simultaneous photometry would be to study the calcium activity index variation, which is obtained from spectroscopy and should be correlated with the photometric variation.

In our analysis, the stellar inclination can be obtained when one dominant active region is present on the stellar surface and if this active region evolves slowly in comparison with the stellar rotation period. The data from HD 189733 and \(\alpha\) Cen B studied in this paper show that this activity configuration is possible, and therefore it is reasonable to think that other stars will show a similar behavior. As another example, 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.

An important point in our analysis is that the temperature of the active region is fixed to the solar value. Looking at stars different from the Sun, HD 189733 and \(\alpha\) Cen B are both K1V dwarfs; there is no reason why the active region temperature for these stars should be similar. In models trying to reproduce stellar activity, the active region temperature is always degenerate with the active region size of first order, because the signal of a big active region with a small contrast

![Figure 6](image-url)
can be reproduced by a smaller active region with a higher contrast. However, the precise size and temperature of an active region are not important in our case, because the degeneracy between both does not significantly affect the estimation of the latitude of the active region, as well as the stellar inclination (see discussion in X. Dumusque et al. 2014, in press and, e.g., Lanza et al. 2009). We note however that 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 here.

Only the stellar inclination for HD 189733 can be compared to previous measurements. The next step will be to test if the stellar inclination found when fitting activity is compatible with other methods, like spectra fitting, CCF fitting, asteroseismology, or ZDI. This last method has the benefit of being able to infer a brightness map of the stellar surface for fast rotators, and therefore an idea on the position of the active region can be obtained (e.g., Donati et al. 2011, 2013; Skelly et al. 2010). An interesting test would be to see if there is a compatibility between the stellar inclination and active region latitude found by ZDI and by fitting stellar activity.

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REFERENCES

Ahlers, J. P., Seubert, S. A., & Barnes, J. W. 2014, ApJ, 786, 131
Aigrain, S., Pont, F., & Zucker, S. 2012, MNRAS, 419, 3147
Ammler-von Eiff, M., & Reiners, A. 2012, A&A, 542, A116
Ballot, J., Appourchaux, T., Toutain, T., & Guiraud, M. 2008, A&A, 486, 867
Barnes, J. W. 2009, ApJ, 705, 683
Barnes, J. W., Linscott, E., & Shporer, A. 2011, ApJS, 197, 10
Benomar, O., Bonfils, X., & Santos, N. C. 2012, A&A, 545, 109
Boisse, I., Bonfils, X., & Santos, N. C. 2010, A&A, 523, 488
Boisse, I., Eggenberger, A., Santos, N. C., et al. 2010, A&A, 523, 488
Bouchy, F., Udry, S., Mayor, M., et al. 2005, A&A, 444, L15
Boué, G., Montalto, M., Boisse, I., Oshagh, M., & Santos, N. C. 2013, A&A, 550, A53
Broeg, C., Fortier, A., Ehrenreich, D., et al. 2013, EPJWC, 47, 3005
Buchhave, L. A., Latham, D. W., Johansen, A., et al. 2012, Natur, 486, 375
Chaplin, W. J., Sanchis-Ojeda, R., Campanette, T. L., et al. 2013, ApJ, 766, 101
Claret, A. 2004, A&A, 428, 1001
Collier Cameron, A., Bruce, V. A., Miller, G. R. M., Triaud, A. H. M. J., & Queloz, D. 2010, MNRAS, 403, 151
Croll, B., Matthews, J. M., Rowe, J. F., et al. 2007, ApJ, 671, 2129
Désert, J.-M., Charbonneau, D., Demory, B.-O., et al. 2011, ApJS, 197, 14
Donati, J.-F., Bouvier, J., Walter, F. M., et al. 2011, MNRAS, 412, 2454
Donati, J.-F., Forveille, T., Collier Cameron, A., et al. 2006, Sci, 311, 633
Donati, J.-F., Gregory, S. G., Alencar, S. H. P., et al. 2013, MNRAS, 436, 881
Dumusque, X., Boisse, I., & Santos, N. C. 2014, ApJ, 796, 132
Dumusque, X., Pepe, F., Lovis, C., et al. 2012, Natur, 491, 207
Dumusque, X., Santos, N. C., Udry, S., Lovis, C., & Bonfils, X. 2011, A&A, 527, A82
Fabrycky, D., & Tremaine, S. 2007, ApJ, 669, 1298
Fabrycky, D. C., & Winn, J. N. 2009, ApJ, 696, 1230
Fares, R., Donati, J.-F., Moutou, C., et al. 2010, MNRAS, 406, 409
Gelman, A., Carlin, J. B., Stern, H. S., & Rubin, D. B. 2004, Bayesian Data Analysis (London: Chapman and Hall)
Gillett, S. L. 1988, AJ, 96, 1967
Gizon, L., & Solanki, S. K. 2003, ApJ, 589, 1009
Gray, D. F. 2008, The Observation and Analysis of Stellar Photospheres (Cambridge: Cambridge Univ. Press)
Groot, P. J. 2012, ApJ, 745, 55
Haario, H., Saksman, E., & Taneminen, J. 2001, Bernoulli, 7, 223
Hale, A. 1994, AJ, 107, 306
Henry, G. W., & Winn, J. N. 2008, AJ, 135, 68
Hirano, T., Sanchis-Ojeda, R., Takeda, Y., et al. 2012, ApJ, 756, 66
Hirano, T., Sanchis-Ojeda, R., Takeda, Y., et al. 2014, ApJS, 783, 9
Huber, D., Carter, J. A., Barbieri, M., et al. 2013, Sci, 342, 331
Jensen, E. L. N., & Akeson, R. 2014, Natur, 511, 567
Kervella, P., Thévenin, F., Ségransan, D., et al. 2003, A&A, 404, 1087
Lai, D., Foucart, F., & Lin, D. N. C. 2011, MNRAS, 412, 2790
Lanza, A. F., Boisse, I., Bouchy, F., Bonomo, A. S., & Moutou, C. 2011, A&A, 533, A44
Lanza, A. F., Pagano, I., Leto, G., et al. 2009, A&A, 493, 193
Lendl, M., Triaud, A. H. M. J., Anderson, D. R., et al. 2014, A&A, 568, A81
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Natur, 380, 606
Lockwood, G. W., Skiff, B. A., Henry, G. W., et al. 2007, ApJS, 171, 260
Lund, M. N., Lundkvist, M., Silva Aguirre, V., et al. 2014, A&A, 570, 54
McLaughlin, D. B. 1924, ApJ, 60, 22
Meunier, N., Desert, M., & Lagrange, A.-M. 2010, A&A, 512, A39
Moutou, C., Donati, J.-F., Savalle, R., et al. 2007, A&A, 473, 651
Nagasawa, M., & Ida, S. 2011, ApJ, 742, 72
Nutzman, P. A., Fabrycky, D. C., & Fortney, J. J. 2011, ApJL, 740, L10
Patil, A., Huard, D., & Fonnesbeck, C. J. 2010, J. Stat. Softw., 35, 1
Pepe, F., Mayor, M., Rupprecht, G., et al. 2002, Mngr, 110, 9
Pont, F., Gilliland, R. L., Moutou, C., et al. 2007, A&A, 476, 1347
Pont, F., Sing, D. K., Gibson, N. P., et al. 2013, MNRAS, 432, 2917
Poppenhaeger, K., Schmitt, J. H. M. M., & Wolk, S. J. 2013, arXiv e-prints
Pourbaix, D., Nidever, D., McCarthy, C., et al. 2002, A&A, 386, 280
Queloz, D., Allain, S., Mermilliod, J.-C., Bouchy, J., & Mayor, M. 1998, A&A, 335, 183
Queloz, D., Eggenberger, A., Mayor, M., et al. 2000, A&A, 359, L13
Rauer, H., Catala, C., Aerts, C., et al. 2014, ExA, 41
Reiners, A. 2006, A&A, 446, 267
Reinhold, T., Reiners, A., & Basri, G. 2013, A&A, 560, A4
Rice, J. B., & Strassmeier, K. G. 2000, A&AS, 147, 151
Ricker, G. R., Winn, J. N., Vanderspeck, R., et al. 2014, Proc. SPIE, 9143, 20
Rossiter, R. A. 1924, ApJ, 60, 15
Sanchis-Ojeda, R., Fabrycky, D. C., Winn, J. N., et al. 2012, Natur, 487, 449
Sanchis-Ojeda, R., & Winn, J. N. 2011, ApJ, 743, 61
Santos, N. C., Israelian, G., Mayor, M., et al. 2005, A&A, 437, 1127
Santos, N. C., Mayor, M., Naef, D., et al. 2002, A&A, 392, 215
Schlaufman, K. C. 2010, ApJ, 719, 602
Shapiro, A. I., Solanki, S. K., Krivova, N. A., et al. 2014, A&A, 569, 38
Shipor, A. Brown, T., Mazeh, T., & Zucker, S. 2012, NewA, 17, 309
Skelly, M. B., Donati, J.-F., Bouvier, J., et al. 2010, MNRAS, 403, 159
Szabó, G. M., Szabó, R., Benkő, J. M., et al. 2011, ApJL, 736, L4
Torres, G., Winn, J. N., & Holman, M. J. 2008, ApJ, 677, 1324
Triaud, A. H. M. J., Queloz, D., Bouchy, F., et al. 2009, A&A, 506, 377
Valenti, J. A., & Fischer, D. A. 2005, ApJS, 159, 141
Valenti, J. A., & Piskunov, N. 1996, A&AS, 118, 595
Van Eylen, V., Lund, M. N., Silva Aguirre, V., et al. 2014, ApJL, 782, 14
Vogt, S. S., Penrod, G. D., & Hatzes, A. P. 1987, ApJ, 328, 957
Winn, J. N. 2010, in Exoplanets, ed. S. Seager (Tucson, AZ: Univ. Arizona Press), 55
Winn, J. N., Fabrycky, D., Albrecht, S., & Johnson, J. A. 2010, ApJL, 718, L145
Winn, J. N., Holman, M. J., Henry, G. W., et al. 2007, AJ, 133, 1828
Winn, J. N., Johnson, J. A., Marcy, G. W., et al. 2006, ApJL, 653, L69
Wu, Y., & Murray, N. 2003, ApJ, 589, 605