Hunt for Starspots in HARPS Spectra of G and K Stars

Brett M. Morris1, H. Jens Hoeijmakers1,2, Daniel Kitzmann1, and Brice-Olivier Demory1

1 Center for Space and Habitability, University of Bern, Gesellschaftsstrasse 6, 3012 Bern, Switzerland
2 Observatoire de Genève, University of Geneva, Chemin des Maillettes, 1290 Sauverny, Switzerland

Received 2020 April 10; revised 2020 May 13; accepted 2020 May 13; published 2020 June 5

Abstract

We present a method for detecting starspots on cool stars using the cross-correlation function (CCF) of high-resolution molecular spectral templates applied to archival high-resolution spectra of G and K stars observed with the High Accuracy Radial Velocity Planet Searcher (HARPS)/HARPS-N. We report nondetections of starspots on the Sun even when the Sun was spotted, the solar twin 18 Scorpii, and the very spotted Sun-like star HAT-P-11, suggesting that Sun-like starspot distributions will be invisible to the CCF technique, and should not produce molecular absorption signals that might be confused for signatures of exoplanet atmospheres. We detect strong TiO absorption in the T Tauri K-dwarfs LkCa 4 and AA Tau, consistent with significant coverage by cool regions. We show that despite the nondetections, the technique is sensitive to relatively small spot coverages on M dwarfs and large starspot areas on Sun-like stars.

Unified Astronomy Thesaurus concepts: Stellar activity (1580); High resolution spectroscopy (2096); Starspots (1572); Stellar magnetic fields (1610)

1. Introduction

Molecular band modeling (MBM) is a technique for measuring starspot coverage and temperatures (see, e.g., Neff et al. 1995; O’Neal et al. 1996, 1998, 2001, 2004; Morris et al. 2019). The MBM technique seeks to describe spectra of active stars as linear combinations of warm (photospheric) and cool (starspot) stellar spectrum components. One useful tracer molecule is TiO, which forms at temperatures <4000 K, so cool starspots near or below this temperature will feature TiO absorption, while the rest of the photosphere of a G or K star will not (Vogt 1979; Ramsey & Nations 1980).

MBM is challenging for several reasons. The size of the expected signal generated by TiO absorption is exceptionally small, because Sun-like stars are typically <1% spotted and the <1% of the photosphere that is covered in spots is intrinsically dimmer than the rest of the photosphere by ≈30% (Solanki 2003). In addition, weak TiO absorption features can be degenerate with continuum normalization over the small wavelength ranges where the TiO absorption is greatest. In addition, all inferences from MBM stem from relying on inaccurate models, for example, due to incomplete line lists. Thus at modest spectral resolutions and signal-to-noise ratios (S/Ns), only the most spotted stars will generate sufficient TiO absorption to be detected confidently with MBM (see discussion in Morris et al. 2019).

However, the need for constraints on the starspot covering fractions of planet-hosting stars continues to grow as we seek to observe the transmission and day-side spectra of Earth-sized exoplanets (see, e.g., Ducrot et al. 2018; Rackham et al. 2018; Morris et al. 2018a; Wakeford et al. 2019). The spectral features generated by exoplanet atmospheres may be degenerate with the signatures of starspots, which also vary in time and wavelength primarily because of the stellar rotation. Therefore, the presence of starspots potentially hinders the interpretation of exoplanet observations. If we seek to measure starspot coverages with sufficient precision to mitigate the effects of starspots we likely need to move beyond MBM.

An analogous contrast-ratio problem occurs when detecting the emission or transmission spectra from exoplanet atmospheres, which has been addressed using the cross-correlation (CCF) technique applied to high-resolution spectroscopy (Snellen et al. 2010; Brogi et al. 2012). The CCF is sensitive to both strong and weak absorption features that occur at all wavelengths throughout the spectrum of the planet, constructively coadding the absorption lines when a template spectrum is matched with the observed spectrum at the correct Doppler velocity.

In this work, we seek to use high-resolution (R ∼ 115,000) spectra from the High Accuracy Radial Velocity Planet Searcher (HARPS; Mayor et al. 2003) and HARPS-North (HARPS-N) of bright, nearby stars to measure their spot coverages via the cross-correlation function (CCF). In Section 2 we construct template spectra for TiO, CO, and H2O. In Section 3 we present simulated observations of spotted stars and examine the significance of spot detections with the cross-correlation technique. In Section 4 we examine which portions of HARPS spectra are sensitive to each molecule given imperfect line lists, and search for TiO absorption in the spectra of the Sun, 18 Scorpii, HAT-P-11, and two T Tauri stars. We briefly conclude in Section 5.

2. Template Construction

We use the library of stellar atmospheric structures published by Husser et al. (2013). The structures are based on calculations with the state-of-the-art PHOENIX stellar atmosphere model (Hauschild & Baron 1999). For this work, we extract the basic structures (temperature–pressure profiles) from this library for a surface gravity of log g = 4.50 and solar elemental abundances. To approximate the atmospheric conditions within the starspots, we use structures for different stellar effective temperatures from 4000 to 2500 K.

Based on the temperature–pressure profiles from the PHOENIX library, we calculate theoretical template emission spectra using our Helios-o spectrum calculator. For emission spectra, Helios-o employs a general discrete
ordinate radiative transfer model based on the CDISORT code (Hamre et al. 2013). We use eight streams to compute the emission spectra in this study.

To determine the chemical composition we employ the fast equilibrium chemistry code FastChem published by Stock et al. (2018). The solar elemental abundances are taken from Asplund et al. (2009).

Collision-induced continuum absorption of He–H, H$_2$–H$_2$, and H$_2$–He pairs is included using data from the HITRAN database (Karman et al. 2019). The description for the continuum cross-section of H$^-$ is taken from John (1988).

To generate the templates for TiO, we use absorption coefficients based on line lists from the Exomol database (McKemmish et al. 2019). To generate the template for water, we use absorption coefficients from Barber et al. (2006).

The theoretical, high-resolution spectra are calculated within the spectral range of HARPS with a constant step size of 0.03 cm$^{-1}$ in wavenumber space.

3. Simulated Observations

3.1. Definition of the CCF

We define the CCF for an observed spectrum $x$, given a template spectrum evaluated at a specific velocity $T(v)$,

$$\text{CCF} = \sum_i x_i T_i(v),$$

where we have normalized the template such that it is positive in molecular absorption features and near-zero in the continuum, and

$$\sum_i T_i(v) = 1.$$

This definition of the CCF can be interpreted as a mean of the flux in each echelle order weighted by the values of the spectral template. When the velocity $v$ is incorrect and/or the template does not match the observed spectrum, the weighted-mean flux is near unity (continuum). When the velocity is correct and the template matches absorption features in the observed spectrum, the absorption features in the spectrum align with the inverse absorption features in the template, and the weighted-mean flux is less than one. We consider detections of molecules with the CCF to be significant if the CCF decrement at the correct radial velocity of the star is less than a few standard deviations smaller than the CCF continuum. In this way, the CCF yields a mean absorption line due to the molecule specified by the template at the velocity of the star.

We provide an open source Python package called hipparchus. The software and documentation are available online.$^3$

3.2. Simulations

We investigate whether one should expect significant detections of starspots with CCFs of high-resolution spectra by assembling a grid of simulated spectra. Each simulated spectrum contains 4000 wavelength bins, similar to a single echelle order of HARPS. We imagine a star that has uniform continuum emission from its photosphere, with no confounding absorption features. We give the star a spot covering fraction $f_s$.

and assign the spotted regions the absorption spectrum of a pure TiO atmosphere.

We simulate noisy spectra of spotted stars by: (1) combining the flux-weighted spectral template with a uniform continuum, given that the flux ratio of the spotted regions compared with the total spectrum will be

$$f_A = \frac{f_s B_s(T_{\text{spot}})}{(1 - f_s) B_s(T_{\text{eff}}) + f_s B_s(T_{\text{spot}})},$$

given a range of spot coverages from 0.1% to 50%; (2) adding random normal noise to the spotted spectra with S/N ranging from 10 to 10$^5$, representing low S/N spectra through very deeply stacked spectra; (3) taking the CCF of the spectral template with the observed noisy, spotted spectra; and (4) computing the amplitude of the CCF peak in relation to the scatter about the continuum.

We plot the S/N curves for the observed CCF as a function of the spot coverage and each spectrum’s S/N in Figure 1.

Figure 1. S/N of the CCF (colored contours) as a function of the S/N of the simulated spectrum, and the spot coverage $f_s$ in the simulated spectrum, for a Sun-like star with $T_{\text{eff}} = 3000$ K (upper) and for an M dwarf with $T_{\text{eff}} = 2500$ K (lower). A typical, high-quality HARPS spectrum of a bright Sun-like star has S/N $\approx 300$, and Proxima Centauri typically has S/N $\approx 200$. 

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$^3$ https://github.com/bmorris3/hipparhus
Each contour represents the S/N of the peak in the CCF for a given combination of the stellar spectral S/N and spot coverage $f_S$. The upper plot shows the results for a Sun-like star with $T_{\text{eff}} = 5770$ K and $T_{\text{spot}} = 3000$ K, and the lower plot represents an M star with $T_{\text{eff}} = 3000$ K and $T_{\text{spot}} = 2500$ K.

We focus first on the Sun-like case in the upper panel of Figure 1. Note that for a typical HARPS spectrum of a bright star with $S/N \sim 300$, and a Sun-like spot coverage $f_S < 5 \times 10^{-3}$, the CCF peak has $S/N < 3$. In other words, Sun-like spot coverages on Sun-like stars should be undetectable with the CCF in individual exposures. If we imagine a bright Sun-like star with 10% spot coverage and HARPS spectra with $S/N \sim 300$, the CCF technique is expected to detect starspots at $5\sigma$ confidence.

The CCF signal is more significant as one inspects stars with smaller $T_{\text{eff}}$ and less extreme (warmer) spot temperatures. For the M dwarf in the lower panel of Figure 1, which has a similar effective temperature to Proxima Centauri and $T_{\text{spot}} = 2500$ K, spots are more readily detectable via the CCF. Proxima Centauri is routinely observed by HARPS with $S/N \sim 200$, so watery spot coverages as small as $f_S = 0.01$ could be detectable at $5\sigma$ if they were present.

4. Hunting for Spots

4.1. Testing the TiO line List

Figure 2 shows the CCF between an observed spectrum of Proxima Centauri, an M5V star, with a $T_{\text{eff}} = 3000$ K (left) and 4000 K (right). Each panel represents one HARPS echelle order, with the central wavelength noted in the title. In black we plot the weighted-mean absorption profile CCF parameterization outlined in Section 3.1.

TiO is detected with $S/N > 3$ in most echelle orders, peaking at $S/N \sim 22$ for the TiO template with the correct effective temperature. The order of magnitude variation in the $S/N$ for Proxima Centauri, which clearly has significant TiO absorption in every echelle order redward of 4500 Å (see Figure A1 in the Appendix), demonstrates that the line list is imperfect, in agreement with Hoeijmakers et al. (2015).

4.2. Search for Cool Spots on Proxima Centauri

In addition to using Proxima Centauri as a control target to identify the orders where the TiO line list is the most reliable, we can search for cool spots on Proxima Centauri. Proxima

$T_{\text{eff}} = 5770$ K and $T_{\text{spot}} = 3000$ K, and the lower plot represents a M star with $T_{\text{eff}} = 3000$ K and $T_{\text{spot}} = 2500$ K.

We focus first on the Sun-like case in the upper panel of Figure 1. Note that for a typical HARPS spectrum of a bright star with $S/N \sim 300$, and a Sun-like spot coverage $f_S < 5 \times 10^{-3}$, the CCF peak has $S/N < 3$. In other words, Sun-like spot coverages on Sun-like stars should be undetectable with the CCF in individual exposures. If we imagine a bright Sun-like star with 10% spot coverage and HARPS spectra with $S/N \sim 300$, the CCF technique is expected to detect starspots at $10\sigma$ confidence.

The CCF signal is more significant as one inspects stars with smaller $T_{\text{eff}}$ and less extreme (warmer) spot temperatures. For the M dwarf in the lower panel of Figure 1, which has a similar effective temperature to Proxima Centauri and $T_{\text{spot}} = 2500$ K, spots are more readily detectable via the CCF. Proxima Centauri is routinely observed by HARPS with $S/N \sim 200$, so watery spot coverages as small as $f_S = 0.01$ could be detectable at $5\sigma$ if they were present.

4. Hunting for Spots

4.1. Testing the TiO line List

Figure 2 shows the CCF between an observed spectrum of Proxima Centauri (HARPS program ID: 072.C-0488(E), PI: M. Mayor) and the TiO model spectra at 3000 K (left column, matching Proxima Centauri which has $T_{\text{eff}} \sim 3000$ K) and 4000 K (right column). Each panel represents one HARPS echelle order, with the central wavelength noted in the title. In black we plot the weighted-mean absorption profile CCF parameterization outlined in Section 3.1.

TiO is detected with $S/N > 3$ in most echelle orders, peaking at $S/N \sim 22$ for the TiO template with the correct effective temperature. The order of magnitude variation in the $S/N$ for Proxima Centauri, which clearly has significant TiO absorption in every echelle order redward of 4500 Å (see Figure A1 in the Appendix), demonstrates that the line list is imperfect, in agreement with Hoeijmakers et al. (2015).

4.2. Search for Cool Spots on Proxima Centauri

In addition to using Proxima Centauri as a control target to identify the orders where the TiO line list is the most reliable, we can search for cool spots on Proxima Centauri. Proxima has $T_{\text{eff}} = 2980 \pm 80$ K (Ribas et al. 2017), so we assume...
that dark starspots may have temperatures of \( \sim 2500 \text{ K} \) (Berdyugina 2005), and search for emission from these spots using the CCF of the spectrum with a template for water at 2500 K. After all, water has even been detected in sunspots (Wallace et al. 1995).

Figure 3 shows that no significant detections of water absorption are present in any of the spectral orders redward of 6000 Å, where the water spectrum has small absorption features (see Figure A1). The lack of detectable spots could indicate that there are few cool spots, or their temperature contrast is significantly different from \( \Delta T = 500 \text{ K} \), or the S/N of these spectra are insufficient to detect the relatively weak absorption lines from water.

### 4.3. Search for Sunspots

The umbrae of sunspots reach temperatures as low as \( \sim 4000 \text{ K} \) (Solanki 2003), and therefore we might expect a very spotted Sun to generate TiO absorption. Fortunately, there are also several Sun-observing spacecraft that have been imaging the Sun for decades, often simultaneously with HARPS observations of reflected sunlight via observations solar system targets, such as the Moon.

For several thousand publicly available lunar spectra from HARPS, we retrieve simultaneous Solar Dynamics Observatory (SDO) Helioseismic and Magnetic Imager (HMI) continuum intensity imaging of the Sun. We find that the Sun was most spotted during lunar HARPS observations on UTC 2015 November 2 (Program ID: 096.C-0210(A), PI: P. Figueira), when two major spot groups were on the Earth-facing solar hemisphere—see Figure 4.

We cross-correlate the solar spectrum with the 4000 K TiO template. We find no significant absorption in any of the nine observations which have S/N \( \geq 100 \) on that night, in any of the four echelle orders where the TiO line list is expected to
produce the strongest CCF signal based on the cross-correlation with the spectrum of Proxima Centauri.

4.4. Search for Starspots on 18 Sco

For more than 20 yr, 18 Scorpii has been studied as a solar twin (Porto de Mello & da Silva 1997), that is, a star with spectroscopic parameters exceptionally similar to the Sun’s (Cayrel de Strobel 1996). Hall & Lockwood (2000) and Hall et al. (2007) showed that 18 Sco has a seven year activity cycle that is similar to the Sun’s in terms of total irradiance variation. Joint asteroseismic and spectroscopic analyses have yielded highly precise measurements of the stellar radius and mass (Bazot et al. 2011, 2012; Li et al. 2012). Petit et al. (2008) used spectropolarimetry to show that its rotation period is 22.7 ± 0.5 days, only a few days shorter than solar, and more recently Bazot et al. (2018) used asteroseismology to suggest that the age of 18 Sco may be consistent with solar (though estimates have varied from 0.3 to 5.8 Gyr; Takeda et al. 2007; Tsantaki et al. 2013; Mittag et al. 2016). Even under intense scrutiny, this star continues to appear remarkably similar to the Sun, so one might expect 18 Sco to have spots like the Sun does.

18 Sco has been the subject of various radial velocity searches for exoplanets with HARPS. We gather 4000 archival HARPS spectra of 18 Sco collected since 2006 under various observing programs. We stack all spectra of 18 Sco together by shifting the wavelength axis of each spectrum to maximize the cross-correlation with the previous spectrum. The coadded spectrum has S/N ∼ 2200.

The CCF of the stacked HARPS spectra and the TiO and water emission templates are shown in Figure 5. Each curve represents the CCF of a single echelle order with the template. If TiO or water absorption were present in the coadded spectrum, there would be a negative absorption feature dipping below unity near the radial velocity of the star (v = 11.90 km s⁻¹), but no signal is detected.

In the case of the spectrum of 18 Sco, we have a Sun-like star with an unknown spot coverage and a coadded S/N ≈ 2200. The null detection of water and TiO in the stacked spectrum of 18 Sco given the simulations in Section 3 places an upper limit on the spot covering fraction f_S ≤ 4 × 10⁻³. This is smaller than the Sun’s most extreme spot coverages near solar maximum, f_S ≈ 5 × 10⁻³ (Morris et al. 2017b).

4.5. Search for the Spots of HAT-P-11

HAT-P-11 is an active K4V dwarf in the Kepler field with a transiting hot Neptune. Transits revealed frequent starspot occultations (Deming et al. 2011; Sanchis-Ojeda & Winn 2011), which yield approximate spot covering fractions f_S = 0.0–0.1 (Morris et al. 2017b). HAT-P-11 appears to have a ~10 yr activity cycle, and may be modestly more chromospherically active than planet hosts of similar rotation periods (Morris et al. 2017a). Recent ground-based photometry of spot occultations within the transit chord yielded spot coverage f_S = 0.14 (Morris et al. 2018b). Morris et al. (2019) model the spectrum of HAT-P-11 as a linear combination of the spectra of HD 5857 and Gl 705, giving the spots ΔT eff ≈ 250 K, similar to typical sunspot penumbra, finding a spot coverage consistent with previous measurements.

We cross-correlate 39 HARPS-N spectra of HAT-P-11 (Program ID: OPT15B_19, PI: D. Ehrenreich) with the TiO template at 4000 K in Figure 6. There is no significant absorption in the CCF due to TiO, despite HAT-P-11 being on average 100× more spotted than the Sun (Morris et al. 2017b).

4.6. Search for the Cool Regions of T Tauri Stars: LkCa 4 and AA Tau

LkCa 4 is a T Tauri star which is often classified as a K7 dwarf (Herbig et al. 1986). Gully-Santiago et al. (2017) used high-resolution near-infrared Immersion GRating Infrared Spectrograph (IGRINS) spectra to show that the stellar surface of LkCa 4 is in fact dominated by cool regions, covering 80% of the stellar surface with T cool ≈ 2700–3000 K. Hot regions make up the other 20% of the surface with T hot ≈ 4100 K.

We examine the CCF of the LkCa 4 HARPS spectrum (Program ID: 074.C-0221(A), PI: J. Bouvier) as a control to verify that TiO can be detected in stars earlier than M type, when they are known to be extremely spotted. Figure 7 shows the CCF, confirming strong absorption features due to TiO near T hot = 4000 K. The clear CCF signal confirms that indeed the star has significant coverage by regions cooler than the K7 spectral type assigned to this star.

AA Tau is a K5 dwarf, and also a T Tauri star. We cross-correlate the HARPS spectrum of AA Tau (Program ID: 074.C-0221(A), PI: J. Bouvier) with the TiO emission template at T hot = 4000 K. Again, we find evidence for significant absorption by TiO in the atmosphere of this K star, confirming that at least one other T Tauri star has significant coverage by cool regions, and that our CCF technique is performing as expected on a highly spotted control star.
5. Conclusion

Starspots on Sun-like stars are functionally invisible in HARPS/HARPS-N spectra when using TiO as a tracer. While the invisibility of starspots to the CCF technique may dismay starspot hunters, exoplanet hunters searching for molecular absorption in exoplanet atmospheres can be confident that the signals they detect come from the exoplanet rather than the star. Starspots should be an insignificant source of TiO absorption in the spectra of exoplanetary systems with FGK host stars. Of course, one could also disentangle the stellar and planetary signals with the difference in velocity between the star and the planet.

This work has been carried out in the framework of the PlanetS National Centre of Competence in Research (NCCR) supported by the Swiss National Science Foundation (SNSF). This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in A&AS 143, 23. This research has made use of NASA’s Astrophysics Data System. Based on observations made with ESO Telescopes at the La Silla Paranal Observatory. Based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundación Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

Facilities: ESO:3.6m, TNG.

Software: astropy (Astropy Collaboration et al. 2013, 2018), sunpy (SunPy Community et al. 2015), ipython (Pérez & Granger 2007), numpy (Van Der Walt et al. 2011), scipy (Jones et al. 2001), matplotlib (Hunter 2007), FastChem (Stock et al. 2018), CDISORT (Hamre et al. 2013), Helios-o (Bower et al. 2019).

Appendix

Spectral Templates

Figure A1 shows the resulting TiO spectral templates each normalized by their maximum flux.
Figure A1. Spectral templates for TiO, H$_2$O, and CO at four temperatures. TiO shows significant absorption bands throughout the HARPS bandpass at all temperatures, while water only deviates significantly from a blackbody at $T < 3000$ K. CO never deviates significantly from a blackbody in the temperature range and HARPS bandpass.

ORCID iDs

Brett M. Morris https://orcid.org/0000-0003-2528-3409
H. Jens Hoeijmakers https://orcid.org/0000-0001-8981-6759
Daniel Kitzmann https://orcid.org/0000-0003-4269-3311
Brice-Olivier Demory https://orcid.org/0000-0002-9355-5165

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