Are Starspots and Plages Co-located on Active G and K Stars?

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Abstract

We explore the connection between starspots and plages of three main-sequence stars by studying the chromospheric and photospheric activity over several rotation periods. We present simultaneous photometry and high-resolution (R ~ 31500) spectroscopy of KIC 9652680, a young, super-flare-producing G1 star with a rotation period of 1.4 days. Its Kepler light curve shows rotational modulation consistent with a bright hemisphere followed by a relatively dark hemisphere, generating photometric variability with a semi-amplitude of 4%. We find that KIC 9652680 is darkest when its S-index of Ca II H & K emission is at its maximum. We interpret this anti-correlation between flux and S to indicate that dark starspots in the photosphere are co-located with the bright plages in the chromosphere, as they are on the Sun. Moving to lower masses and slower rotators, we present K2 observations with simultaneous spectroscopy of EPIC 211928486 (K5V) and EPIC 211966629 (K4V), two active stars in the 650 Myr old open cluster Praesepe. The K2 photometry reveals that both stars have rotation periods of 11.7 days, while their flux varies by 1 and 2% respectively, their Ca II H & K S-indices seem to hold relatively constant as a function of rotational phase. This suggests that extended chromospheric networks of plages are not concentrated into regions of emission centered on the starspots that drive rotational modulation, unlike KIC 9652680. We also note that the Ca II emission of EPIC 211928486 dipped and recovered suddenly over the duration of one rotation, suggesting that the evolution timescale of plages may be of order the rotation period.

Key words: stars: activity – stars: chromospheres – stars: fundamental parameters – starspots – stars: rotation

1. Introduction

Sunspots are regions of the solar photosphere where convection is suppressed by strong magnetic fields (Spruit 1977; Solanki 2003). These spots typically account for a small portion of the photosphere, covering only a fraction of a percent of the solar hemisphere (Howard et al. 1984). Approximately a thousand kilometers above the photosphere lies the chromosphere. Observing the chromosphere in the cores of the Ca II H & K lines reveals regions of bright emission known as plages. Plages show a latitude dependence similar to sunspots, and the largest solar plages are typically spatially associated with dark sunspots. However, smaller plages often appear without cospatial sunspots, although at scales larger than 4 arcsec darker photospheric features, due to flux emergence, are observed to be cospatial with Ca II enhanced sites (Hall 2008; Guglielmino et al. 2010; Mandal et al. 2017).

For distant stars, we are not privy to the same spatially resolved view. However, we can probe the connection between plages and starspots with time resolved spectroscopy and precision photometry. Plages are bright in the cores of the Ca II H & K features, while the broadband Kepler flux of a star, for example, is diminished when starspots face the observer (McQuillan et al. 2013, 2014;Walkowicz & Basri 2013; Douglas et al. 2014, 2016, 2017). In this work, we present a study of chromospheric Ca II H & K emission and photospheric starspot absorption on the rotation period timescale for three stars to address the question: are plages and starspots co-located on active G and K stars?

Synoptic observations of chromospheric emission in Ca II H & K among many stars suggest that the emission variations of older, Sun-like stars increase with the stellar photometric variation; whereas young stars tend to become fainter overall as emission from plages increases (Radick et al. 1998, 2018). These observations are based on long-term monitoring campaigns of many stars with multi-epoch photometry and spectroscopy spread over years, and represent the effect of the activity cycle on the total irradiance and chromospheric emission of each star.

We collected simultaneous ground-based photometry and spectroscopy of young G star KIC 9652680 over the course of several rotations. This star is remarkable for having 8% amplitude flux variations in the Kepler band — see Figure 1 — and for producing a “super-flare” (Notsu et al. 2015a). The largest observed flare of KIC 9652680 reached 1034 erg, or roughly 100× more energy than the Carrington event (Carrington 1859; Neuhauser & Hambaryan 2014; Notsu et al. 2015b). We present a similar analysis of the chromospheric and photospheric activity on this possible proxy for the young Sun.

We also present simultaneous K2 photometry and spectroscopy of two mid-K dwarfs in the young (650 Myr), nearby Praesepe cluster (M44). Confinéd to the ecliptic, the K2 mission provided precision photometry of Praesepe members in Campaigns 5 and 16 (Howell et al. 2014). Campaign 16 was remarkable for being a “forward-looking” campaign, meaning...
that simultaneous observations were possible from ground-based observatories. We took advantage of that opportunity and collected more than 30 hr of high-resolution spectra of EPIC 211928486 and EPIC 211966629 throughout the campaign, allowing us to study the connection between chromospheric and photospheric activity. These two Praesepe members may be young proxies for the well-studied mid-K dwarf HAT-P-11 (Deming et al. 2011; Sanchis-Ojeda & Winn 2011; Morris et al. 2017a, 2017b, 2018a).

We describe our spectroscopy of all targets in Section 2. We measure the rotation periods and flux-activity correlation of the young G star in Section 3, and do the same for two K-dwarfs in Section 4. We discuss the results in Section 5 and conclude with Section 6.

2. APO/ARCES Spectroscopy

The ARC Echelle Spectrograph (ARCES) on the ARC 3.5 m Telescope at Apache Point Observatory is an $R \approx 31,000$ cross-dispersed spectrograph. This analysis closely follows the procedure of Morris et al. (2017a) and makes use of its software (Morris & Dorn-Wallenstein 2018). After stacking all exposures on a given night, we reduce the raw ARCES spectra with TRAP methods to subtract biases, remove cosmic rays, normalize by the flat field, and do the wavelength calibration with exposures of a thorium-argon lamp.\footnote{An ARCES data reduction manual by J. Thorburn is available at \url{http://astronomy.nmsu.edu:8000/apo-wiki/attachment/wiki/ARCES/Thorburn_ARCES_manual.pdf}.} We fit the spectrum of an early-type star with a high-order polynomial to measure the blaze function, and we divide the spectra of each star by the polynomial fit to normalize each spectral order.

Next, the normalized spectra must be shifted in wavelength into the rest-frame by removing their radial velocities (RVs). We remove the RV by maximizing the cross-correlation of the ARCES spectra with PHOENIX model atmosphere spectra (Husser et al. 2013).

3. Young G Star: KIC 9652680

3.1. Stellar Properties

KIC 9652680 is a rapidly rotating, chromospherically active, G-type star. Rapid rotation is often interpreted as a sign of youth, but can also be caused by a tidally interacting companion (e.g., a RS CVn type binary, Eaton & Hall 1979) or as a result of blue straggler formation (e.g., mass accretion Bailyn 1995), though these scenarios require the presence of a stellar companion. According to the second data release of the European Space Agency’s Gaia Mission (DR2 Gaia Collaboration et al. 2018b), this star has RV error 3.42 km s$^{-1}$ from 12 observations (Katz et al. 2018; Soubiran et al. 2018); we measured RVs from our 13 ARCES observations and found a standard deviation of $\approx$1 km s$^{-1}$. These low RV values are consistent with KIC 9652680 being a single, rapidly rotating star, which is suggestive of youth.

Its age is further corroborated by the presence of strong Li absorption at 6707.8 Å, where $\alpha$(Li) = 3.39 dex (Honda et al. 2015), which is unexpected in the alternative scenarios. Considering its rotation and activity via the gyrochronology and activity–age relations and cluster activity data presented in Mamajek & Hillenbrand (2008), together with the lithium data for the Pleiades provided by Bouvier et al. (2018), KIC 9652680 appears to be at least as young as the Pleiades, or $\lesssim$110–125 Myr (Gaia Collaboration et al. 2018a; Stauffer et al. 1998).

Its rapid rotation, and resulting $v \sin i$ $\approx$ 39 km s$^{-1}$, complicates our spectroscopic characterization of KIC 9652680. However, if it is in fact a young star on or near the zero-age main-sequence, then its absolute magnitude or luminosity is actually a powerful indicator of metallicity. We therefore compare KIC 9652680 to other young stars from Gaia DR2 in order to constrain its metallicity.

Figure 2 shows the Gaia DR2 color–magnitude diagram (CMD; $G_{BP} - R_{BP}$ versus $M_G$) for chromospherically active (i.e., relatively young stars, with $\log R'_{HK} < -4.7$ dex corresponding to ages under 2 Gyr), solar-type stars observed with Keck/HIRES by the California Planet Survey (CPS) and characterized with Spectroscopy Made Easy (SME; Valenti & Piskunov 1996; Valenti & Fischer 2005; Piskunov & Valenti 2017) by Brewer et al. (2016) with the procedures outlined in Brewer et al. (2015). We excluded stars with $\log g < 4.3$ dex to ensure that we are focusing on un-evolved dwarf stars, and included stars with HIRES spectra with S/N $> 70$ per pixel to select those with precise spectroscopic properties, and focused on stars with precise DR2 photometry ($\sigma < 0.05$ mag) with parallax-inverted distances within 200 pc to minimize the effect of interstellar reddening and extinction on the CMD. The majority of these stars are presumably single, and on or near the main-sequence. The stars in Figure 2 are color-coded according to their spectroscopic metallicities; as expected, metallicity explains the majority of the apparent scatter in this CMD, and the higher metallicity stars follow a more luminous track in the CMD. KIC 9652680 is found at the top of the main-sequence envelope among a string of 8 stars with the following properties (median ± standard deviation): $[\text{Fe/H}] = +0.205 \pm 0.024$ dex, $\log g = 4.475 \pm 0.023$ dex, and $T_{\text{eff}} = 5844 \pm 90$ K. Fitting a quadratic function to $(G_{BP} - R_{BP})$ versus $T_{\text{eff}}$ for this sequence, KIC 9652680 has $T_{\text{eff}} = 5900 \pm 20$ K, where the uncertainty is calculated as the rms of the spectroscopic values about our quadratic color–$T_{\text{eff}}$ relation.
such star with placement of KIC 9652680 in this CMD is indicative of its metallicity, as any photometrically single and have evolved in isolation as single stars, then the points have HIRES by the California Planet Survey and characterized with SME by Brewer (2016). Stars are color-coded according to their metallicity, where red points have [Fe/H] < 0.0 dex, cyan points have [Fe/H] > +0.16 dex, and gray points have intermediate metallicities. Assuming all stars shown are photometrically single and have evolved in isolation as single stars, then the placement of KIC 9652680 in this CMD is indicative of its metallicity, as any such star with log $R'_{HK}$ ≈ −4.0 dex must be very young and on or near the zero-age main-sequence. The stars HD 222986 and HD 101847, marked with cyan-shaded squares, bracket KIC 9652680 in this diagram, indicating that it likely has properties intermediate to their values of $T_{\text{eff}}$ = 5858 and 5948 K and [Fe/H] = +0.26 and +0.23 dex, respectively, with log $g$ = 4.47 dex.

The two stars with $(G_{BP} - G_{RP})$ closest to KIC 9652680 (marked as cyan-colored squares in Figure 2), and which happen to bracket it, have the following spectroscopic properties: HD 222986 has $T_{\text{eff}}$ = 5858 K, log $g$ = 4.47 dex, [Fe/H] = +0.26 dex, $v$ sin $i$ = 5.8 km s$^{-1}$, and log $R'_{HK}$ = −4.35 dex; HD 101847 has $T_{\text{eff}}$ = 5948 K, log $g$ = 4.47 dex, [Fe/H] = +0.23 dex, $v$ sin $i$ = 5.6 km s$^{-1}$, and log $R'_{HK}$ = −4.43 dex; The $v$ sin $i$ values are much lower than KIC 9652680, which allowed Brewer et al. (2016) to measure precise stellar properties from the HIRES spectra. According to the Mamajek & Hillenbrand (2008) activity–rotation–age relation, their chromospheric emission indices imply ages of 105 and 227 Myr, which is young enough to assume negligible main-sequence evolution through the CMD for these stars. From this analysis, we find the following properties for KIC 9652680 from our Gaia–CPS analysis: $T_{\text{eff}}$ = 5900 K (based on the color–$T_{\text{eff}}$ relation), log $g$ = 4.47 dex (based on these two stars), and [Fe/H] = +0.21 dex (based on the median for the 8 star sequence).

Next, we analyzed our 13 ARCES observations of KIC 9652680 with SME version 522 using the Valenti & Fischer (2005) strategy, which focuses on the 5164–5190Å region centered on the pressure-sensitive Mg i b triplet and seven additional segments spanning 6000–6180 Å. We ran SME with $T_{\text{eff}}$, log $g$, the global metallicity parameter [M/H], and $v$ sin $i$ as free parameters; this yielded $T_{\text{eff}}$ = 6022 ± 99 K, log $g$ = 4.40 ± 0.1 dex, [M/H] = +0.17 ± 0.08 dex, and $v$ sin $i$ = 39 ± 0.5 km s$^{-1}$.

The $T_{\text{eff}}$ from our ARCES spectra is warmer than our Gaia–CPS value by 122 K (1.2σ using the spectroscopic $T_{\text{eff}}$ dispersion for the uncertainty), and this discrepancy and the high dispersion in fitted parameters is likely due to the challenges of analyzing spectra of rapidly rotating stars, especially with such a restricted wavelength range compared to the full optical spectrum observed with ARCES. For this work, we will take the results from our Gaia–CPS analysis as our final adopted stellar properties for KIC 9652680, and assign an uncertainty to $T_{\text{eff}}$ of 100 K to reflect the discrepancy with the SME result. The final values are listed in Table 1.

### Table 1

| Stellar Parameters | KIC 9652680 | EPIC 211928486 | EPIC 211966629 |
|--------------------|-------------|----------------|----------------|
| $T_{\text{eff}}$ [K] | 5900 ± 100  | 4408 ± 100     | 4484 ± 100     |
| log $g$            | 4.47        | 4.66           | 4.66           |
| [Fe/H]             | +0.21       | +0.12          | +0.12          |
| $v$ sin $i$ [km s$^{-1}$] | 39          | 2 ± 2         | 3 ± 2          |
| $P_{\text{rot}}$ [day] | 1.41 ± 0.01 | 11.8 ± 0.1    | 11.6 ± 0.2     |
| log $R'_{HK}$       | −3.92 ± 0.03| −4.16 ± 0.03  | −4.11 ± 0.02   |
| $f_{S,\text{min}}$  | 0.26        | 0.041±0.046    | 0.061–0.083    |

#### 3.2. Rotational Modulation

The Kepler PDCSAP light curve of the G1V star KIC 9652680 shows rotational modulation consistent with a bright hemisphere followed by a relatively dark hemisphere, generating photometric variability with semi-amplitude 4%, see Figure 1. We compute the rotation period and its uncertainty from the Kepler observations by taking the mean and difference between the Lomb–Scargle periodogram and the first peak in the autocorrelation function, finding $P_{\text{rot}}$ = 1.41 ± 0.01 day.

We observed KIC 9652680 over five nights in the SDSS $u$ and g bands with FlareCam on the ARCSAT 0.5 m telescope at Apache Point Observatory; see Figure 3. We computed differential photometry with three neighboring comparison stars—our ARCSAT photometry pipeline is open source and available online.8

We model the flux variations in both bands simultaneously with the multiband Lomb–Scargle (MLS) technique of VanderPlas & Ivezic (2015) with two sinusoidal terms (red curves). MLS estimates the relative flux of the star in each band assuming the periodic signals have the same phase but different amplitudes in each band. The flux variations that we observed with ARCSAT show similar rotational modulation amplitude in the SDSS g band compared to the Kepler semi-amplitude of 4%. The MLS prediction allows us to interpolate between observed fluxes to estimate the flux of the star at the epochs of each ARCES spectrum, to search for correlations between the S-index and broadband flux of the host star.

#### 3.3. Minimum Spot Covering Fractions via Flux Deficit

We can compute the minimum spot covering fractions required to produce the observed rotational modulation from the flux deficit, via

$$f_{S,\text{min}} = \frac{1 - \min \mathcal{F}}{1 - c}$$

where $\mathcal{F}$ is the stellar flux, and $c$ is the spot contrast (where $c = 0$ is a spot with the same intensity as the photosphere and $c = 1$ is a spot that is perfectly dark). Assuming the same

8 https://github.com/bnorris3/arcsat_monitoring
average contrast as sunspots, \( c = 0.3 \) (see, e.g., Morris et al. 2017b), we compute spot covering fraction from the \emph{Kepler} light curve, and find \( f_{S,\text{min}} \geq 0.17 \). This large spot covering fraction is roughly consistent with observations of young G stars like EK Draconis, for example, which has \( f_S = 0.25-0.40 \) according to TiO molecular band absorption measurements by O’Neal et al. (2004).

### 3.4. Flux-S-index Correlation

Figure 4 shows an anti-correlation between the photosphere flux in SDSS \( g \) and the chromospheric emission from KIC 9652680. We interpret this anti-correlation as evidence for spatial association between regions of chromospheric activity and the starspots in the photosphere below, as is observed on the Sun. As the spots and their associated plages rotate into view, the S-index increases and SDSS \( g \) flux decreases in sync.

We note that the minimum in KIC 9652680’s observed S-index does not correspond to the minimum possible S-index for a star of KIC 9652680’s color (\( S \gtrsim 0.15 \)), (see, e.g., Isaacson & Fischer 2010). We still observe significant chromospheric emission when the dark spot which dominates the rotational modulation is out of view—thus the network of plages must extend around all rotational phases of the star,
while a significant component of the chromospheric emission is associated with the dark spot.

4. Mid-K Dwarfs: EPIC 211928486 and EPIC 211966629

4.1. Stellar Properties

EPIC 211928486 and EPIC 211966629 are members of the benchmark open cluster Praesepe (M44, NGC 2632) with an age of 620−790 Myr (Brandt & Huang 2015; Choi et al. 2016; Cummings et al. 2017; Gaia Collaboration et al. 2018a; Gossage et al. 2018), a metallicity of [Fe/H] = +0.12−0.16 dex (although various results in the literature range from +0.038 to +0.27 dex; see Table 4 in Cummings et al. 2017), and suffers little if any interstellar reddening and extinction (E(B−V) = 0.027, Taylor 2006). Allen & Strom (1995) classified these stars with low-resolution optical spectra as K5V and K4V, respectively.

More recently, each star was observed with the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Luo et al. 2015) and stellar properties and RVs were measured and provided in the third data release. EPIC 211928486 and EPIC 211966629 were both classified as K5 dwarfs with the following properties: $T_{\text{eff}} = 4413$ K and $4487$ K, $\log g = 4.69$ dex and 4.49 dex, and $[\text{Fe/H}] = +0.08$ dex and $-0.03$ dex.

Each star appears to be effectively single. First, their Gaia DR2 RVs have small errors ($\sigma \leq 1$ km s$^{-1}$) and are consistent with the cluster’s bulk velocity. We also measured relative RVs between the two stars on seven separate nights (six in 2017 December, one in 2018 February), and found that they are constant to within 0.5 km s$^{-1}$. Second, EPIC 211928486 is within 0.02 mag of, and EPIC 211966629 is 0.10 mag brighter than, the Praesepe single-star main-sequence, according to the Gaia DR2 CMD for Praesepe using the membership from Gaia Collaboration et al. (2018a). We attribute this modest apparent magnitude enhancement to the cluster’s depth (at 186 pc, a cluster with an angular size of 2.5 has a physical radius of $\sim 8$ pc; this translates to a $\pm 0.09$ mag distance modulus effect); alternatively, there could be a $\sim$M3V companion, but it would likely be non-interacting due to the observed low RV dispersion.

While Andrae et al. (2018) provided $T_{\text{eff}}$ values inferred from the Gaia DR2 photometry, we opted to re-calibrate the DR2 $T_{\text{eff}}$ scale using the benchmark sample of K and M dwarfs characterized with interferometry and bolometric fluxes by Boyajian et al. (2012) by fitting a quadratic function between the DR2 color ($G_{\text{BP}} - G_{\text{RP}}$) and $T_{\text{eff}}$ for these stars. We adopted the Taylor (2006) value of $E(B−V) = 0.027$ and used it to de-redden the DR2 photometry for EPIC 211928486 and EPIC 211966629, then infer $T_{\text{eff}} = 4408$ K and 4484 K, respectively, whereas the DR2 catalog listed values of 4683 K and 4922 K. Our values are much closer to the LAMOST DR3 values, being only 5 and 3 K cooler, whereas the DR2 catalog values are 275 K and 438 K warmer than our values. Combining our results with LAMOST, we conclude that EPIC 211966629 is only 75 K warmer than EPIC 211928486.

We also fit the APO/ARCES spectra for these stars with SME, despite the fact that the Valenti & Fischer (2005) strategy we followed is optimized for late-F to early-K dwarfs. According to Gaia Collaboration et al. (2018a), Praesepe’s DR2 CMD can be approximately described with a PARSEC isochrone (Bressan et al. 2012; Marigo et al. 2017) with an age of 700 Myr and [Fe/H] = +0.12 dex. We decided to ignore the $V$ b order (5164−5190 Å) which is challenging to accurately normalize for mid-K dwarfs, then fixed the metallicity to [Fe/H] = +0.12 dex, and fixed $\log g$ to 4.65 dex based on this isochrone. We fit the spectrum for $T_{\text{eff}}$ and $v\sin i$, then combined the results from the multiple observations as the median and standard deviation, and report the following properties: for EPIC 211928486, $T_{\text{eff}} = 4510 \pm 28$ K and $v\sin i = 2 \pm 2$ km s$^{-1}$; for EPIC 211966629, $T_{\text{eff}} = 4592 \pm 19$ K, and $v\sin i = 3 \pm 2$ km s$^{-1}$, where the $v\sin i$ error is primarily due to the uncertain spectral resolution at each epoch, as well as the macroturbulent broadening. Here, we found that EPIC 211966629 is 82 K warmer than EPIC 211928486, which is nearly identical to the relative $T_{\text{eff}}$ we found from our photometric calibration and the LAMOST DR3 value, although the spectroscopic $T_{\text{eff}}$ values are systematically warmer than these other results by $\sim 100$ K. We set this offset as our $T_{\text{eff}}$ uncertainty, and adopt the photometric results as our final values. For metallicity, we adopt [Fe/H] = +0.12 $\pm$ 0.05 dex (a value commonly cited for the cluster, with uncertainty estimated to encompass most modern estimates of the cluster’s metallicity). For surface gravity, we set $\log g = 4.66$ dex, taken from the 700 Myr PARSEC isochrone with this metallicity at these temperatures. These final values are listed in Table 1.

4.2. Rotation Periods

We use K2 photometry processed with PDCSAP pipeline for Campaigns 5 and 16, see Figure 5. Both stars show rotational modulation consistent with 1−2 starspots. We measure the rotation periods for each star by taking the autocorrelation...
function and Lomb–Scargle periodogram for each target and each campaign; see Figure 6. We take the mean and standard deviation of the four rotation period measurements (one LS and one ACF period for each campaign) and find $P_{\text{rot}} = 11.80 \pm 0.11$ days for EPIC 211928486, and $P_{\text{rot}} = 11.68 \pm 0.22$ days for EPIC 211966629.

The rotation periods of EPIC 211966629 measured in Campaigns 5 and 16 appear to be slightly different, though within the observational uncertainties. It is possible that the differing period measurement is astrophysical, and not an artifact of noise. If it is astrophysical, we may be measuring slightly different periods as starspots emerge at different latitudes on the star throughout the stellar activity cycle, giving a hint at differential rotation on this star. We refrain from making such a claim, as previous work has made it clear that differential rotation is exceptionally hard to determine from rotational modulation (Aigrain et al. 2015).

4.3. Minimum Spot Covering Fractions via Flux Deficit

We compute the flux deficit as in the previous section. The flux deficit indicates that both stars have similar spot covering fractions, between 1% and 4%. Both stars are 100× more spotted than the Sun, and they appear to be similar to the K4 dwarf HAT-P-11 ($f_s = 0.14$), which has a longer rotation period $P_{\text{rot}} = 29$ day (Morris et al. 2017b, 2018a). If we assume that these stars are young proxies for HAT-P-11, it’s interesting to note that while they have more chromospheric activity, their spot coverage is similar to their slower rotating counterpart HAT-P-11.
4.4. Lack of Flux-S-index Correlation

Figure 7 shows the $K_2$ photometry of each target (top panels), along with the S-indices that we measured with ARCES spectrograph in the bottom panels. Excluding the two spectra of EPIC 211928486 near BJD = 2458095, the other 13 S-index measurements are more or less consistent with constant $S \approx 0.9$ for both stars, at all rotational phases. The lack of correlation between the observed stellar flux in the $Kepler$ band and the S-index is demonstrated in Figure 8. This lack of correlation is interesting given that the corresponding $R'_{HK} \sim -4.1$ is generally considered “very active” (Wright et al. 2004), though the minimum spot coverage inferred from rotational modulation is only a few percent.

One could interpret the high S-index and small minimum spot coverage to imply that there are many plages without accompanying starspots, generating significant CaII H & K emission at all rotational phases, but not contributing significantly to the rotational modulation in the $Kepler$ band. This is frequently the case on the Sun. An alternative scenario is that the star is blanketed in spots that all generate CaII emission and photospheric absorption, and as each spot rotates into view, another rotates out of view, causing the relatively small changes in the observed $Kepler$ flux ($\lesssim 2\%$).

4.5. Precipitous Decline in S-index of EPIC 211928486

The S-indices of both stars are relatively constant with a significant exception. There is a 50% decline in the emission in the cores of the CaII H & K lines during two consecutive epochs; see Figures 7 and 9. We have simultaneous $K_2$ photometry for the second low-S observation, but not the first (see Figure 7). We have inspected the spectra to verify that there were no additional sources of continuum emission, due to interloping nearby stars or solar contamination (reflected off of clouds or the sky, though these observations were not collected near twilight), which may appear to suppress the S-index.
flares could increase the continuum relative to the Ca II emission (Kowalski et al. 2013), which would make the emission core appear weaker. If a flare was responsible, however, we would also expect to see significant Hα emission; we have verified that the Hα line does not show any change during these epochs.

As a result, it appears that one hemisphere had significantly less plages for a duration of about one rotation, and that the plages had recovered to their near-axisymmetric distribution by the next rotation. We are unaware of any observations in the solar literature that show a similar precipitous decline in chromospheric activity without an accompanying signature in the number of sunspots, indicating perhaps that this surprising phenomenon may be relevant to cooler or younger stars than the Sun. Continued observations of this star, preferably at higher cadence, would be valuable to constrain whether or not this phenomenon occurs regularly.

5. Discussion

A large sunspot in the solar photosphere is almost always spatially associated with a bright active region plages in co-temporal Ca II K images of the chromosphere (Stix 1989; Mandal et al. 2017). Thus, we expected to find some degree of anti-correlation between the chromospheric emission and broadband flux for Sun-like stars with large spots/plages. We observed such an anti-correlation on the young G star KIC 9652680, perhaps indicative of large plages that accompany its most-spotted hemisphere. Similar association between plages and starspots has been observed many stars, including: 12 Oph (K1V) and 61 Cyg A (K5V) (Dorren & Guinan 1982), several stars in the famous sample of Olin Wilson’s (Radick et al. 1983), several Hyades members (Lockwood et al. 1984), and the RS CVn variable UX Ari (K0IV) (Gu 2005).

We do not find a correlation between the broadband flux and chromospheric emission for the two mid-K stars EPIC 211928486 and EPIC 211966629. This may indicate that the plages are distributed axisymmetrically about the stellar surface, or that the spots that contribute to rotational modulation are too small to generate substantial chromospheric emission. From spot occultations during planetary transits of HAT-P-11 b, we know that the spots on mid-K stars can be as large as the largest spots on the Sun at solar maximum (Morris et al. 2017b, 2018a), and therefore one might expect plages to accompany those large spots. Thus, we posit that the near-constant significant chromospheric emission of EPIC 211928486 and EPIC 211966629 is more likely due to an axisymmetric distribution of plages (and perhaps spots as well).

The sudden decrease and recovery in the $S$-index of EPIC 211928486 may indicate that the evolution timescale of plages on these mid-K dwarfs is of order the rotation period. Large active regions on the Sun can last from days up to several rotations (Solanki 2003). What we are observing is a curious lack of activity lasting only a rotation, without an accompanying brightening of the star, as one might expect if the spots vanished, or dimming of the star, as one might expect if a planet or companion eclipsed the active regions. We invite observers to monitor the Ca II emission of this star, for want of an explanation. We note that solar plages are observed at highest contrast with at the solar limb, and therefore their rotational signal on other stars will be slightly more complicated than the simplistic anti-correlation with total flux that we outline in this work. However, the brightening effect of faculae is small compared to the dimming due to starspots over the course of a full solar rotation. In broad optical bandpasses, the majority of the rotational modulation signal is produced by sunspots rather than faculae (Shapiro et al. 2016).

We also note that the observations presented here do not represent complete phase coverage for all stars. The photometric and spectroscopic observations are expensive and require large telescopes with dedicated observing programs, such as the one we have provided in this work. There are no other proxies for activity indices that we can draw upon for further analysis, other than the rotational modulation of the flux recorded by Kepler/FlareCam.

In future work, it would be interesting to measure the full-disk $S$-index of the Sun as if it were a star, to determine: (1) whether or not the simple anti-correlation between broadband flux and $S$ indeed holds up for the Sun; and (2) whether or not the Sun exhibits dips significant dips in $S$ like EPIC 211928486.
6. Conclusions

We have observed a young G star and two mid-K dwarfs with simultaneous photometry and spectroscopy to probe the connection between the distribution of plages and starspots on their surfaces as they rotate. We find that the young G star KIC 9652680 exhibits Sun-like behavior: when its most spotted hemisphere is facing us and its broadband Kepler flux is minimal, we observe enhanced chromospheric emission.

The same is not true for the pair of K dwarfs EPIC 211928486 and EPIC 211966629 in Praesepe. Their chromospheric emission remains relatively constant as a function of rotational phase. There is one exceptional rotation of EPIC 211928486 where the S-index declined by 50%, without the expected corresponding increase in broadband stellar flux, for which we have few good explanations. Future simultaneous observations will be possible with NASA’s TESS mission, which may allow us to determine whether the uncorrelated S-index dipping phenomenon occurs regularly for this star or mid K dwarfs like it.

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Facilities: K2, APO/ARC 3.5 m, APO/ARCST.

Software: astropy (Morris et al. 2018b), astropy (The Astropy Collaboration et al. 2018), arceshk (Morris 2017), gatsby (Vanderplas 2015), emcee (Foreman-Mackey et al. 2013), ipython (Pérez & Granger 2007), numpyp (Van Der Walt et al. 2011), scipy (Jones et al. 2001), matplotlib (Hunter 2007), SML (Valenti & Piskunov 1996).

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