Sounding stellar cycles with *Kepler* – III. Comparative analysis of chromospheric, photometric, and asteroseismic variability

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**ABSTRACT**

By combining ground-based spectrographic observations of variability in the chromospheric emission from Sun-like stars with the variability seen in their eigenmode frequencies, it is possible to relate the changes observed at the surfaces of these stars to the changes taking place in the interior. By further comparing this variability to changes in the relative flux from the stars, one can obtain an expression for how these activity indicators relate to the energy output from the stars. Such studies become very pertinent when the variability can be related to stellar cycles as they can then be used to improve our understanding of the solar cycle and its effect on the energy output from the Sun. Here, we present observations of chromospheric emission in 20 Sun-like stars obtained over the course of the nominal 4 yr *Kepler* mission. Even though 4 yr is too short to detect stellar equivalents of the 11 yr solar cycle, observations from the *Kepler* mission can still be used to analyse the variability of the different activity indicators thereby obtaining information of the physical mechanism generating the variability. The analysis reveals no strong correlation between the different activity indicators, except in very few cases. We suggest that this is due to the sparse sampling of our ground-based observations on the one hand and that we are likely not tracing cyclic variability on the other hand. We also discuss how to improve the situation.

**Key words:** Sun: activity – Sun: helioseismology – stars: activity – stars: oscillations.

1 INTRODUCTION

Our Sun shows variability on a number of time-scales, where the most pronounced are the 5 min p-mode oscillations, the 25–30 d rotational modulation, and the 11 yr solar cycle (Shapiro et al. 2017). While we have witnessed significant progress in our understanding of the first two phenomena over the last decades, our knowledge of the 11 yr solar cycle is still deficient. Especially, our understanding of the long-term modulation of the amplitude of the 11 yr solar cycle, where the occurrence of so-called grand minima, such as the 17th century Maunder Minimum, constitutes a huge challenge (Eddy 1976). This challenge can be met by making better observations and better models of the Sun and by comparing these to observations and models of other stars (Schrijver & Zwaan 2008).

Most of the important information we have of the 11 yr solar cycle comes from either direct observations of sunspots or from observations of standing oscillations inside the Sun through helioseismology (Christensen-Dalsgaard 2002; Gizon 2004). With helioseismology, we have learned about the differential rotation pattern of the Sun’s deep interior and about the meridional circulation in the Sun’s convection zone.

For other Sun-like stars (stars with masses and radii similar to the Sun), we have so far mainly obtained information of their magnetic cycles through observations of the temporal evolution of the emission in the Ca II H and K lines as has been done from the Mount Wilson and Lowell observatories (Baliunas et al. 1995; Wright 2005). Expectations where therefore high, when the
As Kepler was designed for exoplanet detection, the photometry is not suited for identifying stellar activity cycles or the effect of stellar activity. The main reason for this is that the mean level of the photometry is normalized by the calibration method every 3 months. A solution to this was found by Montet, Tovar & Foreman-Mackey (2017), who employed the so-called full-frame images (FFI) for reconstruction of the photometric long-term variability. They used these measurements to show a transition from spot-dominated to faculae-dominated variability for rotation periods between 15 and 25 d. Another solution was found by Reinhold, Cameron & Gizon (2017), who used the variability rather than the intensity to search for stellar cycles in active solar-type stars. Both studies suffered from the short lifetime of the Kepler mission and were thus not able to identify bona fide stellar cycle variability in any of their targets.

The issue with the short lifetime of the Kepler mission was, however, not a problem for the high-metallicity Sun-like star KIC 8006161. This star was not only part of our NOT program, it was also observed as part of the Mount Wilson HK project (Balunais et al. 1995) and the California Planet Search program (Wright 2005). We were thus able to reconstruct a time series of the chromospheric activity measurements dating back to the mid-nineties (with even a few data points in the late seventies and early eighties) that allowed us to measure a bona fide cycle period of 7.41 ± 1.16 yr. As the rising phase of the last cycle was covered by observations from the Kepler mission, this allowed us to compare the realization of the magnetic activity in different activity indicators related to the chromosphere, photosphere, and interior. The relation between these indicators agreed very nicely with theoretical predictions for this high-metallicity star, indicating that the cycle in KIC 8006161 does indeed have the same nature as the solar cycle (Karoff et al. 2018).

This study continues the work in Paper I and Paper II. In Paper I, we presented the idea behind the Sounding stellar cycles with Kepler program and discussed the strategy for selecting targets. In Paper II, we presented the first measurements of chromospheric activity emission and analysed the dependence between the mean values of these measurements and fundamental stellar parameters obtained from asteroseismology. At the time of submission and publication, we expected that Kepler would continue the observations in the Cygnus field for 10 yr. Shortly after the publication of Paper II, the second reaction wheel failed and the Cygnus field was abandoned. As the idea from the beginning of the program was that we would only make simultaneous observations with the NOT as long as Kepler was operational, we thus also interrupted our NOT program – meaning that we stopped submitting proposals. In this study, we thus present 4 yr of simultaneous observations of magnetic activity related variability in our 20 target stars.

The main scope of this study is to present the measurements of chromospheric variability from the NOT made simultaneously with the observations by Kepler. In order to evaluate the information content in the measurements, we also compare our measurements of chromospheric activity variability with asteroseismic measurements (Santos et al. 2018) and photometric measurements (Montet et al. 2017).

Though we did interrupt our NOT program when the second reaction wheel on Kepler failed, we have continued working on a solution for multidecadal observations of the 20 targets, with a dedicated spectrograph installed at the Hertzsprung Stellar Observations Network Group (SONG) telescope at Teide Observatory (Grundahl et al. 2017). We will provide a brief overview of this idea and discuss the lesson learned from our NOT program with respect to S/N, sampling, and observation time span.
2 OBSERVATIONS

The spectroscopic observations are described in Paper II. They were obtained with the high-resolution Fibre-fed Echelle Spectrograph (FIES) mounted on the NOT (Frandsen & Lindberg 2000). The target list is provided in Table 1. Most stars were observed for 3 epochs per year in 2010, 2011, 2012, and 2013 (12 epochs in total). The low-resolution fibre (R \( \approx 25,000 \)) was used for the observations. The spectra were obtained with 7 min exposures resulting in an S/N above 100 at the blue end of the spectrum for the faintest stars.

The spectra were reduced as described in Paper II using FIEStool.\(^1\)

3 ANALYSIS

The most common activity indicator utilizing the Ca II \( H \) and \( K \) lines is the so-called \( S \) index (Duncan et al. 1991):

\[
S = \alpha \cdot \frac{H + K}{R + V},
\]

where \( H \) and \( K \) are the recorded counts in 1.09 Å full width at half-maximum triangular bandpasses centred on the Ca II \( H \) and \( K \) lines at 396.8 and 393.4 nm, respectively, \( R \) and \( V \) are two \( 20 \) Å wide reference bandpasses centred on 390.1 and 400.1 nm, respectively, while \( \alpha \) is a normalization constant.

The normalization constant \( (\alpha) \) can be obtained by measuring a number of stars that were part of the Mount Wilson HK project (Duncan et al. 1991). The calibration does not have to be linear (Isaacson & Fischer 2010). This approach was, however, not followed in Paper II as there was only one star in common between the Mount Wilson HK project and our targets. Instead the excess flux \( \Delta F_{\text{Ca}} \) was used as the activity indicator. The excess flux is defined as the surface flux arising from magnetic sources, which is calculated as the flux in the Ca II \( H \) and \( K \) lines, subtracting the photospheric flux and the so-called basal flux.

\(^1\)http://www.not.iac.es/instruments/fies/fiestool/FIEStool.html

In Karoff et al. (2018) we, however, identified 21 stars that were observed by both the California Planet Search program (Wright 2005; Isaacson & Fischer 2010) and by some of our programs at the NOT (including both the targets in Paper I and Paper II). These stars were used by Karoff et al. (2018) to calculate a linear transformation between the instrumental \( S \) indices measured with the NOT and the \( S \) indices measured as part of the California Planet Search program. In order to minimize numerical effects in the calculation of the \( S \) indices, all spectra from the NOT and Keck telescope were reanalysed using the same code. The uncertainties of the NOT measurements were obtained using nights with multiple observations to obtain the following relation between the uncertainty of the mean value of the chromospheric activity measured that night and signal-to-noise ratio \( (\text{S/N}) \): \( \sigma = 0.011 / \sqrt{\text{S/N}} \). An additional flat noise term of 0.002 was added in quadrature (Lovis et al. 2011).

Our calibrated \( S \) indices can be used to calculate the excess flux (Rutten 1984):

\[
F_{\text{Ca}} = 10^{-14} \cdot S \cdot C_{\text{eff}} T_{\text{eff}}^3,
\]

where \( C_{\text{eff}} \) is the conversion factor given in Middelkoop (1982):

\[
\log C_{\text{eff}} = 0.25(B - V)^3 - 1.33(B - V)^2 + 0.43(B - V) + 0.24.
\]

A number of asteroseismic estimates are available for the effective temperatures, but we recommend the effective temperatures provided in Creevey et al. (2017).

Our calibrated \( S \) indices can also be used to calculate the so-called \( R'_{\text{HK}} \) activity indicator, defined as

\[
R'_{\text{HK}} = R_{\text{HK}} - R_{\text{phot}},
\]

where \( R_{\text{phot}} \) is the photospheric contribution to the indicator, which can be calculated using the \( B - V \) colour index (Noyes et al. 1984):

\[
\log R_{\text{phot}} = -4.898 + 1.918(B - V)^2 - 2.893(B - V)^3
\]

and \( R_{\text{HK}} \) is calculated based on the \( S \) indices and the conversion factor given above:

\[
R_{\text{HK}} = 1.34 \cdot 10^{-4} C_{\text{eff}} S.
\]
After various tests, we decided to use the $S$ index as the activity indicator. Generally, the results are not significantly affected depending on if the $S$ index or $R_{HK}$ is used as the activity indicator. The reason for this is that our 20 targets span a rather small range in effective temperature. Also, the focus of this study is the temporal variability of individual stars, so the calibration is a minor issue.

4 RESULTS

The Sun shows a strong direct correlation between chromospheric activity, photometric flux, and eigenmode frequencies (see Karoff et al. 2018, and reference herein). The reason for this is that changes in all three parameters are caused by magnetic flux tubes rising up through the Sun. In the outermost regions of the near surface convection zone, they change the turbulent velocity affecting the eigenmode frequencies (Dziembowski & Goode 2004, 2005), in the photosphere they lead to dark sunspots and bright faculae and in the chromosphere they lead to plages (see Solanki, Krivova & Haigh 2013, for a recent review). For KIC 8006161, we were able to measure a similar effect for the rising phase of the cycle that started in 2010. We therefore search for similar correlations for the remaining 19 targets. This is done by comparing our measurements of chromospheric emission to the relative flux of the stars measured in the FFI with the method by Montet et al. (2017) with a method similar to what was done for KIC 8006161 by Karoff et al. (2018). In this work, we include a larger region to search for suitable reference targets, encompassing 125 pixels from the observed image of the star on the detector, including its bleed trail, rather than 125 pixels from the stellar centroid. We note that for three targets, KIC 2837475, 6116048, and 10124866, faint background stars overlap with the point spread function of the target star, which, if variable, may affect the photometry at the ppm level. The measurements of chromospheric emission is also compared to the eigenmode frequencies presented in Santos et al. (2018). We use the frequency shifts calculated as the mean of the five central orders of the radial and dipolar modes (see Santos et al. 2018, for detailed description of this). We present the comparison in Fig. 1. Three stars KIC 3733735, KIC 10124866, and KIC 11244118 were not included in the analysis by Santos et al. (2018). The comparison between the chromospheric emission and the relative flux of these stars is presented in Fig. 2.

Based on the results presented in Figs 1 & 2, we have calculated the standard deviations of each time series. These are provided in Table 1 and in Figs 3–5 we show the correlation between these standard deviations of the different activity indicators. We have also calculated the correlation between the chromospheric emission and the eigenmode frequencies (Fig. 6) and between the chromospheric emission and the relative flux (Fig. 7).

We did test all results using $R_{HK}$ instead of the $S$ index and no significant differences were found.

5 DISCUSSIONS

So far, KIC 8006161 is the only star observed by Kepler that is known to show a bona fide cycle comparable to the 11 yr solar cycle (see Karoff et al. 2018, for a detailed analysis of this star). In our analysis, it is also the only star to show a correlation above the 95 percent significance level between the variability in the chromospheric emission, the eigenmode frequency shifts, and the relative flux.

KIC 10124866 shows a very weak correlation between the chromospheric emission and the relative flux, but the correlation is not above the 95 per cent significance level. No other star shows correlations between the different activity indicators that are above the 95 per cent significance level.

KIC 8379927 shows a nice correlation between the variability in the chromospheric emission and the eigenmode frequencies, but the significance is only 61 per cent. This star is known to be a spectroscopic binary with a 1743.3 ± 2.5 d period (Griffin 2007). KIC 8379927 was flagged by Santos et al. (2018) as one of the stars that showed evidence of activity-related frequency shifts. Though the significance is very low, we do agree with this interpretation that between 2010 and early 2012 KIC 8379927 shows a continuous rise and falls in the frequency shifts that is also seen in the chromospheric emission. It is, however, not clearly seen in the relative flux, though the measurements in 2011 seem to show larger than average scatter. It is still too early to conclude if the variability we see in KIC 8379927 is related to a stellar cycle. Looking at the combined frequency shifts and chromospheric emission, there could be hints of a 2 yr periodic variability, with maxima in mid-2009, mid-2011, and early/mid-2013. The time series is, however, too short to make any claims about the significance of such periodic variability.

According to Creevey et al. (2017), KIC 8379927 is a Sun-like star with a radius of 1.105 M$_\odot$, a mass of 1.08 M$_\odot$, and an age of 1.65 Gyr. According to García et al. (2014), the star has a rotation period of 16.99 ± 1.35 d. KIC 8379927 is in other words likely a very Sun-like star, and we would therefore expect any periodic variability to be longer than 2 yr (Bohm-Vitense 2007). This, however, assumes a large mass difference between the two binary components.

Recently, there has been a number of claims of a biennial cycle in the Sun (Fletcher et al. 2010; Broomhall et al. 2012; Simoniello et al. 2012, 2013). What we are seeing in KIC 8379927 could thus be the manifestation of a second dynamo (Fletcher et al. 2010) comparable to the biennial cycle in the Sun. A number of other G-type dwarfs, such as HD 190406, HD 78366, and HD 114710, also show such a secondary biennial cycles (Baliunas et al. 1995; Oldh et al. 2016). Unlike the variability seen in the F-type dwarfs, these secondary biennial cycles seen in the more Sun-like G-type dwarfs could be true polarity reversing solar-like activity cycles (Jeffers et al. 2018). More observations are, however, needed before we can make any solid claims. Zeeman-Doppler imaging would be especially useful here, as it can be used to evaluate if we see a polarity flip.

In general, the comparison of the standard deviation of the different activity indicators does not show any correlation (Figs 3–5). In fact, there might be hints of an inverse correlation between the standard deviation of the frequency shifts and the chromospheric emission for stars with $S$ indices with a standard deviation less than 0.0177 (Fig. 3). The correlation does not seem to be related to any effective temperature or metallicity effects. As no good explanation for such an inverse correlation exists, this may simply be due to noise.

In Fig. 4, we see an inverse relation between the standard deviation of the relative flux $\sigma I$ and the chromospheric emission $\sigma S$ for the stars with mean chromospheric emission larger than 0.15. This behaviour could be explained by a scenario where stars slightly more active than the Sun goes from being spot dominated to being faculae dominated and in this transition $\sigma I$ decreases with increasing chromospheric activity. Such an inverse relation would not show up for the inactive stars as they would be expected to have a more constant spot-to-faculae ratio throughout the cycle. This means that any spot darkening is balanced out by faculae brightening. The chromospheric emission is, however, not affected by this phenomenon.
Figure 1. Comparison of chromospheric activity, photometric flux, and eigenmode frequencies shifts for the 17 stars with measured eigenmode frequencies in Santos et al. (2018). Tables with the measured parameters are provided in the supplementary material.
Figure 1. – continued
Figure 2. Comparison of chromospheric activity and photometric flux for the three stars without measured eigenmode frequencies in Santos et al. (2018). Tables with the measured parameters are provided in the supplementary material.

Figure 3. Relation between the standard deviation of the eigenmode frequencies $\sigma(\delta\nu)$ and the chromospheric emission $\sigma S$. Grey mark stars with an S index less than 0.15. The crosses mark G-type dwarfs and the diamonds mark F-type dwarfs. The spectral-type classification has been made based on the effective temperatures.

Figure 4. Relation between the standard deviation of the relative flux $\sigma I$ and the chromospheric emission $\sigma S$. Symbols as in Fig. 3.

Figure 5. Relation between the standard deviation of the relative flux $\sigma I$ and the eigenmode frequencies $\sigma(\delta\nu)$. Symbols as in Fig. 3.

Alternately, the inverse relation between $\sigma I$ and $\sigma S$ could be explained by shifts in the distributions of active regions, where the area covered by spots increases, but the area covered by plage becomes more spatially homogeneous. These sorts of patterns are seen in more active stars (Radick et al. 2018).

If lack of correlations for the inactive stars is due to a missing degeneracy of the signals from spots and faculae, then the problem could be solved using multiband photometry as because of their different temperatures, faculae and spots cannot successfully cancel each other out at all wavelengths.

We do note that we were able in Paper II to see a correlation between the mean value of the excess flux and both the rotation period and age.

We further investigated if the correlation between the different activity indicators depends on the absolute level of the chromospheric emission (Figs 6 & 7). Again, no correlation was found. It is not unlikely that the missing correlation is due to the sparse sampling of the measurements of the chromospheric emission and the fact that the relative flux measurements have to be interpolated for this comparison. In other words, even though we do not see any strong correlation between the different activity indicators, it is not the same as claiming that they are not there.
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optimized for measuring accurate radial velocities with the use of an iodine cell and is therefore optimized for the wavelengths covered by the main iodine lines (4900–6200 Å). This means that the Ca II H and K lines do not even fall on the detector.

At SONG, we would try to follow an observing strategy that comes closer to the observing strategy used in the Mount Wilson project, where the targets were observed weekly, when visible, than the observing strategy we have used, where the targets were only observed three times per semester. We propose to follow such a strategy, even though it would result in fewer observed targets. There are two main reasons for such a prioritization. First, as we argue that the missing correlation between the different activity indicators in this study is due to the sparse sampling (and resulting interpolation), a higher sampling cadence should result in higher correlations between the different activity indicators and therefore also more reliable measurements. Secondly, a higher sampling rate would allow a robust mean and standard deviation of the amplitude of the rotational modulation to be calculated. Thirdly, as shown in Karoff et al. (2018), it is possible to use seasonal measured rotation rates to see indications of surface differential rotation caused by active regions at different latitudes. This is, however, only possible if sufficient observations are available each semester for determining the rotation period.

Based on our experience with our NOT program, we recommend that the S/N should not be much less than 100 at the blue part of the spectrum in order to be able to obtain reliable activity measurements.

It is our aim that the new spectrograph for measuring stellar activity with SONG should be fully ready for science observations when NASA’s Transiting Exoplanet Survey Satellite (TESS) will start new observations of the Kepler field. This will allow us to test if a denser sampling will lead to a better correlation between the different activity indicators. Apart from this, TESS will provide us with asteroseismic measurements of the fundamental stellar parameters of the stars in which activity cycles have been observed from the Mount Wilson and Lowell observations and will therefore constitute a nice continuation of our sounding stellar cycles with Kepler program. This is especially true if TESS is extended beyond the nominal mission, which would allow the Kepler field to be revisited each summer.

6 CONCLUSIONS

We present 4 yr of observations of emission in the Ca II H and K lines in 20 Sun-like stars. The observations were undertaken simultaneously with observations by the Kepler mission. This has allowed us to analyse the relation between cycle-induced changes on the surface and in the interior in the metal-rich Sun-like star KIC 8006161 as seen in the chromospheric emission, in the eigenmode frequencies, and in the relative flux (Karoff et al. 2018).

The comparison for the different activity indicators for the remaining 19 stars does, however, not show the same agreement as seen for KIC 8006161. We suggest that this is mainly due to two effects. First, the sparse sampling of our spectrographic observations makes it difficult to compare with the photometric Kepler observations and secondly, due to the failure of Kepler’s reaction wheels, we only have 4 yr of observations available, which is not sufficient to detect an activity cycle similar to the 11 yr solar cycle. We are therefore trying to set up multidecadal observations of the 20 stars with a new dedicated spectrograph at the SONG telescope.

A correlation between the \( R'_{\text{HK}} \) calibration and metallicity has been noted by Saar (2006), Jenkins et al. (2008), and Saar & Testa (2012) indicating that metallicity suppresses the measured \( R'_{\text{HK}} \) values. We searched for such a correlation between metallicity and the other measured parameters, but did not find any. Again, this could be due to our limited sample size, but also that our stars span a narrow range in effective temperature.

In general, the main conclusion from our work on sounding stellar cycles with Kepler is that we need a longer time baseline for the observations. In the most optimal case, this means following the 20 targets in our sample and may be even more stars indefinitely. We did not find such an approach feasible by submitting new observing proposals to the NOT every semester. Instead, we have installed an eShell spectrograph system from Shelyak Instruments at the Hertzsprung SONG telescope at Teide Observatory and are at the moment testing if it can be used, with minor modifications, to measure chromospheric activity in our targets. If these tests turn out to be successful, we will have the option to monitor the variability of the chromospheric emission in these stars for as long as SONG is operational. We note that the main spectrograph at SONG is

Figure 6. Correlation between the eigenmode frequencies shifts and the chromospheric emission as a function of the mean value of the chromospheric emission. The crosses mark G-type dwarfs and the diamonds mark F-type dwarfs.

Figure 7. Correlation between the relative flux and the chromospheric emission as a function of the mean value of the chromospheric emission. Symbols as in Fig. 6.
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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

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