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Dynamo Sensitivity in Solar Analogs with 50 Years of Ca II H & K Activity

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Abstract

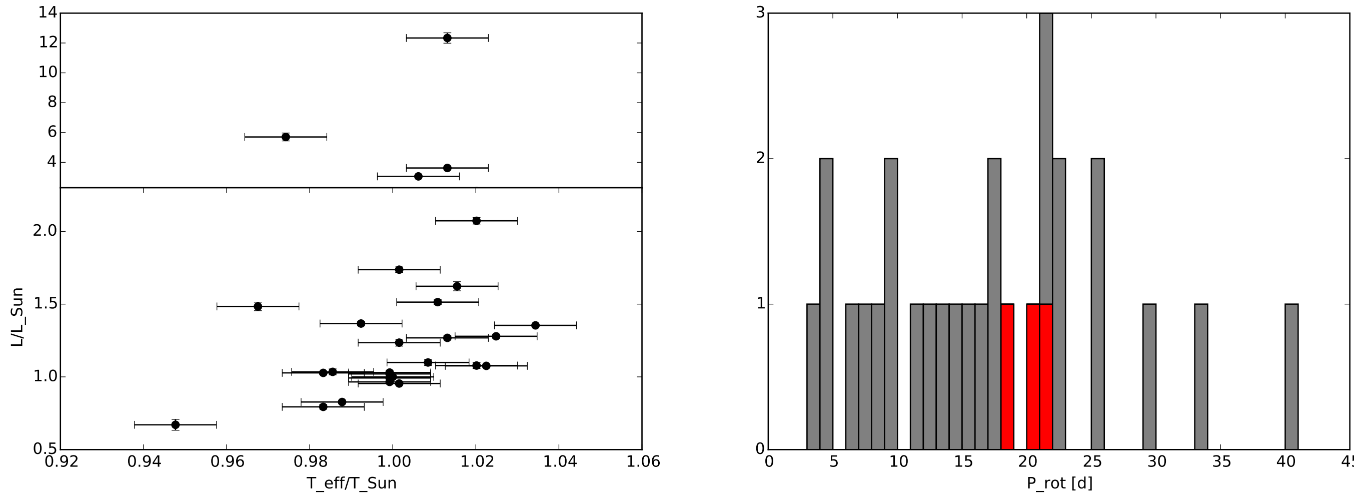
The Sun has a steady 11-year cycle in magnetic activity most well-known by the rising and falling in the occurrence of dark sunspots on the solar disk in visible bandpasses. The 11-year cycle is also manifest in the variations of emission in the Ca II H & K line cores, due to non-thermal (i.e. magnetic) heating in the lower chromosphere. The large variation in Ca II H & K emission allows for study of the patterns of long-term variability in other stars thanks to synoptic monitoring with the Mount Wilson Observatory HK photometers (1966-2003) and Lowell Observatory Solar-Stellar Spectrograph (1994-present). Overlapping measurements for a set of 27 nearby solar-analog (spectral types G0-G5) stars were used to calibrate the two instruments and construct time series of magnetic activity up to 50 years in length. Precise properties of fundamental importance to the dynamo are available from Hipparcos, the Geneva-Copenhagen Survey, and CHARA interferometry. Using these long time series and measurements of fundamental properties, we do a comparative study of stellar "twins" to explore the sensitivity of the stellar dynamo to small changes to structure, rotation, and composition. We also compare this sample to the Sun and find hints that the regular periodic variability of the solar cycle may be rare among its nearest neighbors in parameter space.

1 Introduction

Emission in the Ca II H & K line cores has long been known to be a good proxy for magnetic activity in the Sun (Hall, 2008). Wilson (1978) was the first to use this emission to demonstrate the magnetic variability for an ensemble of Sun-like stars, using a decade of synoptic Ca II H & K observations from the Mount Wilson Observatory (MWO). The MWO HK project began in 1966 and continued until 2003, with the largest compendium of stellar activity for 111 stars with up to 25 years of observations appearing in Baliunas *et al.* (1995). The MWO HK project was the basis of numerous investigations of activity, its relationship to stellar age and rotation, and implications for dynamo theory (see Baliunas *et al.*, 1998, , and references therein).A complimentary synoptic observation program began at Lowell Observatory in the mid-1990's using the Solar Stellar Spectrograph (SSS), designed to take low resolution spectra covering the Ca II H & K region for the Sun and stars with the same spectrograph (Hall & Lockwood, 1995; Hall *et al.*, 2007). The SSS program continues to this day, and 57 of its ∼100 targets overlap with the MWO HK project. We combine the data from these two surveys making time series of nearly 50 years in length. This was done for the first time in Egeland *et al.* (2015) for the young solar analog HD 30495. In that case, the long time series allowed for the identification of three and a half stellar cycles, with a mean period of ∼12 years, for a star that previously appeared to be acyclically variable. Work is ongoing to calibrate, combine, and analyze MWO+SSS time series for a sample of 27 solar analog stars with $0.59 \leq (B-V) \leq 0.69$ (Cayrel de Strobel, 1996), in order to understand the solar dynamo in the stellar context. In particular, we seek to better understand (1) whether the pattern of solar variability is common among Sun-like stars (2) how the patterns of long-term variability in the ensemble depend on stellar properties such as mass, luminosity, radius, metalicity, and rotation. Preliminary results from this project were presented at this conference (Egeland *et al.*, 2016a,b) and are summarized in these proceedings. The full details and final results are to appear in a peer-reviewed journal in the near future.

2 Solar-Analog Sample

Our sample consists of the Sun and 27 solar-analog stars ($0.59 \leq (B-V) \leq 0.69$) with synoptic observations from both MWO and the SSS. Of these, 20 stars (including the Sun) have activity time series of nearly 50 years in length, with the remainder having somewhat less coverage but nonetheless with at least 20 seasons of observations. Our cut in $(B-V)$ color index keeps the sample within roughly 10% of the solar mass for stars firmly on the main sequence, though some subgiants are in the sample as we shall see below. From the perspective of the stellar dynamo, perhaps a more important result of this limitation is that the stars share a roughly sim-



(a) Luminosity vs. effective temperature

(b) Rotation distribution

Figure 1: Stellar properties for the MWO+SSS solar analog sample. Note that the error bars in the luminosity are often hidden behind the data point.

ilar luminosity, which puts limits on the energy available to drive convection in our sample. Our limited parameter space is designed with the hope that a larger fraction of the stars in the sample have dynamos driven by processes similar to that of the Sun. More massive stars with thin convection zones and high convective energy, as well as less massive stars with deep convection zones and lower convective energy are excluded from this sample.

We characterize our sample using results from the Geneva Copenhagen Survey (GCS) based on Strömgren $ubvy\beta$ photometry and Hipparcos parallaxes (Holmberg *et al.*, 2009). Each star in our sample is nearby and bright ($V < 7$), typically with a long literature of observations. From the GCS, we obtain the absolute magnitude, effective temperature, and metalicity. We convert the absolute magnitudes from the GCS to luminosity using the bolometric correction of Torres (2010), based on the work of Flower (1996). Luminosity and effective temperature are then converted into stellar radius using the Stephan-Boltzman law. Figure 1(a) shows luminosity versus effective temperature for our sample. Effective temperatures are within 5% of the solar nominal value of 5772 K, with most stars within 2σ of the solar temperature, where $\sigma = 57$ K is the estimated measurement uncertainty for GCS temperatures (Holmberg *et al.*, 2009). Five stars in our sample have $L > 2_\odot$ and are thus appreciably evolved. Excluding these five, luminosities range from 0.67 to 1.74 $L_\odot$. The median temperature, luminosity, and radius for our sample is 1.00, 1.17, and 1.06 the solar value, respectively. Metalicities range from -0.78 to +1.3 dex with a median value of -0.1 dex.

Rotation periods are taken from various literature sources, the majority coming from the rotation studies of Donahue *et al.* (1996) and Baliunas *et al.* (1996), who used a periodogram analysis on seasonal MWO HK time series to measure rotation. Figure 1(b) shows a histogram of the rotation periods for our sample. Rotation periods for three stars, estimated from their projected rotation velocities ($v \sin(i)$) and radii, are shown by red bins and are only a lower limit dependant on the inclination, $P_{\rm rot}/\sin(i)$. All other rotation periods are measured using a periodogram analysis of S-index or Strömgren by photometry time series, which are modulated by the passage of active regions on the stellar surface. Work is ongoing to measure rotation from such time series for the three $P_{\rm rot}/\sin(i)$ stars. Figure 1(b) shows that our sample has relatively uniform sampling in rotation up to about $P_{\rm rot} = 22$ days, after which the sampling is sparse. Six stars have a rotation within 20% of the solar rotation period, here taken to be 25 days, although the three $P_{\rm rot}/\sin(i)$ stars may also have rotations within that range. The median rotation period is 15 days.

In summary, our sample generally has properties close to solar values, but the sample centroid is slightly more luminous and metal-poor, and rotates faster than the Sun.

3 Analysis Methods

Consider the stellar dynamo to be an unknown function which maps measurable global properties such as effective temperature, luminosity, composition and rotation into a time varying, spatially distributed magnetic field collapsed into a one-dimensional time series by integrating chromospheric Ca II HK emission over the stellar surface. Then with the dynamo *inputs* characterized by the GCS and rotation measurements described above, our next job is to characterize the dynamo *outputs* using our long S-index time series. Firstly, we characterize the statistical properties of the variability using rank-based measures that are robust against outliers and appropriate for use on non-Gaussian distributions. For each S-index time series, we calculate the median $\overline{S}$, the upper $99^{\rm th}$ percentile and the lower $1^{\rm st}$ percentile. The difference of these percentiles gives A_{98}, the amplitude of the inner 98% of the measurements. This amplitude is designed to estimate the total range of the measurements while being robust to small numbers of outliers. The S-index binned into 1-year observing seasons and the amplitude $A_{98,s}$ is computed for each season. We report the median seasonal amplitude, $\overline{A}_{98,s}$ as an estimate of the typical amplitude of variability in a 1-year period. We thus obtain an estimate of the amplitude of long-term (decades) and short-term (1 year) variability for each star.

We perform a Lomb-Scargle periodogram analysis on each of our composite time series following the methods of Baliunas *et al.* (1995) and Horne & Baliunas (1986). We search for statistically significant peaks by computing a power spectral density threshold above a false alarm probability (FAP) of 0.1%, the minimum confidence threshold for a "poor" cycle in Baliunas *et al.* (1995). The FAP gives the probability that a given periodogram peak is due to random noise, and the confidence level that the signal exists is 1 - FAP > 99.9%. The top three statistically significant peak periods, $P_{\rm var}$, are stored for further consideration according to the quality metric, described below. In many previous works, (e.g. Baliunas *et al.*, 1995), the top two statistically significant periodogram peaks are reported as "primary" and "secondary" cycles. One of our aims in this work is to define a quantitative basis for classifying a periodogram peak as a "cycle", which satisfies our qualitative notions of what constitutes a cycle.

Using the solar cycle as the primary model of how we would like to define a stellar activity cycle, we note two important qualities: (1) the cycle pattern *approximately* repeats for dozens of iterations, lasting centuries (2) the cycle pattern is dominant; other periodicities, if and when they are present, are of much lower amplitude than the primary ≈11 year cycle. We seek to define a quality metric which can be used to find variations which have these two characteristics. By contrast the FAP of a Lomb-Scargle periodogram peak at period $P_{\rm var}$, when low, gives us confidence that a sinusoidal signal is *present*, and not simply due to random noise. Defining "noise" to be everything that is *not* the primary long-term cycle in a record of solar activity (i.e. rotational modulations; active region growth and decay; other short-period variations that may be dynamo-related), then we find that the solar cycle in MWO or SSS S-index has a signal to noise ratio of ≈10. Therefore in the search for solar-like cycles, we are *not* faced with the problem of extracting a faint signal from noisy data. FAP is therefore not an appropriate tool to quantitatively compare stellar cycles.

Besides this, FAP scales with the number of data points in the time series. As a result, the 4-class system (poor, fair, good, excellent) used in Baliunas *et al.* (1995) cannot be applied to other data sets which may have more or less observations. For our nearly 50-year time series, *nearly every star has an "excellent" cycle*, even though inspecting the time series one would have great difficulty finding the purportedly "excellent" signal.

We therefore define a new quality metric:

$$\mathrm{ASD} = \sqrt{\frac{2}{N}\,\mathrm{PSD}}$$

$$Q_{\rm cyc} = 100\left(1 - 0.5\frac{P_{\rm var}}{T}\right)\,\mathrm{ASD}$$

where ASD is the amplitude spectral density, and PSD is the power spectral density, normalized by the variance of the data as described in Horne & Baliunas (1986), T is the duration of the time series, and N is the number of samples. With the PSD normalized by the variance σ^2, ASD has units of $X\sigma_X^{-1}T^{-1}$, where X represents the units of the time series and T represents the time units. For a pure sinusoidal signal of *any* amplitude, the ASD has a value of 1, indicating that the rms amplitude of the signal is 1 σ. ASD is therefore bounded from [0, 1]. The factor $(1 - 0.5P_{\rm var}/T)$ is a penalty factor for infrequently observed cycles. If only one full cycle of a pure sinusoid is observed, $Q_{\rm cyc} = 50$. As $T \to \infty$ for a pure sinusoid, there is no penalty and $Q_{\rm cyc} \to 100$. $Q_{\rm cyc}$ is always positive so long as $P_{\rm var} > T$, which is ensured in our analysis since we do not search for periods longer than the time series. Therefore, in general, $Q_{\rm cyc}$ ranges from [0, 100] with 100 only achievable with an infinite time series of a pure sinusoid. The solar cycle is not a pure sinusoid, and we do not have an infinite record, so even in the best cases $Q_{\rm cyc}$ will be somewhat less than 100. ASD is insensitive to the number of observations N, therefore two separate instruments observing the same star during the same period should in principle obtain the same $Q_{\rm cyc}$ even with different sampling, which is not true of a quality scale based on FAP.

In an upcoming work, we will explore the properties and caveats of $Q_{\rm cyc}$ in more detail, but so far we are satisfied with the qualitative ranking of cycles by this metric. For the Sun $Q_{\rm cyc} = 59$, and stars with $Q_{\rm cyc} > 50$ have cycles that are easy to identify from simple inspection of the time series. $Q_{\rm cyc} > 40$ are still identifiable but not so obvious, and as $Q_{\rm cyc} \to 0$ no obvious periodicity can be seen in the time series, despite the FAP indicating that the $P_{\rm var}$ is statistically significant. The functional form and coefficient of 0.5 in the observation time penalty factor are arbitrary, but they serve the important purpose of reducing $Q_{\rm cyc}$ for relatively flat time series that have a long-term trend and, therefore, a periodogram peak near the window length. Furthermore, our criteria that a "cycle" is something that repeats warrants a penalty for any pattern that is only seen once.

Finally, we evaluate the sensitivity of the stellar dynamo to fundamental properties by examining pairs of stellar "twins" using the Euclidean distance metric:

$$d(\mathbf{p},\mathbf{q}) = \sqrt{\sum_{i=1}^{N}(p_i - q_i)^2}$$

where $\mathbf{p}$ and $\mathbf{q}$ are stellar property vectors { $T_{\rm eff}$, R, $P_{\rm rot}$ } for two different stars, all measured in solar units. With this distance metric, stellar twins are identified as those with a short distance. We can then examine the dynamo *outputs* of stellar twins to answer the question: *Do identical stars have identical patterns of magnetic variability?*

Despite scaling to solar units, the relative importance of these three parameters is not the same, because as can be seen in Figure 1 the range of rotations is much larger than the range of effective temperatures, for example. However, it is reasonable to allow rotation to have more weight in the distance metric than effective temperature, since rotation has a larger effect on activity.

4 Results

Measurements for each star in our sample can be seen in our poster[1], which is also published as part of these proceedings (Egeland *et al.*, 2016b). A sample panel from the poster is shown for HD 30495 in Figure 2, and the variability of this star was studied in detail in Egeland *et al.* (2015). The top plot is the time series of MWO observations in red,

[1] https://doi.org/10.5281/zenodo.57921

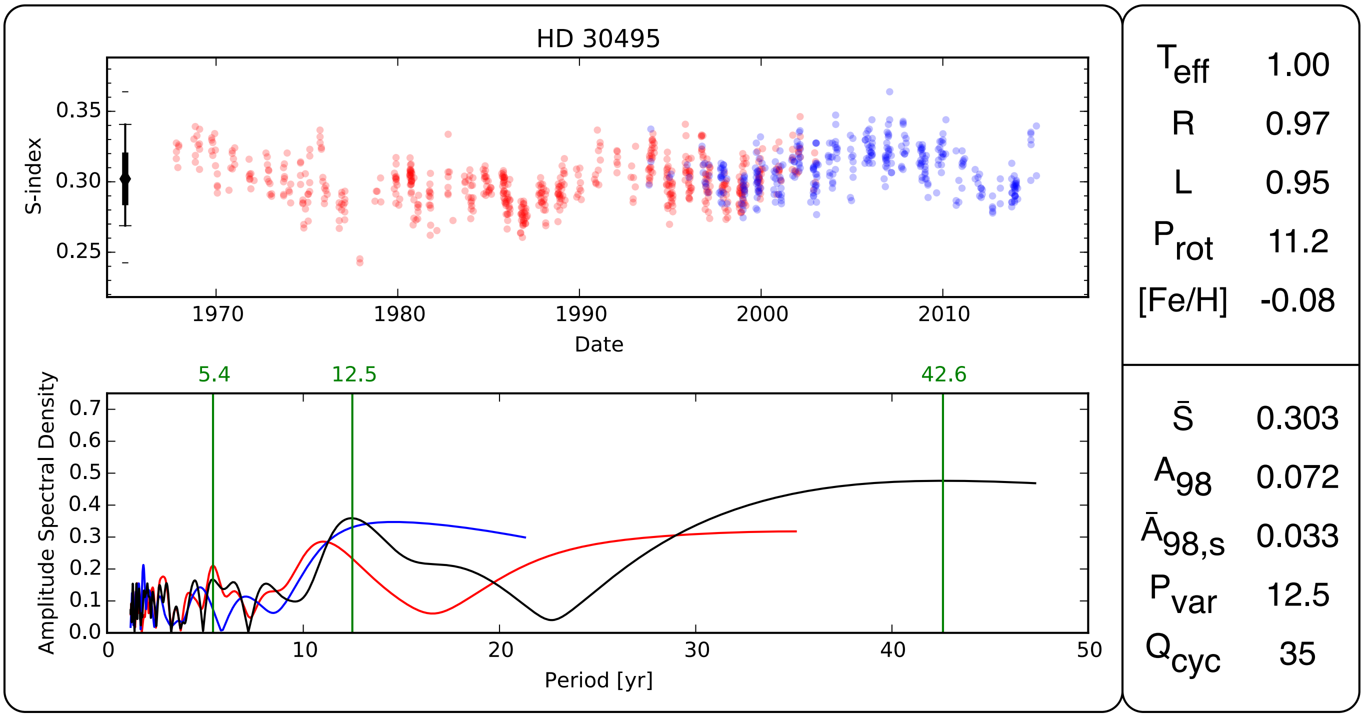


Figure 2: Time series, periodogram, stellar properties and variability measurements for HD 30495.

and SSS observations in blue. The bottom plot is the periodogram for the time series shown as an amplitude spectral density (ASD), with the black line utilizing all observations, the red line utilizing only MWO and the blue line only SSS. The top table gives the stellar properties in solar units, except for $P_{\rm rot}$, which is given in days. The bottom table gives the median activity, long-term and seasonal amplitudes, statistically significant periods of variability ($P_{\rm var}$ in years), and the cycle quality metric $Q_{\rm cyc}$. The black bar to the left of the time series visually shows the full range of measurements (short dashes), the long-term amplitude A_{98} (bar caps), short-term amplitude $\overline{A}_{98,s}$ (thick bar), and the median activity $\overline{S}$ (center diamond). The highest three statistically significant periodogram peaks are indicated by vertical green lines along with their period.

Ensemble trends are still being analyzed, and final results will appear in a future publication. However, we will qualitatively summarize some of our findings below.

Amplitude of variability scales with rotation and activity. Stars with faster rotation have larger amplitudes on both the long-term and short-term time scales. This was seen also in Radick *et al.* (1998) for long-term time scales using a sample of FGK-type stars. The increases in amplitude are significant. Fast rotating stars have about twice the solar cycle amplitude in *one year*. There are linear trends in amplitude vs. median activity.

Long cycles are found in the 50 year time series. HD 20630 has variability on two time scales, 5.7 years and 36 years, the latter being remarkably long and only visible in these long time series. A single 38-year cycle is found in HD 224930 with a relatively high $Q_{\rm cyc}$ = 44. This cycle is easily identifiable and has a fast rise and *very* slow decay, similar to the solar cycle, but exaggerated. Addition of these long-term cycles to the famous $P_{\rm cyc}$ vs $P_{\rm rot}$ plot of Böhm-Vitense (2007) introduces points far above the two branches of activity discussed in that work, complicating the discussion of multiple dynamo "modes" even further.

Similar stars have similar patterns of long-term variability. Stellar twins identified by our distance metric appear to have similar median activity levels and amplitudes of variability on long and short time scales. There are even indications that periods of variability are shared among some close pairs. This evidence seems to imply stability in the stellar dynamo, which is not guaranteed given the nonlinearity of the equations thought to govern the dynamo.

Very clear, clean cycles like the Sun are the minority. Using our cycle quality metric, only two other stars have cycles with $Q_{\rm cyc}$ very close to the solar value of 59. One of them, HD 81809, has an $\sim$8 year cycle with $Q_{\rm cyc} = 61$, higher than the Sun. However this signal is possibly due to a low-mass G9V component of the binary (Duquennoy & Mayor, 1988; Baliunas *et al.*, 1995), which is mistakenly in our sample due to its blended $(B-V)$ with an evolved, inactive companion. However, (Pourbaix, 2000) finds component masses of 1.7 and 1.0 solar masses, putting the low-mass component at the solar value. The properties of the source of this excellent cycle may only be resolved by further spectroscopic observations able to separate the components. The second high-quality cycle comes from HD 197076, which has an $\sim$5 year cycle with $Q_{\rm cyc} = 53$. The luminosity, temperature, and radius for this star are all equivalent to solar within the measurement uncertainty, but no rotation period is available. The lower limit rotation period derived from $v\sin(i)$ and the radius is $P_{\rm rot} > 18.7$. Five more stars with $Q_{\rm cyc} > 40$ have easily identifiable cycles that might be subjectively classified as very "solar like". Those stars (20 of 28) with $Q_{\rm cyc} < 40$ either have flat activity or tend to have more erratic behavior that appears quite removed from the regularity of the solar variations. This is usually indicated by multiple significant periods in the periodogram both above and below the "main" period of variability, HD 30495 (Figure 2) being a good example of this.

5 Conclusion

Diligent long-term observation programs by the Mount Wilson and Lowell Observatory provide unique data for understanding the variability patterns of Sun-like stars, with composite time series now approaching 50 years in length. Questions on the uniqueness of the solar cycle, and the sensitivity in stellar dynamos to changes in fundamental properties can be approached using these data, improving our understanding of the dynamo and our Sun in context. Work is ongoing to carefully quantify what these data can tell us about these questions, but the initial results indicate that the clean, clear solar cycle may be an exceptional case in the limited parameter regime of solar analogs.

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