PROJECT SUMMARY

Overview:
The magnetic activity of the Sun becomes stronger and weaker over roughly an 11 year cycle, modulating the radiation and charged particle environment experienced by the Earth as "space weather". Decades of spectroscopic Ca II H & K (Ca HK) observations from Mount Wilson and Lowell revealed that other stars also show regular activity cycles, and identified two distinct relationships between the length of the cycle and the rotation rate of the star. The solar cycle appears to be an outlier, falling between the two stellar relationships -- potentially threatening the very foundation of the solar-stellar connection. Recent work has started to shed light on this perplexing result, suggesting that the Sun's rotation rate and magnetic field may be in a transitional phase that occurs in all middle-aged stars, but additional observations are needed to test and refine this hypothesis. The results will have implications for a broad range of disciplines related to the magnetic evolution of low mass stars, and the unanticipated shutdown of their global dynamos.

The proposed research effort will obtain, analyze, and interpret new time-series Ca HK observations of stellar activity in two samples of stars with known rotation rates, designed to probe both the precursors and the contemporaries of the Sun. For a sample of young solar analogs from the Mount Wilson survey that rotate faster than the Sun, the project will obtain queue-scheduled Ca HK observations over several years to search for the relatively short activity cycles that appear to be the precursors of the 11-year solar cycle. For these bright targets, precise asteroseismic masses and ages from the Transiting Exoplanet Survey Satellite (TESS) will become available during the project (2018-2020), under a separate effort already funded by NASA. The second sample will focus on fainter stars with asteroseismic properties and rotation rates already determined from the Kepler mission, including targets with a range of evolutionary states that span the middle-age magnetic transition. The project will obtain queue-scheduled Ca HK observations of this sample to characterize the onset and duration of the transition, and to place limits on the variability of stellar activity at various stages as the global dynamo shuts down. All of the observations will be obtained using the Las Cumbres Observatory global telescope network, which has already started gathering useful data for this project.

Intellectual Merit:
This research program will establish an observational foundation for understanding how activity cycles change over the lifetime of the Sun and stars, including possible connections to planetary habitability. The resulting constraints on how the properties of magnetic cycles depend on rotation, mass, and age will have implications for theoretical models of angular momentum loss from magnetized stellar winds, and will inform predictions of long term "space weather" for the Sun and other planetary systems. These developments will provide important clues about the fundamental physics that drive magnetic dynamos, which operate in accretion disks at a variety of scales, inside Sun-like stars, and in laboratory plasmas.

Broader Impacts:
The proposed activities will directly contribute to the training of young scientists in the techniques of spectroscopic data processing and time-series analysis, through the participation of summer REU students in the research. The PI will also continue his award-winning monthly science column "Lab Notes" for the Boulder Weekly newspaper, connecting recent science discoveries with the activities of local scientists and the laboratories where they work.

1 Magnetic Evolution of Sun-like Activity Cycles

The periodic rise and fall in the number of sunspots every 11 years was first noted by Schwabe (1844), and the detailed patterns of spot orientation and migration throughout this solar activity cycle have now been characterized with exquisite observations spanning many decades. Stellar dynamo theory attempts to understand these patterns by invoking a combination of convection, differential rotation, and meridional circulation to modulate the global magnetic field (see Charbonneau, 2010). Observations of other Sun-like stars are necessarily more limited because in most cases we cannot spatially resolve spots on their surfaces. However, the solar activity cycle is clearly detectable without spatial resolution from observations of the intensity of emission in the Ca II H (396.8 nm) and K (393.4 nm) spectral lines (hereafter Ca HK). These lines have long been used as a proxy for the strength and filling factor of magnetic field because the emission traces the amount of non-radiative heating in the chromosphere (Leighton, 1959). The most comprehensive spectroscopic survey for Ca HK variations in Sun-like stars was conducted over more than 30 years from the Mount Wilson Observatory (Wilson, 1978; Baliunas et al., 1995), yielding the first large sample of stars with known rotation rates and activity cycles to help test stellar dynamo theory.

Initial results from the Mount Wilson sample suggested that both the stellar cycle period and the mean activity level depend on the Rossby number—the rotation rate normalized by the convective turnover time (Ro $\equiv P_{\rm rot}/\tau_c$, see Noyes et al., 1984). Cycle periods were shortest for the most rapidly rotating young stars, while they were longer for older stars with slower rotation. Brandenburg et al. (1998) suggested that there were actually two distinct relationships between the rotation rate and the length of the cycle, with one sequence of stars showing a cycle every 300–500 rotations, and another sequence of shorter cycles requiring fewer than $\sim$100 rotations. At moderate rotation rates (10–22 days), some stars exhibited cycles simultaneously on both sequences. Böhm-Vitense (2007) interpreted this dual pattern as evidence for two stellar dynamos operating in different shear layers, possibly at the bottom of the outer convection zone (the *tachocline*), or in the near-surface regions as suggested by helioseismic inversions (Thompson et al., 1996).

Evidence for the ubiquity of short and even dual activity cycles in young solar analogs has been growing over the past several years. García et al. (2010) found asteroseismic signatures of a short activity cycle in the F2V star HD 49933 using observations from the CoRoT satellite. The solar-like pattern of anti-correlated changes in the oscillation frequencies and amplitudes suggested a cycle period less than 2 years, and the size of the effect showed a frequency dependence similar to that observed in the Sun (Salabert et al., 2011; Libbrecht & Woodard, 1990). Metcalfe et al. (2010) discovered a 1.6-year activity cycle in the F8V star ι Hor (HD 17051), which has subsequently been confirmed with x-ray observations of the stellar corona (Sanz-Forcada et al., 2013). Metcalfe et al. (2013) documented dual activity cycles with periods of 3 years and 12.7 years in the K2V star ϵ Eri (HD 22049). Egeland et al. (2015) identified activity variations with periods of 1.7 years and 12.2 years in the G1.5V star HD 30495, falling squarely on the two rotation-activity sequences identified by Brandenburg et al. (1998). Most recently, Salabert et al. (2016) detected a 1.5-year cycle in a Kepler target using asteroseismic and photometric proxies of activity.

One of the most perplexing results from the Mount Wilson survey is that neither of the stellar-based relationships between the length of the cycle and the rotation rate match the properties of the Sun. With a mean cycle period of 11 years and a sidereal rotation period of 25.4 days ($P_{\rm cyc}/P_{\rm rot}\sim$160), the Sun falls between the two stellar sequences (Böhm-Vitense, 2007). Recent work may have identified the reason why the solar activity cycle does not fit the pattern established by other stars: the Sun's rotation rate and magnetic field may be in a transitional phase that occurs in all middle-aged stars (van Saders et al., 2016; Metcalfe et al., 2016), so the cycle might currently be growing longer (Metcalfe & van Saders, 2017). The 4.1 Gyr solar twin 18 Sco exhibits a normal cycle of 7 years (Hall et al., 2007a), falling close to the short-cycle sequence. The 5.4 Gyr solar analog α Cen A shows a longer cycle of 19 years (Ayres, 2014), while the 7.0 Gyr stars 16 Cyg A & B have reached a low activity state with no cyclic variations (Hall et al., 2007b).

The goal of this proposal is to gather new time series observations that will document how stellar activity cycles change over the lifetimes of Sun-like stars, informing a dramatic transformation in our understanding of magnetic stellar evolution. After reviewing the current evidence for a magnetic transition in middle-aged stars (**section 2**), we describe our plans to observe two samples of targets with known rotation rates and precise asteroseismic masses and ages, either already known from Kepler, or expected soon from the TESS mission (**section 3**). We discuss opportunities to involve summer REU students in the research program (**section 4**), and we present a detailed plan of work and metrics of success (**section 5**).

2 Magnetic Metamorphosis in Middle-aged Stars

The idea of using rotation as a diagnostic of stellar age dates back to Skumanich (1972), and a decade of effort has gone into calibrating the modern concept of *gyrochronology* (Barnes, 2007). Although stars are formed with a range of initial rotation rates, the stellar winds entrained in their magnetic fields lead to angular momentum loss from magnetic braking (see Kawaler, 1988). The angular momentum loss scales strongly with the angular rotation velocity $dJ/dt \propto \omega^3$, which forces convergence to a single rotation rate at a given mass after roughly 500 Myr in Sun-like stars (Pinsonneault et al., 1989). The evidence for this scenario relies on studies of rotation in young clusters at various ages, and until recently the only calibration point for ages beyond ∼1 Gyr was from the Sun.

The situation changed after the Kepler space telescope provided new data for older clusters and field stars. The initial contributions from Kepler included observations of stellar rotation in the 1 Gyr-old cluster NGC 6811 (Meibom et al., 2011) and the 2.5 Gyr-old cluster NGC 6819 (Meibom et al., 2015), extending the calibration of gyrochronology significantly beyond previous work. The first surprises emerged when asteroseismic ages became available for Kepler field stars with measured rotation periods (Metcalfe et al., 2014; García et al., 2014). Initial indications of a possible conflict between asteroseismology and gyrochronology were noted by Angus et al. (2015), who found that no single mass-dependent relationship between rotation and age could simultaneously describe the cluster and field populations. Although they used low-precision asteroseismic ages from grid-based modeling (Chaplin et al., 2014), the difference was still evident.

2.1 Breakdown of Magnetic Braking

The source of disagreement between the age scales from asteroseismology and gyrochronology came into focus after van Saders et al. (2016) scrutinized Kepler targets with precise ages from detailed modeling of the individual oscillation frequencies (Mathur et al., 2012; Metcalfe et al., 2012, 2014). They confirmed the existence of a population of field stars rotating more quickly than expected from gyrochronology. They discovered that the anomalous rotation became significant near the solar age for G-type stars, but it appeared at ∼2–3 Gyr for hotter F-type stars and at ∼6–7 Gyr for cooler K-type stars. This dependence on spectral type suggested a connection to the Rossby number, because cooler stars have deeper convection zones with longer turnover times. They postulated that **magnetic braking may operate with a dramatically reduced efficiency beyond a critical Rossby number**, and they reproduced the observations with models that eliminated angular momentum loss beyond Ro ∼ 2. This value is derived from a model-dependent estimate of the convective turnover time one pressure scale-height above the base of the outer convection zone.

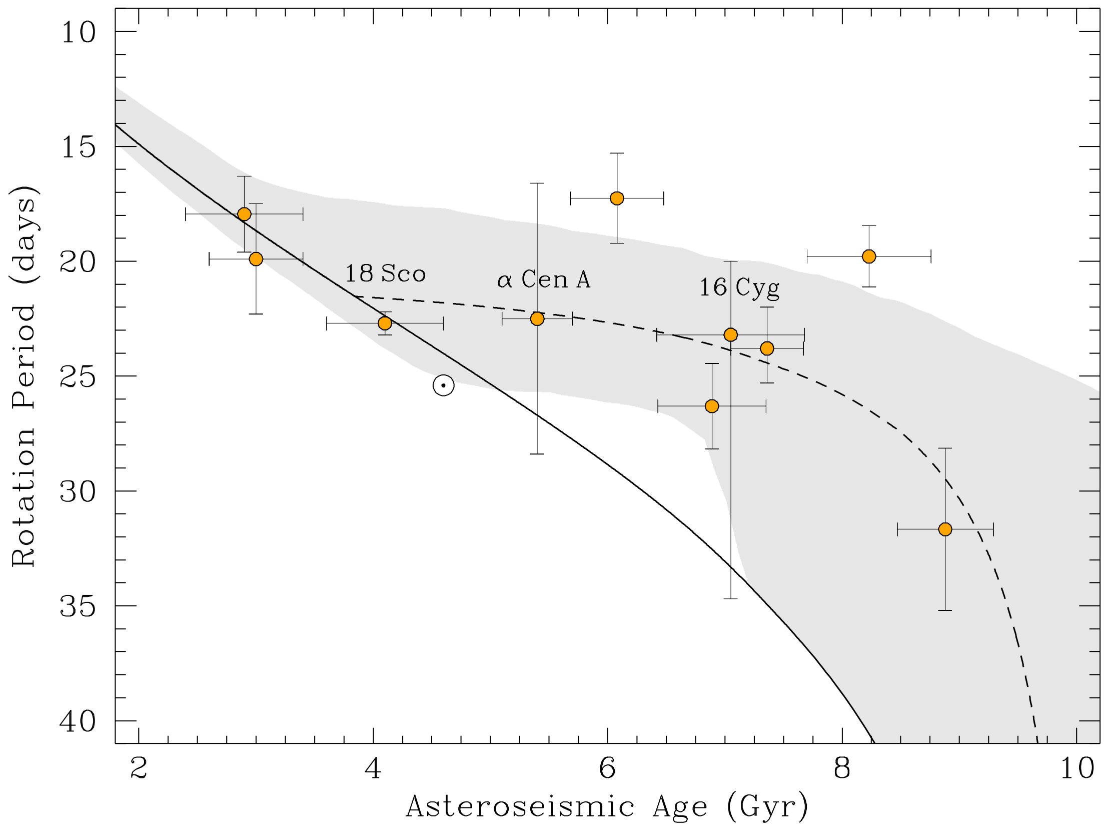

Figure 1: *Stellar evidence for the shutdown of magnetic braking in G-type stars. The solid line shows a standard rotational evolution model, which is calibrated using young star clusters and the Sun. The dashed line shows the modified model of van Saders et al. (2016), which eliminates angular momentum loss beyond a critical Rossby number determined from a fit to Kepler field stars with precise asteroseismic ages. The shaded region represents the expected dispersion due to the range of masses and metallicities within the sample. A few bright solar analogs are labeled.*

Although the specific value obtained by van Saders et al. (2016) depends on mixing-length theory, the observed trend for stars of various masses and ages is robust.

The anomalous rotation discovered by van Saders et al. (2016) is illustrated for G-type stars in **Figure 1**. A standard rotational evolution model (solid line) and the modified model that eliminates angular momentum loss beyond a critical Rossby number (dashed line) are from the original paper, which also used hotter and cooler stars to constrain the fit. Note that the solar age and rotation rate (marked with a $\odot$ symbol) were used to calibrate the standard model beyond the 0.5–2.5 Gyr age range of clusters. Asteroseismic ages for the Kepler sample have been updated with values from Creevey et al. (2017). The shaded region represents the expected dispersion due to the range of masses and metallicities within the sample (e.g., the two high points are lower metallicity stars, giving them thinner convection zones that reach the critical Rossby number at faster rotation rates). The asteroseismic rotation rates and ages for a $\sim$3 Gyr-old solar analog binary system (White et al., 2017) have been overplotted, validating asteroseismic rotation measurements and the age scale for G-type Kepler stars. A few well-characterized solar analogs are labeled, including 18 Sco (Petit et al., 2008; Li et al., 2012; Mittag et al., 2016), α Cen A (Bazot et al., 2007, 2012), and 16 Cyg A & B (Davies et al., 2015; Creevey et al., 2017). Although some uncertainties remain for 18 Sco and α Cen A, these bright stars appear to follow the same pattern of anomalous rotation observed in the Kepler sample.

Theoretical interpretation: van Saders et al. (2016) suggested that magnetic braking might become less efficient in older stars from a concentration of the field into smaller spatial scales. Réville et al. (2015) demonstrated that the dipole component of the global field is responsible for most of the angular momentum loss due to the magnetized stellar wind (see also Garraffo et al., 2016). The Alfvén radius is greater for the larger scale components of the field, and because both the open flux and the effective lever-arm increase with a larger Alfvén radius, low-order fields consequently shed more angular momentum. The inverse of this shift in magnetic topology may be responsible for the onset of efficient magnetic braking in very young stars (Brown, 2014).

2.2 Triggering the Magnetic Transition

Metcalfe et al. (2016) identified a magnetic counterpart to the rotational transition discovered by van Saders et al. (2016). They compiled published Ca HK measurements for the Kepler sample and compared them to a selection of G-type stars from the Mount Wilson survey (Baliunas et al., 1996; Donahue et al., 1996). Such a comparison requires the Ca HK measurements to be represented using a chromospheric activity scale ($\log R'_{\rm HK}$) that accounts for different bolometric fluxes.

The relationship between chromospheric activity and rotation is illustrated in **Figure 2**. The Kepler targets are plotted by spectral type, including F-type (blue triangles), G-type (yellow circles), and K-type stars (red squares), while the Mount Wilson targets are shown as star symbols. Several rotational evolution models from van Saders et al. (2016) are shown, converted from Rossby number to chromospheric activity using the rotation-activity relation of Mamajek & Hillenbrand (2008). The activity levels that correspond to key Rossby numbers are shown as shaded regions on either side of the Vaughan-Preston gap (dotted line; Vaughan & Preston, 1980). The dashed line connects some well-characterized solar analogs, including the bright stars shown in Figure 1.

The magnetic evolution of Sun-like stars appears to change dramatically when they reach the critical Rossby number identified by van Saders et al. (2016). The shutdown of magnetic braking near the activity level of 18 Sco ($\log R'_{\rm HK}$=−4.93; Hall et al., 2007b) keeps the surface rotation rate nearly constant as the activity level continues to decrease with age toward α Cen A ($\log R'_{\rm HK}$=−5.00; Henry et al., 1996) and 16 Cyg ($\log R'_{\rm HK}$=−5.09; Wright et al., 2004). A similar transition occurs at faster rotation rates for hotter stars (blue triangles), and at slower rotation rates for cooler stars (red squares). The influence of this magnetic transition on stellar activity cycles is described in the following subsection.

Theoretical interpretation: Metcalfe et al. (2016) proposed that a change in the character of differential rotation is the mechanism that ultimately disrupts the large-scale organization of magnetic fields in Sun-like stars. The process begins at Ro ∼ 1, where the rotation period becomes comparable to the convective turnover time. Differential rotation is an emergent property of turbulent convection in the presence of Coriolis forces, and Gastine et al. (2014) showed that many global convection simulations exhibit a transition from solar-like to anti-solar differential rotation near Ro ∼ 1 (see also Brun et al., 2017). The Vaughan-Preston gap can then be interpreted as a signature of rapid magnetic evolution triggered by a shift in the character of differential rotation. Pace et al. (2009) used activity measurements of stars in several open clusters to constrain the age of F-type stars crossing the gap to be between 1.2 and 1.4 Gyr. The two most active F-type stars in the Kepler sample have ages of 0.94 and 1.64 Gyr and fall on opposite sides of the gap, validating the asteroseismic age scale for hotter stars.

Emerging from the rapid magnetic evolution across the Vaughan-Preston gap, stars reach the Ro ∼ 2 threshold where magnetic braking operates with a dramatically reduced efficiency, possibly

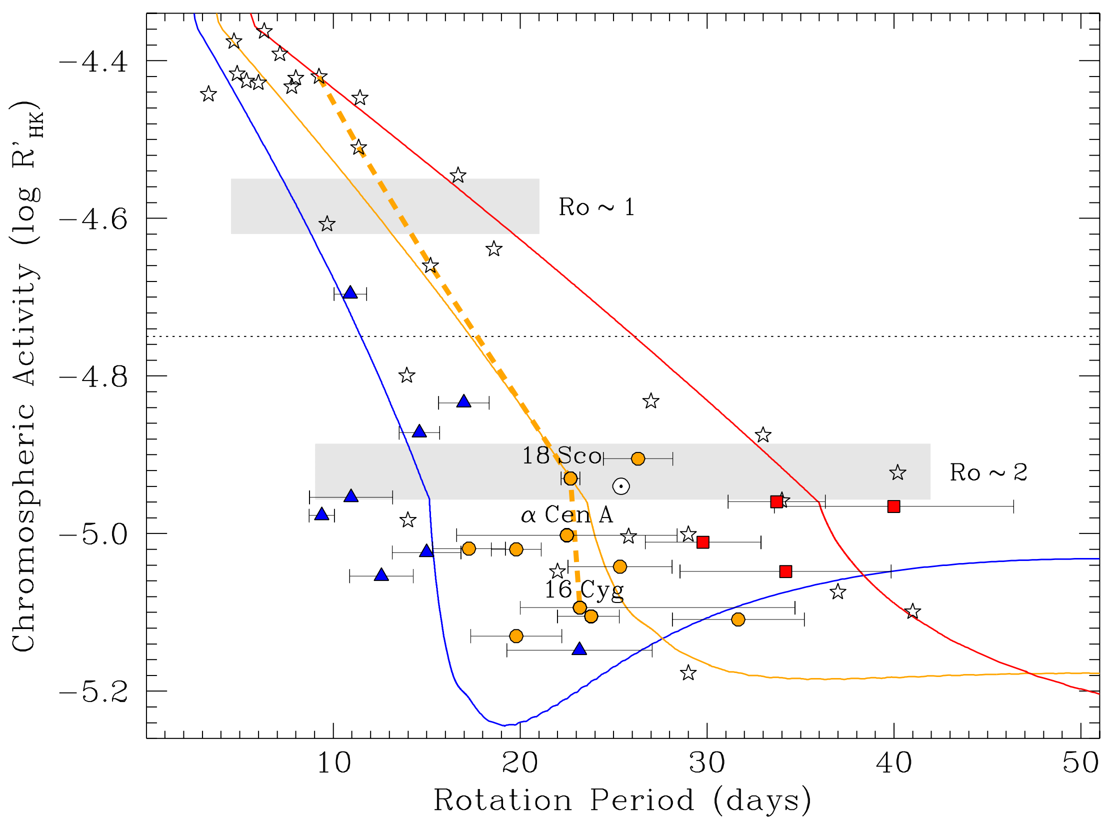

Figure 2: *The evolution of chromospheric activity in Sun-like stars. Points are colored by spectral type, indicating F-type (blue triangles), G-type (yellow circles), and K-type stars (red squares). A selection of Mount Wilson targets are shown as star symbols and several rotational evolution models from van Saders et al. (2016) are shown as solid lines. A few solar analogs are connected with a yellow dashed line, crossing the Vaughan-Preston gap (dotted line) before reaching the critical Rossby number (Ro ∼ 2, shaded region) where magnetic braking becomes less efficient.*

due to a shift in magnetic topology. The rotation period then evolves as the star undergoes slow expansion and changes its moment of inertia as it ages. At the same time, the activity level decreases with effective temperature as the star expands and mechanical energy from convection largely replaces magnetic energy driven by rotation as the dominant source of chromospheric heating (Böhm-Vitense, 2007).

2.3 Manifestation in Stellar Activity Cycles

The new picture of rotational and magnetic evolution provides a framework for understanding some observational features of stellar activity cycles that have until now been mysterious. An updated version of a diagram published by Böhm-Vitense (2007) is shown in **Figure 3**, using data from Brandenburg et al. (1998). More recent data have been added from Hall et al. (2007a), Bazot et al. (2007), Petit et al. (2008), Metcalfe et al. (2010, 2013), Ayres (2014), Egeland et al. (2015), and Salabert et al. (2016).

The stellar sequence along the bottom of Figure 3 has three distinct regimes. For faster rotators ($P_{\rm rot} < 22$ days), this sequence is dominated by short cycles for stars that also show longer cycles on the upper sequence (vertical dotted lines). Many of the Mount Wilson targets in this

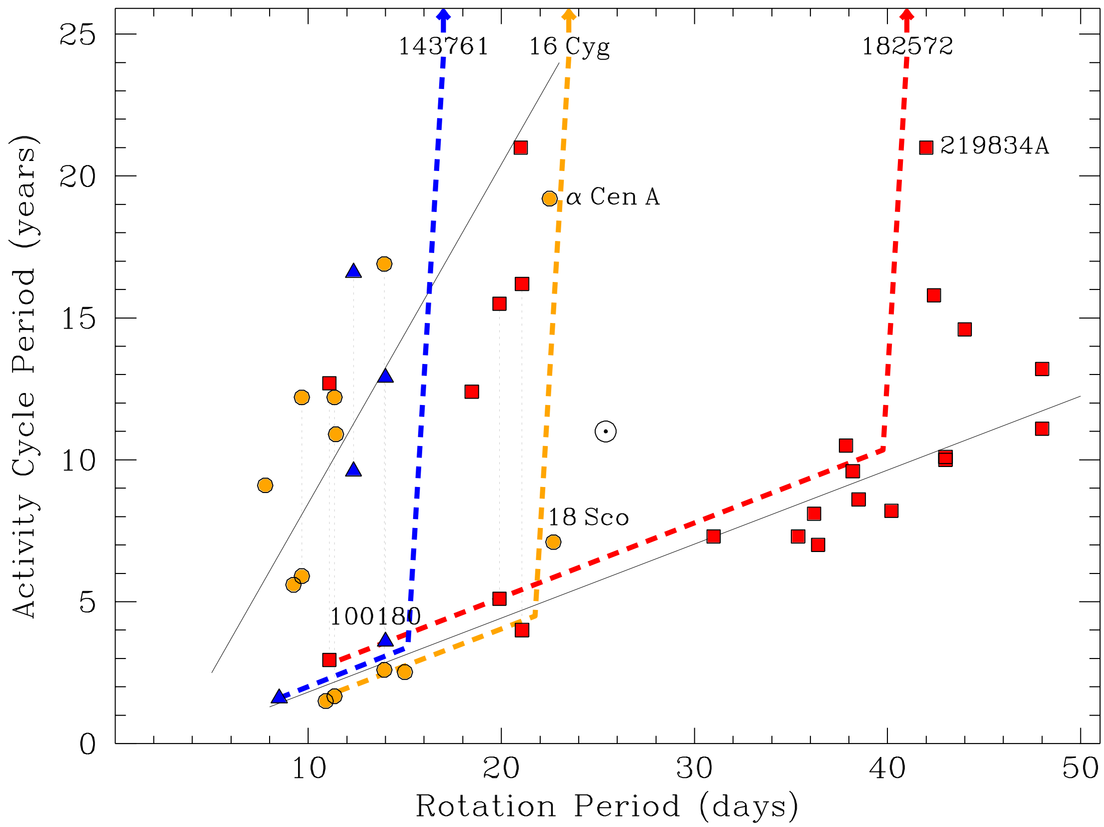

Figure 3: *Updated version of a diagram originally published by Böhm-Vitense (2007), showing two distinct relationships between rotation period and the length of the activity cycle (solid lines). Cycles operating simultaneously in the same star are connected with a vertical dotted line. Points are colored by spectral type, indicating F-type (blue triangles), G-type (yellow circles), and K-type stars (red squares). Schematic evolutionary tracks are shown as dashed lines, leading to stars with constant activity (along the top) that appear to have completed the magnetic transition.*

regime appeared to have "chaotic variability" in their chromospheric activity. This may be due to the ubiquity of short period cycles on the lower sequence, combined with seasonal data gaps that failed to sample these timescales adequately. F-type stars are expected to begin the magnetic transition at rotation periods ∼15 days, but there are very few hot stars with well determined cycles. The oldest cycling F-type star in the Mount Wilson sample is HD 100180 (2.0 ± 0.4 Gyr; Barnes, 2007), which has $P_{\rm rot}$=14 days and shows normal cycles on both sequences. The more evolved star HD 143761 has $P_{\rm rot}$=17 days, and shows constant activity at $\log R'_{\rm HK}$=-5.04 for 25 years (Baliunas et al., 1995). The age from gryochronology implied by this rotation period (a lower limit on the actual age) is 2.5 ± 0.4 Gyr (Barnes, 2007), which agrees with the asteroseismic age of F-type stars observed by Kepler that have reached the critical Rossby number (blue dashed line) where the surface rotation period subsequently evolves much more slowly (van Saders et al., 2016).

The transition across Ro$\sim$2 for G-type stars occurs at rotation periods comparable to the Sun ($P_{\rm rot}\sim$22–30 days). Before reaching this threshold, magnetic braking continues in these stars and their cycle periods evolve along the two sequences in Figure 3 as their rotation slows. When they reach the critical Rossby number, the surface rotation rate changes much more slowly and we postulate that the cycle period responds to the magnetic transition. If we consider the evolutionary sequence defined by 18 Sco (4.1±0.5 Gyr; Li et al., 2012; Mittag et al., 2016), the Sun (4.6 Gyr), and α Cen A (5.4±0.3 Gyr; Bazot et al., 2012), the data suggest that a normal cycle on the lower sequence may grow longer across the transition (yellow dashed line). Eventually stars reach a low activity state like 16 Cyg A & B ($P_{\rm rot}$∼23.5 days at 7 Gyr; Davies et al., 2015; Metcalfe et al., 2015), where cyclic activity is no longer detected (Hall et al., 2007b). The Sun falls to the right of this evolutionary sequence because it is slightly less massive than the other stars (with a longer convective turnover time), so it does not reach the critical Rossby number until its rotation is a bit slower. Considering other Sun-like stars, we propose that the solar cycle may be growing longer on stellar evolutionary timescales, and that the cycle might disappear sometime in the next 0.8–2.4 Gyr (between the ages of α Cen and 16 Cyg). Although α Cen A appears in the same region of Figure 3 as several K-type stars, the broader evolutionary scenario suggests that the current cycle evolved from a shorter period on the lower sequence near 18 Sco. The expected cycle period on the upper sequence for G-type stars at the rotation period of α Cen A is ∼35 years, much longer than the observed cycle (Brandenburg et al., 2017). In addition, there is no evidence of a shorter cycle in α Cen A (see Ayres, 2014), even though 18 Sco shows a cycle on the lower sequence at essentially the same rotation period.

All of the slowest rotators with cycles ($P_{\rm rot}$>30 days) are K-type stars, which is now understandable: magnetic braking shuts down in more massive main-sequence stars before they reach these long rotation periods. Depending on the effective temperature, K-type stars reach the critical Rossby number at rotation periods longer than 35 days. The hottest cycling K-type star in Figure 3 is HD 219834A, and it appears to be well along the magnetic transition (red dashed line). All of the stars to the right of HD 219834A are significantly cooler, so they have not yet reached the critical Rossby number (Brandenburg et al., 2017). The slightly hotter star HD 182572 ($P_{\rm rot}$∼41 days; Baliunas et al., 1996) appears to have already completed the magnetic transition like 16 Cyg A & B, showing constant activity at $\log R'_{\rm HK}=-5.10$ for 13 years (Baliunas et al., 1995).

The greatest obstacle to understanding how the magnetic transition influences stellar activity cycles is the sparsity of suitable observations. The bright sample of stars that were monitored for decades by the Mount Wilson survey have well-characterized long activity cycles and rotation periods, but their basic stellar properties are uncertain. In particular, the precise masses and ages that would allow us to identify evolutionary sequences are currently available for just a few stars (e.g. asteroseismology of 18 Sco and α Cen A, Li et al., 2012; Bazot et al., 2012). This situation will soon improve, after the Transiting Exoplanet Survey Satellite (TESS) yields asteroseismic data for bright stars across the sky during a two year mission (2018–2020). Although the time series photometry will span only 27 days for most TESS targets, this was sufficient to detect solar-like oscillations in hundreds of Kepler and K2 stars down to V∼12 (Chaplin et al., 2011, 2015). Similar detections are expected from TESS down to V∼7 (Campante et al., 2016), particularly in F-type and hotter G-type stars with larger intrinsic oscillation amplitudes.

Although the basic stellar properties of the fainter Kepler sample are well-constrained from asteroseismology, chromospheric activity data have not been collected with sufficient cadence and duration to detect stellar cycles or establish constant activity. About a dozen stars in the van Saders et al. (2016) sample were monitored in Ca HK several times per year during the Kepler mission (2009–2013, Karoff et al., 2013). The cadence was insufficient to detect the shortest activity cycles, and the limited duration prevented the identification of longer cycles. So far, the only credible cycle in a Kepler target was detected using asteroseismic and photometric proxies of activity (Salabert et al., 2016), revealing a 1.5-year cycle on the lower sequence at $P_{\rm rot}$∼ 11 days. Most of the Kepler sample has already made the transition across Ro ∼ 2, so we might expect them to be constant activity stars like 16 Cyg A & B (Hall et al., 2007b), but this needs to be confirmed observationally.

3 Proposed Research

We propose to obtain new time series observations of stellar activity in two samples of stars with known rotation rates, designed to probe both the precursors and the contemporaries of the Sun. All of the data will be obtained using the Las Cumbres Observatory (LCO) global telescope network, with a queue-scheduled observation program informed by previous experience running a similar survey on the SMARTS telescopes (**section 3.1**). For a sample of bright stars from the Mount Wilson survey that rotate faster than the Sun, we will obtain observations over several years to search for the relatively short activity cycles that appear to be the precursors of the 11-year solar cycle (**section 3.2**). For these bright targets, precise asteroseismic masses and ages from the Transiting Exoplanet Survey Satellite (TESS) will become available during the project (2018–2020), under a separate effort already funded by NASA (NNX16AB97G, PI: T. Metcalfe, 2016–2019). The second sample will focus on fainter stars with asteroseismic properties and rotation rates already determined from the Kepler mission, including targets with a range of ages that span the magnetic transition ($\log R'_{\rm HK} \approx -4.95 \pm 0.05$). We will obtain observations of this sample to characterize the onset and duration of the transition, and to place limits on the variability of stellar activity at various stages as the global dynamo shuts down (**section 3.3**).

3.1 Queue-scheduled Observations

The SMARTS southern HK project (Metcalfe et al., 2009b) began in August 2007 with the primary objective of characterizing stellar activity cycles for the brightest stars (V<6) in the southern hemisphere. The 58 solar-type stars in the sample, defined as a subset of the Henry et al. (1996) sample, included all of the most likely future asteroseismic targets of the Stellar Observations Network Group (SONG; Grundahl et al., 2008). Several targets near the celestial equator provided an overlap with the Mount Wilson and Lowell surveys (Baliunas et al., 1995; Hall et al., 2007b), allowing the calibration of derived Ca HK S-indices onto the Mount Wilson scale.

During the 5.5-year survey, the project used the *RC Spec* instrument on the SMARTS 1.5-m telescope to obtain low-resolution ($R \sim 2500$) spectra of all available targets on 1–2 epochs per month. Standard IRAF routines were used on the 5–1000 s integrations to apply bias and flat field corrections, and a wavelength calibration was applied using a reference He-Ar spectrum obtained just prior to each pair of stellar exposures. Following Duncan et al. (1991), the calibrated spectra were integrated in 1.09 Å triangular bandpasses centered on the cores of the Ca HK lines and were compared to 20 Å continuum regions from the wings of the lines to generate a SMARTS stellar activity index. Data for 26 targets that were observed contemporaneously with the Solar-Stellar Spectrograph at Lowell Observatory were used to make the conversion to Mount Wilson indices. An example of the time series S-index measurements from SMARTS, for the young solar analog HD 30495 (Egeland et al., 2015), is shown in **Figure 4**. Several short-period activity cycles were discovered during the program (Metcalfe et al., 2010, 2013), demonstrating the benefits of queue-scheduling where useful observations can be obtained for 8–9 months per year for each target. The SMARTS survey ended in February 2013 when the *RC Spec* instrument was decommissioned.

The National Optical Astronomy Observatory (NOAO) began coordinating public access to the LCO global telescope network in April 2017, funded by the NSF Mid-Scale Innovations Program. LCO currently operates 9 × 1-m robotic optical telescopes at 4 sites (in Chile, South Africa, Australia, and Texas), optimized for time-domain studies and operated as a single observatory. Additional 1-m telescopes are planned for China and the Canary Islands. In 2012, LCO received NSF Major Research Instrumentation funding to design, build, and deploy the Network of Robotic Echelle Spectrographs (NRES). This network consists of 6 identical fiber-fed, cross-dispersed echelle

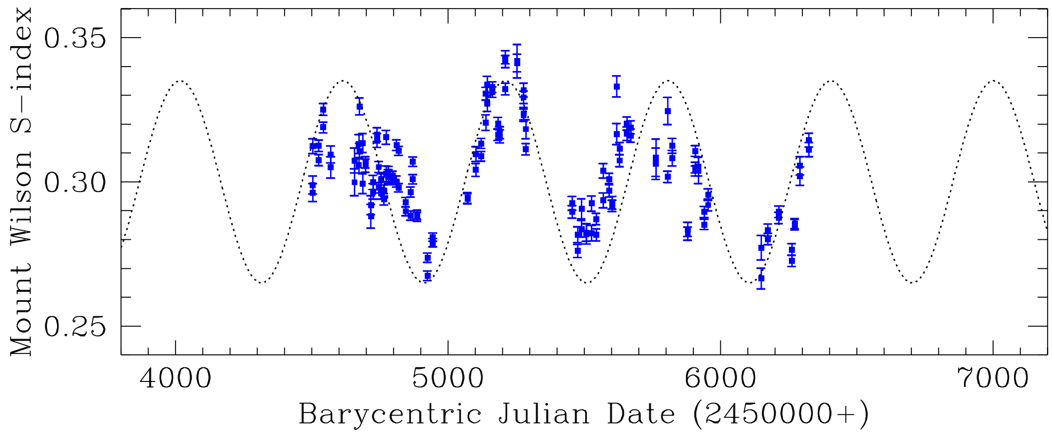

Figure 4: *Chromospheric activity data for HD 30495 from the SMARTS 1.5-m telescope between 2008–2013, revealing a short 1.7-year activity cycle. Narrow seasonal data gaps from the queue-scheduled observations enabled the discovery of this short activity cycle.*

spectrographs, each able to accept light from two of LCO's 1-m telescopes. The NRES spectrographs have R = 53,000, almost complete coverage from the Ca HK lines to the Ca infrared triplet, peak throughput above 10% (including losses in the atmosphere, telescope, fiber, and detector), and radial velocity accuracy at the few m/s level. Additional details about LCO and NRES are available in the "Facilities, Equipment, and Other Resources" document.

The first NRES spectrograph was installed in Chile, and began gathering useful data for our southern and equatorial targets in September 2017. The second spectrograph was installed in Texas, and became available for public access in November 2017. The third spectrograph was recently installed in South Africa. Approximately 1220 hours of time on the 1-m network are available to the U.S. community each semester. **We propose to conduct queue-scheduled observations of stellar activity for two samples of stars using the NRES spectrographs on the LCO global telescope network.** The scientific motivation and target lists for both samples are presented in the following subsections.

3.2 Stellar Activity Cycles in Solar Analogs

Although the solar activity cycle does not fall along either of the rotational sequences established by other stars (see Figure 3), the available evidence suggests that it more closely resembles the cycles on the lower sequence. Böhm-Vitense (2007) proposed that the lower sequence represents stellar cycles driven at the base of the convection zone, while cycles on the upper sequence are driven in a near-surface shear layer. This idea is consistent with Zeeman Doppler imaging observations of magnetic topology on the two sequences, which show that cycles on the upper sequence are dominated by toroidal fields while those on the lower sequence are poloidal (See et al., 2016). Magnetic flux generated near the tachocline takes longer to reach the surface, while flux generated in the near-surface shear layer takes less time to rise and is more likely to emerge in a stressed toroidal state. Our best example of a possible precursor to the Sun—the 4.1 Gyr solar twin 18 Sco—shows a 7-year cycle on the lower sequence (Hall et al., 2007a), suggesting that the solar cycle may have become longer over the past several hundred million years.

We have compiled a target list of 34 bright FGK stars for the LCO observing program, with a specific focus on sensitivity to short activity cycles (see **Table 1**). The highest priority targets include 19 stars from Brandenburg et al. (1998) with rotation periods shorter than 22 days and at

Table 1: Target List for the TESS Solar Analog Sample.

HD	Name	R.A.(2000)	Dec.(2000)	V	Type	$P_{\rm rot}$(d)	$P_{\rm cyc}$(yr)
1835	9 Cet	00 22 51.79	−12 12 34.0	6.4	G3V	7.8	9.1
12235	112 Psc	02 00 09.16	+03 05 49.2	5.9	G2IV	14	···
17051*	ι Hor	02 42 33.47	−50 48 01.1	5.4	F8V	8	1.6
20630	κ^1 Cet	03 19 21.70	+03 22 12.7	4.8	G5V	9.2	5.6
22049*	ϵ Eri	03 32 55.84	−09 27 29.7	3.7	K2V	11.3	3.0 + 12.7
26913	V891 Tau	04 15 25.79	+06 11 58.7	6.9	G8V	7.2	7.8
30495*	58 Eri	04 47 36.29	−16 56 04.0	5.5	G1.5V	11.4	1.7 + 12.2
37394	V538 Aur	05 41 20.33	+53 28 51.8	6.2	K1V	11	3.6?
43587		06 17 16.14	+05 00 00.4	5.7	G0V	20	···
49933*		06 50 49.83	−00 32 27.2	5.8	F3V	3.4	<2?
75332		08 50 32.22	+33 17 06.2	6.2	F7V	4	3.5?
76151*		08 54 17.95	−05 26 04.1	6.0	G3V	15	2.5?
78366		09 08 51.07	+33 52 56.0	5.9	G0V	9.7	5.9 + 12.2
82443	DX Leo	09 32 43.76	+26 59 18.7	7.0	K0V	5.4	2.8?
82885	11 LMi	09 35 39.50	+35 48 36.5	5.3	G8V	18.6	7.9
88737		10 14 29.75	+21 10 05.0	6.0	F9V	8	21
98230B	ξ UMa B	11 18 10.95	+31 31 45.7	4.7	G2V	4	2.2?
100180	88 Leo	11 31 44.94	+14 21 52.2	6.2	F9.5V	14.0	3.6 + 12.9
114710	β Com	13 11 52.39	+27 52 41.5	4.2	F9.5V	12.4	9.6 + 16.6
115383*	59 Vir	13 16 46.52	+09 25 27.0	5.2	G0V	3.3	4.3?
115404		13 16 51.05	+17 01 01.9	6.7	K2V	18.5	12.4
120136	τ Boo	13 47 15.74	+17 27 24.9	4.5	F6IV	3.3	<1?
126053		14 23 15.28	+01 14 29.6	6.3	G1.5V	22	14
136202	5 Ser	15 19 18.80	+01 45 55.5	5.1	F8IV	16	23
149661	12 Oph	16 36 21.45	−02 19 28.5	5.8	K2V	21.1	4.0 + 16.2
152391	V2292 Oph	16 52 58.80	−00 01 35.1	6.6	G8.5V	11.4	10.9
154417	V2213 Oph	17 05 16.82	+00 42 09.2	6.0	F9V	7.8	7.4
165341A*	70 Oph A	18 05 27.37	+02 29 59.3	4.2	K0V	19.9	5.1 + 15.5
176051		18 57 01.61	+32 54 04.6	5.3	G0V	16	10
182101		19 22 48.35	+09 54 47.3	6.4	F6V	5.0	5.1?
187691	o Aql	19 51 01.64	+10 24 56.6	5.1	F8V	10	5.4?
190406*	15 Sge	20 04 06.22	+17 04 12.6	5.8	G0V	13.5	2.6 + 16.9
194012		20 22 52.37	+14 33 04.0	6.2	F7V	7.0	5.4? + 16.7
206860	HN Peg	21 44 31.33	+14 46 19.0	6.0	G0V	4.9	6.2

least one longer-period cycle on the upper sequence, such that a short activity cycle ($P_{\rm cyc}$<5 years) on the lower sequence might be undetected in the Mount Wilson data. Five of these are G-type stars that probe the gap between $P_{\rm rot}$=15–22 days in Figure 3. We supplement this exploratory sample by adding 15 stars that have shown some evidence of short-term activity variations, including a few with confirmed cycles to validate our detection limits. **We propose to conduct a short-cycle survey spanning three years, using NRES to obtain 1–2 Ca HK measurements per month over the entire observing season for each target in our sample of young solar analogs.** Telescope time estimates are provided in section 5.

The immediate objective of our new observations is to discover short activity cycles that are precursors of the solar cycle, which may have been missed by previous surveys due to low signal-to-noise measurements and large seasonal data gaps. These observations will also allow us to probe the onset of the magnetic transition in hotter stars, and to confirm the existence of a few suspected short activity cycles with high-cadence data. The long-term activity records (1966–1995) for the Mount Wilson targets have been released through an archive at the National Solar Observatory, and more recent observations for many stars are available from the Solar Stellar Spectrograph at Lowell Observatory (Hall et al., 2007b). In addition, higher-cadence observations from the SMARTS survey (2007–2013) are available for 8 of the targets, marked with a "*" in Table 1. Merging our new time series observations from LCO with the previous measurements from Mount Wilson, Lowell, and SMARTS will also allow us to improve the characterization of longer cycles on the upper sequence, even during the limited duration of the current project.

To create an evolutionary sequence of activity cycles, we need reliable estimates of the mass and age for each target. All of the stars in Table 1 will have photometric observations from TESS with a cadence of 2 minutes for at least 27 days. The probability of detecting oscillations is high for most of the targets, but marginal for the fainter and cooler stars. Consequently, we can expect to determine the radius, mass, and age for at least 75% of the solar analog sample from asteroseismology, under a separate effort already funded by NASA. In case of marginal asteroseismic detections, gyrochronology can still provide reliable age estimates for cooler G- and K-type stars at these rotation periods, while masses good to 10% can be derived from the granulation timescale determined by TESS and a Gaia parallax (Stassun et al., 2017).

3.3 Stellar Activity across the Magnetic Transition

The sample of Kepler targets with known rotation periods and precise asteroseismic properties currently represents our best opportunity to understand the nature of the magnetic transition in middle-aged stars. We can consider the evolution of stellar cycles in a few bright solar analogs to set our general expectations: relatively short cycles on the lower sequence (e.g. 18 Sco, Hall et al., 2007a) may gradually become longer over ∼1 Gyr (e.g. α Cen A, Bazot et al., 2007, 2012; Ayres, 2014) before transitioning to a constant activity state up to 2 Gyr later (e.g. 16 Cyg A & B, Hall et al., 2007b; Metcalfe et al., 2015). The position of the Sun as an outlier in Figure 3 suggests that it has already started the magnetic transition. The normal cycle in 18 Sco, which is several hundred million years younger than the Sun (Li et al., 2012), establishes an approximate timescale for when the solar magnetic transition began. This roughly coincides with the emergence of land-based life on Earth (e.g., Garwood & Edgecombe, 2011), suggesting a (highly speculative but) possible connection to planetary habitability. This intriguing idea can be refined by expanding the sample of Sun-like stars with precise ages and measured activity cycles.

The fact that the magnetic transition is connected to the Rossby number allows us to derive useful constraints from the full range of rotation rates and spectral types that are available in the Kepler sample. This is particularly helpful for F-type stars, which begin the transition at rotation periods shorter than $P_{\rm rot}\sim$15 days. In this range of rotation periods, stellar activity cycles on the lower sequence have $P_{\rm cyc}$<3–4 years, allowing a characterization of the magnetic transition in F-type stars on the timescale of this project. There is already evidence of a 1.5-year activity cycle in KIC 10644253 (Salabert et al., 2016), and we might expect the gradual lengthening and eventual disappearance of activity cycles in the older F-type stars that fall along the same evolutionary sequence (dashed blue line in Figure 3). Through the Rossby number, observations of stellar activity in F-type stars will also place constraints on the trajectory of the solar activity cycle.

The sample of targets analyzed by van Saders et al. (2016) included 21 stars with asteroseismic properties from Metcalfe et al. (2014) and rotation periods determined by García et al. (2014). We have recently expanded the sample to 34 stars, including an updated asteroseismic analysis of the full-length Kepler data sets (Lund et al., 2017; Creevey et al., 2017) and additional detections of rotation from Nielsen et al. (2015) and White et al. (2017). We exclude from the Kepler magnetic transition sample the Lowell targets 16 Cyg A & B, and we focus on V<10 to keep integration times reasonable, leaving 15 targets (see **Table 2**). This sample will add six F-type stars to the two that currently define the magnetic transition, and it will probe the variability of six G-type stars with rotation periods longer than 15 days (see Figure 3). Although the Kepler targets are fainter than the solar analog sample, many of them are expected to show minimal activity variations. **We propose to obtain queue-scheduled Ca HK measurements of the Kepler sample to characterize the onset and duration of the magnetic transition, and to place limits on the variability of stellar activity at various stages as the global dynamo shuts down.**

Table 2: Target List for the Kepler Magnetic Transition Sample.

KIC	R.A.(2000)	Dec.(2000)	V	Type	$P_{\rm rot}$(d)	$\log R'_{\rm HK}$	M ($M_\odot$)	Age (Gyr)
3427720	19 05 45.26	+38 31 22.6	9.5	F9IV-V	13.94	−4.78	1.14 ± 0.06	2.17 ± 0.16
5184732	19 24 30.33	+40 19 23.7	8.6	G1V	19.79	−5.15	1.25 ± 0.03	4.45 ± 0.25
6116048*	19 17 46.36	+41 24 36.6	8.7	F9IV-V	17.26	−5.14	1.03 ± 0.01	5.90 ± 0.25
6278762	19 19 00.55	+41 38 04.6	8.9	K0V	34.40	···	0.75 ± 0.01	11.22 ± 0.56
7871531	18 51 39.61	+43 38 09.9	9.8	G5V	33.72	−4.96	0.82 ± 0.03	8.72 ± 0.34
7970740	19 41 45.64	+43 44 51.7	8.0	G9V	40.00	−4.97	0.79 ± 0.02	10.22 ± 0.35
8006161*	18 44 35.15	+43 49 59.9	7.9	G8V	29.79	−5.00	1.02 ± 0.02	4.50 ± 0.23
8379927*	19 46 41.29	+44 20 54.7	7.3	F9IV-V	16.99	−4.86	1.09 ± 0.02	1.29 ± 0.24
9139151*	18 56 21.26	+45 30 53.1	9.5	G0.5IV	10.96	−5.04	1.15 ± 0.06	1.89 ± 0.32
10124866	18 58 03.46	+47 11 30.6	8.1	G4V	17.95	−4.99	0.92 ± 0.05	2.90 ± 0.29
10454113*	18 56 36.63	+47 39 23.1	8.9	F9IV-V	14.61	−4.96	1.23 ± 0.04	2.09 ± 0.17
10644253	18 43 42.42	+47 56 16.0	9.5	G0V	10.91	−4.82	1.18 ± 0.09	0.90 ± 0.24
10963065	18 59 08.68	+48 25 23.6	9.0	F8V	12.58	−5.13	1.03 ± 0.01	4.19 ± 0.25
12009504*	19 17 45.80	+50 28 48.2	9.6	F9IV-V	9.39	−5.18	1.13 ± 0.03	3.25 ± 0.31
12258514*	19 26 22.08	+50 59 14.1	8.4	G0.5IV	15.00	−5.18	1.25 ± 0.03	5.66 ± 0.38

The cadence of observations will be optimized for each target to capture the expected timescale of variability, with adjustments if the data defy our expectations. The faster rotating stars that are expected to show short activity cycles are also brighter, so the need for higher cadence is offset by shorter integration times. Stars that have made the magnetic transition are typically fainter, but we do not expect them to show much short-term variability. For the 7 targets marked with a "*" in Table 2, we will probe longer-term variability by merging our new observations with the measurements made by Karoff et al. (2013) several times per year over the lifetime of the Kepler mission. Note that useful observations of the Kepler field can be obtained from March through October each year, so the time requirements for this sample are uneven across semesters. Telescope time estimates are provided in section 5.

Updated asteroseismic properties for the Kepler sample will become available during the project (2018–2019), by using DR2 parallaxes from Gaia (Perryman et al., 2001) to provide luminosity constraints. Although previous asteroseismic results are consistent with the luminosities derived from Hipparcos parallaxes (van Leeuwen, 2007; Creevey et al., 2017), the more precise parallaxes from Gaia promise to break the well-known correlation between mass and initial helium abundance in stellar models (e.g., see Lebreton & Goupil, 2014), yielding more accurate stellar properties. This work will be done under a separate effort already funded by NASA.

Summary of Intellectual Merit: The research program described above will establish an observational foundation for understanding how activity cycles change over the lifetime of the Sun and stars, including possible connections to planetary habitability. The resulting constraints on how the properties of magnetic cycles depend on rotation, mass, and age will have implications for theoretical models of angular momentum loss from magnetized stellar winds, and will inform predictions of long term "space weather" for the Sun and other planetary systems. These developments will provide important clues about the fundamental physics that drive magnetic dynamos, which operate in accretion disks at a variety of scales, inside Sun-like stars, and in laboratory plasmas.

4 Broader Impacts

The proposed activities will directly contribute to the training of young scientists in the techniques of spectroscopic data processing and time series analysis, through the participation of undergraduate students in the research. Space Science Institute is a participating institution in the Research Experiences for Undergraduates (REU) program organized by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado. This program has been operating since 2007, and a renewal proposal to continue it for three more years was approved in 2017. The 10-week summer program introduces students to authentic research in solar and space physics in an interdisciplinary environment. After a week of introductory lectures and a course in scientific computing, the students work on individual research projects guided by scientist mentors from the participating institutions. The program concludes with each student giving a 30 minute oral presentation of their work and preparing a poster or manuscript of their findings.

The LASP program provides support for 12 students each summer, and it typically has 10 times more applicants than positions. Prospective science mentors at participating institutions around Boulder submit project proposals each January, and most of the projects are ultimately matched with a student—in the past five years there were typically only 1–2 more proposals than students. The first summer project will involve calibrating new NRES spectra onto the Mount Wilson scale and merging the data with previous observations from SMARTS. The second summer project will attempt to place limits on the chromospheric variability of stars crossing the magnetic transition, and the third summer project will focus on detecting the shortest activity cycles in solar analogs. The PI has previously mentored several undergraduate summer students through the Significant Opportunities in Atmospheric Research and Science (SOARS) program at NCAR. Any projects that are not matched with a summer REU student will be performed by the PI.

In addition to mentoring summer REU students, the PI will continue his award-winning monthly science column "Lab Notes" for the *Boulder Weekly* newspaper, devoting 5% of his time to the series. With so many federal laboratories and research institutes concentrated around Boulder, the column highlights the role of local scientists in research that captures the public imagination. It also promotes informal education related to the scientific topics covered by the series. The PI began writing the column in 2015, with articles covering a range of topics including: astrophysics, climate science, commercial spaceflight, exoplanet discoveries, planetary exploration, solar physics, and space weather. The Rocky Mountain chapter of the Society of Professional Journalists recognized the inaugural year of the series with a first place award in the category of Science Enterprise Reporting (print circulation of 30,000 to 75,000). The citation from the judges read: *"Nice job of explaining highly technical topics in ways that readers will understand. The series turns boring into interesting and readable."* During the second year, the PI coordinated 20 volunteer writers representing all of the major research laboratories around Boulder, but only a small fraction actually wrote an article. The series clearly thrived without the diffusion of responsibility, so the PI will commit to writing monthly articles for the duration of NSF support.

5 Plan of Work

Timeline: We began using NRES in September 2017 to gather some of the new observations outlined in section 3 through NOAO public access to the LCO global telescope network. Until November 2017, NRES only operated in the southern hemisphere, but roughly 75% of the bright solar analog sample was still accessible. To monitor this subsample, we were allocated 40 hours from the 1220 hours of 1-m public access time in 2017B. The initial observations will allow us to develop an analysis pipeline to derive S-indices from the reduced and wavelength-calibrated data provided by LCO. The early data will also allow us to refine our estimates of the time required to monitor the complete samples of bright solar analogs and magnetic transition targets (see below).

We were allocated 60 hours in 2018A to begin monitoring the complete solar analog sample in December 2017. We will submit a proposal to NOAO in 2018B to begin a long-term program (2 year duration) that will continue monitoring this sample from June 2018 through May 2020. The

SMARTS survey began with time from partner institutions (Yale, STScI, GSU), but it continued as a long-term program (2008B-0039 and 2011B-0001) through NOAO. Long-term status is reserved for observing programs that cannot achieve their principal science goals without the full allocation of time. They remain accountable to the telescope allocation committee by submitting progress reports each semester. We submitted a proposal with LCO institutional partners (IAC & U. Hawaii) to begin monitoring the Kepler magnetic transition sample in 2018A, and we plan to continue this work with a renewal proposal each semester or through another NOAO long-term proposal.

To work with an REU student during the first summer, we will submit a project proposal in January 2018. By the time the student arrives, we will have more than six months of observations for the solar analogs sample. This will allow us to complete the development of an analysis pipeline, and to make an initial attempt to calibrate the derived S-indices onto the Mount Wilson scale. To appreciate the scientific value of this work, the student will also analyze a combined SMARTS and Mount Wilson time series for HD 76151, which shows hints of a 2.5-year cycle in both data sets.

Resources: We estimate that the bright solar analogs sample will require 60 hours of telescope time each semester, comparable to the SMARTS program. Although the sample is 34 instead of 58 stars, we will aim for a higher cadence of Ca HK observations than SMARTS achieved. The smaller aperture of the LCO telescopes (1-m instead of 1.5-m) is offset by the higher efficiency of the NRES spectrographs and queue-scheduling system (SMARTS relied on service observers). The magnetic transition sample is entirely in the Kepler field, so the time requirements are uneven across semesters: roughly 50 hours during the "A" semesters (December–May), and 85 hours during the "B" semesters (June–November). Although the targets are typically 3 magnitudes fainter than the solar analogs sample, we aim to keep the time requirements reasonable with a lower cadence of observations and a lower signal-to-noise goal. This is appropriate because many of the stars should have already made the magnetic transition and are expected to show minimal short-term variability. The observational overhead will also be reduced, because the targets are all within a relatively small area of the sky.

Responsibilities: The proposed work will be carried out by the PI, Travis Metcalfe, at Space Science Institute in Boulder, Colorado. He will be responsible for writing the proposals for telescope time, requesting observations through the LCO queue-scheduling system, downloading and analyzing the data to generate stellar activity indices, archiving the data products on the project archive, regularly evaluating the time series observations for signatures of stellar activity cycles, preparing scientific findings for publication, presenting the results at annual conferences, and mentoring summer REU students who are involved in all of the above aspects of the research. As the principal investigator for the SMARTS survey, he carried out all of these responsibilities over the 5.5-year lifetime of the project.

Metrics of success: Because our observing program is a multi-year survey, we will initially judge progress by the number and cadence of high-quality spectra that we obtain for each sample. During the second year, the emphasis will shift to the number, quality, and intrinsic interest of conference talks and peer-reviewed publications. In the first year, we will begin our Ca HK monitoring program for all targets and we will complete the data analysis pipeline and initial calibration. In the second year, we will publish our first discoveries of short activity cycles and set initial limits on the variability of stellar activity across the magnetic transition. In the third year, we will publish the final results on short activity cycles, as well as longer-term variability by merging our data with previous surveys. If the results would benefit from continued monitoring, and if LCO continues to offer public access, we will also request a renewal for our NOAO long-term program(s).

6 Results from Prior NSF Support

The most recent NSF award to the PI, Travis Metcalfe, was an Astronomy and Astrophysics Postdoctoral Fellowship (AST-0401441, $109,000, 9/1/2004–2/28/2006, "Asteroseismology of Sun-like Stars"). Motivated by the Kepler mission, the primary goal of the project was to develop a stellar model-fitting pipeline for asteroseismic observations of solar-type stars.

Intellectual merit: The PI successfully adapted a parallel genetic algorithm to run on NCAR supercomputers, and coupled it to some well-established stellar evolution and pulsation codes in collaboration with J. Christensen-Dalsgaard. Together they began conducting "hare & hounds" tests to validate the optimization method (Metcalfe et al., 2009a). During code development and testing, the PI continued to apply the method to pulsating white dwarf stars. After an initial study to test the predictions of diffusion theory in white dwarf surface layers (Metcalfe et al., 2005), he performed a follow-up study to quantify the relative importance of various interior structures (Metcalfe, 2005c). These results provided new asteroseismic evidence supporting one of the central assumptions of spectral evolution theory (linking the DB white dwarfs to PG 1159 stars), and ultimately identified an asteroseismic model for CBS 114 that simultaneously included surface structure in agreement with diffusion theory, and core structure consistent with the expected nuclear burning history of the progenitor. During the fellowship, the PI also initiated a study of asteroseismic signatures of stellar activity cycles with W. Dziembowski and others (Metcalfe et al., 2007).

Broader impacts: For the education component of the NSF fellowship, the PI contributed to the *Windows to the Universe* web-outreach project at NCAR. By the end of 18 months he finished a complete review of the astrophysics section, making updates to 35 of the existing pages and adding more than 120 new images and multimedia files to the site. He also created 7 new pages, including video and audio representations of pulsating stars and a short educational video documenting a trip to McDonald Observatory. In addition, he supervised Ph.D. student Orlagh Creevey and designed the curriculum for a professional development seminar that he led through a weekly discussion in the fall of 2005, with two dozen participants at the University of Colorado.

Publications: While supported by the NSF fellowship, the PI published three papers on white dwarf asteroseismology and one paper related to bibliometrics. He also began two major projects that were subsequently published in 2007 and 2009.

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Metcalfe, T. S. (2005c) *A deeper understanding of white dwarf interiors.* Monthly Notices of the Royal Astronomical Society, 363:L86–L90.

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