NOAO Observing Proposal *Longterm proposal* **Panel:** *For office use.*
Date: October 2, 2017 **Category:** Low Mass Stars

Activity Cycles in Asteroseismic Solar Analogs

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)***:**
The magnetic activity of the Sun becomes stronger and weaker over roughly an 11-year cycle. Decades of 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. Neither of these relationships correctly describe the properties of the Sun, a peculiarity that demands further investigation. Recent work suggests 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 this hypothesis. We propose to begin long-term monitoring of Ca II H and K emission for a sample of 34 bright stars with known rotation rates ($P_{\rm rot} < 22$ days), to identify the short activity cycles ($P_{\rm cyc} < 5$ years) that are precursors of the 11-year solar cycle. For most of these targets, asteroseismic masses and ages are soon expected from the Transiting Exoplanet Survey Satellite (TESS), currently scheduled for launch in March 2018.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	LCO-1m	NRES	6	bright	Dec - May	Dec - May
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to six lines).*

Investigators *List the name, status, and current affiliation for all investigators. The status code of "P" should be used for all investigators with a Ph.D. or equivalent degree. For graduate students, use "T" if this proposal is a significant part of their thesis project, otherwise use "G".*

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Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

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 activity cycle have subsequently 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 from disk-integrated 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 measured rotation rates and activity variations to help validate stellar dynamo theory.

Initial results from the Mount Wilson sample suggested that both the cycle period and the mean activity level depend on the Rossby number—the rotation period normalized by the convective turnover time (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 ∼100 rotations (see also Brandenburg et al. 2017). 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).

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 correctly describe the properties of the Sun (**see Figure 1**). 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. 2007b), falling close to the lower 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. 2007a).

We propose new observations to test this hypothesis, using NRES to obtain an average of 1–2 Ca HK measurements per month over the entire observing season for each star in our sample of 34 TESS asteroseismic targets. **The immediate objective of our new observations is to discover short activity cycles ($P_{\rm cyc} < 5$ years) 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, to confirm the existence of a few suspected short activity cycles with high-cadence data, and to improve the characterization of longer cycles by combining our new observations with previous measurements from the Mount Wilson and Lowell surveys.

References

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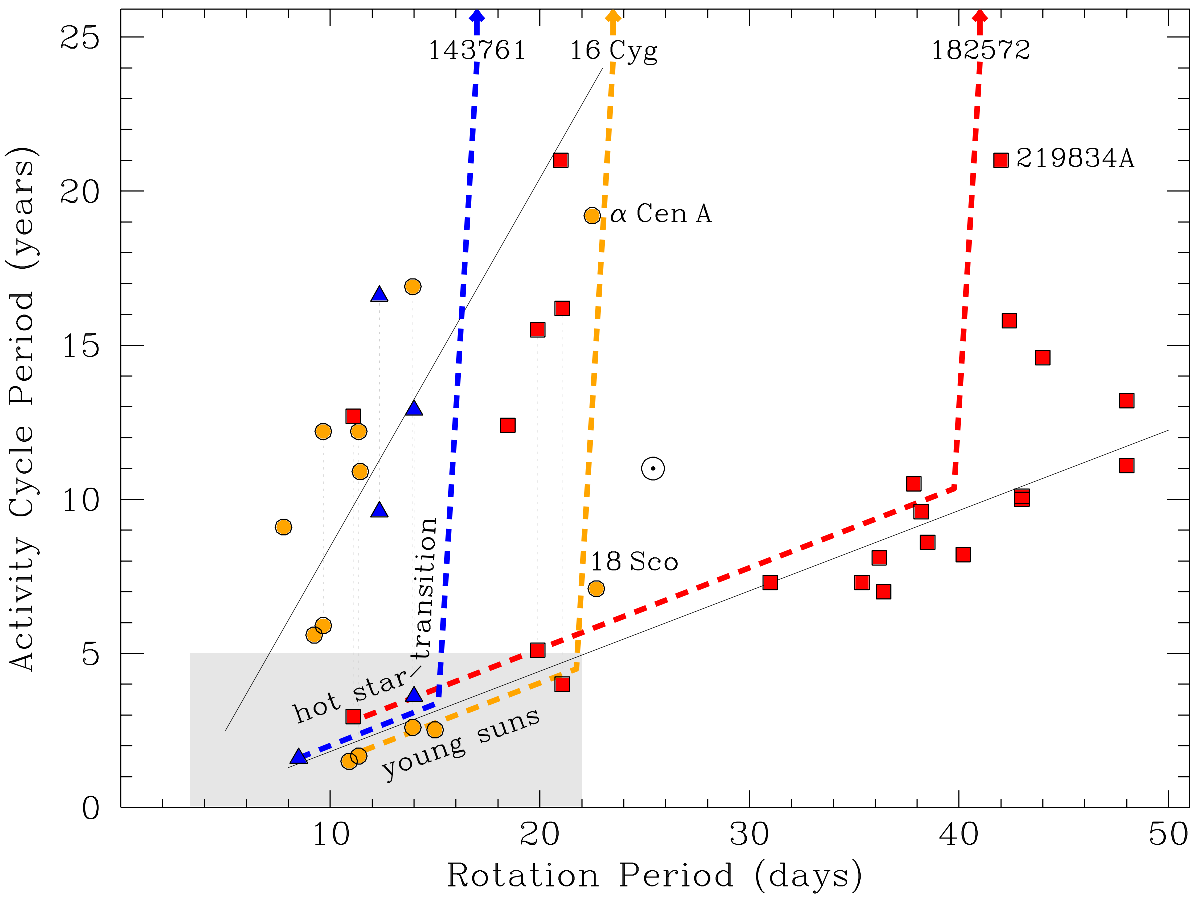

Figure 1: Updated version of a diagram originally published by Böhm-Vitense (2007), showing two distinct relationships between rotation period and the length of the activity cycle (solid lines). Cycles operating simultaneously in the same star are connected with a vertical dotted line. Points are colored 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 that appear to have completed the magnetic transition (Metcalfe & van Saders 2017). Considering the evolutionary sequence defined by 18 Sco (4.1 Gyr), α Cen A (5.4 Gyr) and 16 Cyg (7.0 Gyr), the data suggest that a normal sun-like cycle on the lower sequence may grow longer across the transition (yellow dashed line) before disappearing entirely. The Sun falls to the right of this evolutionary sequence because it is slightly less massive than the other stars. **We propose time-series observations of stars with rotation periods shorter than 22 days to discover new cycles on the lower sequence with cycle periods shorter than 5 years (shaded region), which appear to be precursors of the 11-year solar cycle. This range of periods will also probe the onset of the magnetic transition for hotter stars (blue dashed line).**

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

This is a long-term request to support an all sky time-domain survey of bright stars, designed to discover and characterize activity cycles shorter than 5 years in TESS asteroseismic targets.

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. The highest priority targets include 19 stars from Brandenburg et al. (1998) with rotation periods shorter than 22 days and at least one cycle on the long-period sequence, such that a short activity cycle ($P_{\rm cyc} < 5$ years) on the lower sequence might be undetected in the Mount Wilson data. 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. These stars span V-band magnitudes from 3.73 to 7.01, with rotation periods in the range $P_{\rm rot} = 3.3$–22 days.

Recent discoveries suggest a rotational and magnetic transition in middle-aged stars (van Saders et al. 2016, Metcalfe et al. 2016). The greatest obstacle to understanding how this transition influences stellar activity cycles is the paucity of suitable observations. The bright sample of stars that were monitored for decades by the Mount Wilson survey only yielded a few activity cycles shorter than 5 years, probably due to low signal-to-noise measurements and large seasonal data gaps. Our latest results suggest that these short cycles are the precursors of the 11-year solar cycle (Metcalfe & van Saders 2017), and additional short-cycle detections will help to test this hypothesis. For the hotter stars in our sample, the new observations will directly probe the range of rotation periods in which the magnetic transition is expected to occur, where new cycles that fall between the two stellar sequences are predicted.

We have estimated the exposure times required to yield S/N$\sim$70 for each of our target stars based on their magnitudes and colors, rounded to the nearest 30 or 60 seconds. These estimates are based on the measured performance of NRES, which has obtained observations of the S-index with $\sim$1% precision in 20 minutes at V = 7. The time required to observe all 34 stars (including overhead) is 13.7 hours, so an allocation of 60 hours per semester will allow an average of 1–2 observations per accessible target every month, assuming that each target can be observed during 75% of the year. Our experience with the SMARTS program suggests this cadence is sufficient to sample the relatively short activity cycles ($P_{\rm cyc} < 5$ years) that are expected in these targets.

The requested allocation is comparable to previous allocations for the SMARTS program. Although this 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) will be offset by the higher efficiency of the NRES spectrographs and queue-scheduling system (SMARTS relied on service observers).

Proprietary Period: 12 months

Use of Other Facilities or Resources *(1) Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

(1) All of the stars in our sample will have photometric observations from TESS with a cadence of 2 minutes for at least 27 days in 2018–2020. The probability of detecting solar-like 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 most of our sample from asteroseismology. In case of marginal asteroseismic detections, gyrochronology can still provide reliable age estimates for the cooler G- and K-type stars at these rotation periods. The observations proposed here will provide the final ingredient needed to create an evolutionary sequence that demonstrates how the prevalence and characteristics of activity cycles change over the lifetime of a sun-like star.

(2) A grant proposal to the National Science Foundation is currently under revision to support data processing, analysis, and publication of the observations proposed for this long-term program. A previous proposal was not funded due to reviewer skepticism of the NRES deployment timeline, which is now secure. We have private funding from White Dwarf Research Corporation to support analysis of the initial observations obtained between December and May.

Long-term Details *If you are requesting long term status, list the observing runs (telescope, instrument, number of nights) requested in subsequent semesters to complete the project.*

We request long-term status on the LCO-1m using NRES with an allocation of 6 nights each semester for 3 additional semesters (2018B, 2019A, 2019B).

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

The PI ran a time-domain Ca HK survey on the CTIO 1.5m telescope from 2007B–2013A. The survey started in 2007B–2008A with SMARTS time purchased through Georgia State University, and it continued for two years under NOAO long-term program 2008B-0039. It operated in 2010B again with purchased SMARTS time, and in 2011A with CTIO Director's discretionary time. It continued for three more semesters under NOAO long-term program 2011B-0001, until 2013A when the *RCSpec* instrument was decommissioned.

The results of the survey, including raw and calibrated time-series measurements of the Ca HK emission for the sample of 58 solar-type stars, are available without restriction through the project website (solar-stellar.org). Analysis of the survey data led to several significant publications, including: discovery of the shortest known activity cycle in a solar-type star (Metcalfe et al. 2010), dual activity cycles in a K-type exoplanet host (Metcalfe et al. 2013), and sun-like activity variations in a rapidly rotating young solar analog (Egeland et al. 2015).

Program 2017B-0009* was approved for 40 hours of initial observations of the subset of our sample that is accessible from the southern hemisphere. The first NRES spectrograph was deployed in Chile during the spring of 2017, but commissioning extended into September so we only recently obtained data under this allocation. The first NRES in the northern hemisphere has now been installed in Texas, providing full-sky coverage to support the current long-term program.

Observing Run Details for Run 1: LCO-1m/NRES

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).*

This proposal is for queue-scheduled all sky time-domain monitoring of bright stars. LCO operates the only queue-scheduled small telescopes with spectroscopic capability (NRES) that includes Ca HK, after the SMARTS 1.5m telescope decommissioned the *RCSpec* instrument in February 2013. Because all targets are brighter than V = 7, there are no lunar constraints (bright time is fine). We are requesting 6 nights equivalent (60 hours) during each of the next four semesters. This will be sufficient to observe each target 9 times per year on average, spread as evenly as possible across the target's observing season as is feasible. Each observation consists of 450 seconds of overhead (180 seconds for slew & settle, 270 seconds for acquisition & setup), plus the specified exposure time and 142 second readout for 2 target spectra with Th-Ar calibration spectra obtained simultaneously through adjacent fibers. The two consecutive exposures for each target guard against losses from cosmic rays and allow us to estimate systematic uncertainties prior to co-adding the spectra to obtain a higher S/N ratio. The long exposure times for our faintest and reddest targets will be split in half, but not repeated. Expected reductions in the NRES observation overhead will be invested in improved cadence for future semesters.

Instrument Configuration

Filters:	Slit:	Fiber cable:
Grating/grism: R4	Multislit:	Corrector:
Order: I	λ_{start}: 380 nm	Collimator:
Cross disperser: prism	λ_{end}: 860 nm	Atmos. disp. corr.:

R.A. range of principal targets (hours): 0 to 22

Dec. range of principal targets (degrees): -51 to +54

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

Target Table for Run 1: LCO-1m/NRES

Obj ID	Object	α	δ	Epoch	Mag.	Filter	Exp. time	# of exp.	Lunar days	Sky	Seeing	Comment
001	HD1835	00:22:51.8	-12:12:34.0	2000	6.39	-	720	2	14	spec	> 2.0	G3V
002	HD12235	02:00:09.1	+03:05:49.2	2000	5.90	-	360	2	14	spec	> 2.0	G2IV
003	HD17051	02:42:33.5	-50:48:01.1	2000	5.40	-	180	2	14	spec	> 2.0	F8V
004	HD20630	03:19:21.7	+03:22:12.7	2000	4.85	-	180	2	14	spec	> 2.0	G5V
005	HD22049	03:32:55.8	-09:27:29.7	2000	3.73	-	180	2	14	spec	> 2.0	K2V
006	HD26913	04:15:25.8	+06:11:58.7	2000	6.92	-	1200	1	14	spec	> 2.0	G8V
007	HD30495	04:47:36.3	-16:56:04.0	2000	5.50	-	300	2	14	spec	> 2.0	G1.5V
008	HD37394	05:41:20.3	+53:28:51.8	2000	6.23	-	1200	1	14	spec	> 2.0	K1V
009	HD43587	06:17:16.1	+05:06:00.4	2000	5.70	-	300	2	14	spec	> 2.0	G0V
010	HD49933	06:50:49.8	-00:32:27.2	2000	5.78	-	90	2	14	spec	> 2.0	F3V
011	HD75332	08:50:32.2	+33:17:06.2	2000	6.21	-	300	2	14	spec	> 2.0	F7V
012	HD76151	08:54:18.0	-05:26:04.1	2000	6.00	-	480	2	14	spec	> 2.0	G3V
013	HD78366	09:08:51.0	+33:52:56.0	2000	5.90	-	360	2	14	spec	> 2.0	G0V
014	HD82443	09:32:43.7	+26:59:18.7	2000	7.01	-	1800	1	14	spec	> 2.0	K0V
015	HD82885	09:35:39.5	+35:48:36.5	2000	5.34	-	480	2	14	spec	> 2.0	G8V
016	HD88737	10:14:29.8	+21:10:05.0	2000	6.03	-	300	2	14	spec	> 2.0	F9V
017	HD98230B	11:18:10.9	+31:31:45.7	2000	4.73	-	120	2	14	spec	> 2.0	G2V
018	HD100180	11:31:44.9	+14:21:52.2	2000	6.20	-	360	2	14	spec	> 2.0	F9.5V
019	HD114710	13:11:52.3	+27:52:41.5	2000	4.25	-	60	2	14	spec	> 2.0	F9.5V
020	HD115383	13:16:46.5	+09:25:27.0	2000	5.22	-	180	2	14	spec	> 2.0	G0V
021	HD115404	13:16:51.1	+17:01:01.9	2000	6.52	-	2400	1	14	spec	> 2.0	K1V
022	HD120136	13:47:15.7	+17:27:24.9	2000	4.49	-	60	2	14	spec	> 2.0	F6IV
023	HD126053	14:23:15.3	+01:14:29.6	2000	6.27	-	540	2	14	spec	> 2.0	G1.5V
024	HD136202	15:19:18.8	+01:45:55.5	2000	5.10	-	90	2	14	spec	> 2.0	F8IV
025	HD149661	16:36:21.5	-02:19:28.5	2000	5.77	-	720	2	14	spec	> 2.0	K1V
026	HD152391	16:52:58.8	-00:01:35.1	2000	6.64	-	1200	1	14	spec	> 2.0	G8.5V
027	HD154417	17:05:16.8	+00:42:09.2	2000	6.01	-	360	2	14	spec	> 2.0	F8V
028	HD165341A	18:05:27.4	+02:29:59.3	2000	4.12	-	240	2	14	spec	> 2.0	K0V
029	HD176051	18:57:01.6	+32:54:04.6	2000	5.25	-	180	2	14	spec	> 2.0	G0V
030	HD182101	19:22:48.4	+09:54:47.3	2000	6.36	-	240	2	14	spec	> 2.0	F6V
031	HD187691	19:51:01.6	+10:24:56.6	2000	5.10	-	120	2	14	spec	> 2.0	F8V
032	HD190406	20:04:06.2	+17:04:12.6	2000	5.80	-	300	2	14	spec	> 2.0	G0V
033	HD194012	20:22:52.4	+14:33:04.0	2000	6.17	-	240	2	14	spec	> 2.0	F7V
034	HD206860	21:44:31.3	+14:46:19.0	2000	5.95	-	300	2	14	spec	> 2.0	G0V