PROJECT SUMMARY

Overview:

Sun-like stars stars are born with relatively rapid rotation and strong magnetic fields. Through a process known as magnetic braking, the rotation slows over time as stellar winds gradually remove angular momentum from the system. Recent observations suggest that the efficiency of magnetic braking decreases dramatically in stars near the middle of their main-sequence lifetimes at a critical level of stellar activity. The coincident disappearance of Sun-like activity cycles strongly suggests a magnetic origin for the lower rate of angular momentum loss. One hypothesis to explain these observations is a shift in magnetic complexity and a weakening of the global dipole field. This hypothesis was recently tested with spectropolarimetric snapshots of two stars that sample activity levels on opposite sides of the proposed magnetic transition. As predicted, the more active star exhibited a significant circular polarization signature due to a dipole magnetic field, while the less active star showed a much weaker signal than expected from its relative activity level, suggesting that most of the field was concentrated in smaller spatial scales. A wind modeling prescription revealed that the magnetic braking torque decreased by more than an order of magnitude between the ages of these two stars, primarily due to the shift in morphology toward smaller spatial scales but reinforced by the evolutionary change in mass-loss rate and other properties. The project will repeat this successful experiment across a range of spectral types, probing the evolution of magnetic complexity across the transition for several pairs of older Sun-like stars.

The objective of the proposed research program is to constrain the presence and strength of large-scale magnetic field in a carefully selected sample of stars that are near or below the critical activity level where magnetic braking and global dynamo action appears to shut down. The constraints will be derived from new spectropolarimetric observations that will directly test whether and how the complexity of magnetic field and the strength of magnetic braking changes for Sun-like stars beyond the middle of their main-sequence lifetimes. These new observations will be interpreted using a wind modeling prescription to estimate the change in magnetic braking torque that results from the observed changes in field morphology relative to other contributions, as well as rotational evolution modeling to assess the compatibility of the observational constraints with either standard spin-down or weakened magnetic braking. The evolution of magnetic complexity for younger stars has been investigated by others using previously published spectropolarimetric data. The proposed observations and modeling will extend direct studies of magnetic complexity beyond stellar middle-age for the first time.

Intellectual Merit:

This research program will establish an observational foundation for understanding how stellar magnetism and 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 stellar magnetism depend on rotation and mass beyond middle-age will have implications for theoretical models of angular momentum loss from magnetized stellar winds, the use of gyrochronology as a technique for inferring stellar ages, 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 development of a diverse, globally competitive STEM workforce through the participation of graduate students in the research. The observations and modeling outlined in this proposal will comprise a substantial fraction of Ph.D. theses at the University of Colorado and the University of Hawaii. The PI will supplement this collaborative research experience by leading a 15-week professional development seminar "Survival Skills for Scientists" at the University of Colorado, with weekly readings and informal group discussion. The Co-PI will mentor a summer Research Experience for Teachers participant at the University of Hawaii in two of the three summers during the award, engaging local Hawaii high school teachers in scientific research on the islands.

1 The Evolution of Magnetic Complexity in Old Sun-like Stars

The coupled evolution of rotation and magnetic activity in Sun-like stars has been an active area of research since the pioneering work of Skumanich (1972). The availability of reliable stellar ages has always been a limiting factor, with the earliest studies relying entirely on the Sun and a few young star clusters. The basic picture that emerged was that Sun-like stars begin their lives with relatively rapid rotation and strong magnetic activity, but that both properties gradually decay with the square-root of the age. The Sun was the oldest star with a reliable age beyond ∼1 Gyr until the Kepler mission began to yield asteroseismic ages for older field stars (Mathur et al., 2012; Metcalfe et al., 2012, 2014). This led to the discovery of unexpectedly rapid rotation in this sample (Angus et al., 2015), which could be understood if magnetic braking becomes much less efficient beyond the middle of main-sequence lifetimes (van Saders et al., 2016; Hall et al., 2021). A coincident shift in the observed properties and prevalence of stellar activity cycles strongly suggested a magnetic origin for this weakened braking (Metcalfe & van Saders, 2017).

Metcalfe et al. (2016) and van Saders et al. (2016) proposed that the reduced efficiency of angular momentum loss in middle-aged stars could be due to a change in the magnetic field morphology. Charged particles in a stellar wind are tied to the magnetic field lines until they reach a critical distance known as the Alfvén radius, which is largest for the dipole component of the field and progressively smaller for higher-order components (Réville et al., 2015). As a consequence of the longer lever-arm, most of the angular momentum loss from magnetized stellar winds can be attributed to the dipole component of the field (See et al., 2019b), so a shift in magnetic morphology from larger to smaller spatial scales would reduce the efficiency of magnetic braking. With this in mind, Garraffo et al. (2018) suggested a change in magnetic complexity as a unifying explanation for the persistent fast rotators in young clusters and the anomalously fast rotating old Kepler field stars. Evidence has accumulated over the past few years that even our own Sun may be near this magnetic transition (Reinhold et al., 2020), with a current rate of angular momentum loss that is roughly half the value predicted from the Skumanich relation (Finley et al., 2019, 2020).

There are good reasons why we might have expected a magnetic morphology shift in middle-aged stars. According to van Saders et al. (2016), spin-down stalls at a critical value of the Rossby number (Ro $\equiv P_{\rm rot}/\tau_c$), when the rotation period becomes comparable to the convective turnover time. In this regime, convective motions are no longer dominated by Coriolis forces, and the pattern of solar-like differential rotation (i.e. faster at the equator and slower at the poles) either becomes uniform (Featherstone & Hindman, 2016), or might transition to an anti-solar pattern (Gastine et al., 2014). Observationally, two-thirds of the sample of Kepler targets with constraints on latitudinal differential rotation are consistent with uniform rotation, and none are significantly anti-solar (Benomar et al., 2018). Metcalfe & Egeland (2019) suggested that the resulting loss of latitudinal shear ($dv/d\theta$) might disrupt the production of large-scale magnetic field by the global dynamo, explaining the reduction in angular momentum loss and the gradual disappearance of activity cycles in stars beyond the middle of their main-sequence lifetimes.

Metcalfe et al. (2019) recently tested this new understanding of magnetic stellar evolution using spectropolarimetric measurements of two stars with activity levels on opposite sides of the proposed magnetic transition. The more active star 88 Leo has a rotation period near 14 days and exhibits clear activity cycles, while the less active star ρ CrB has a rotation period near 17 days and shows constant activity over several decades of monitoring (Baliunas et al., 1995, 1996). The snapshot observations with the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI; Strassmeier et al., 2015) on the Large Binocular Telescope (LBT) appeared to confirm the predicted loss of large-scale magnetic field (**Figure 1**). The data produced a clear detection of a dipole field in 88 Leo (pre-transition), and an upper limit on the dipole field strength in ρ CrB

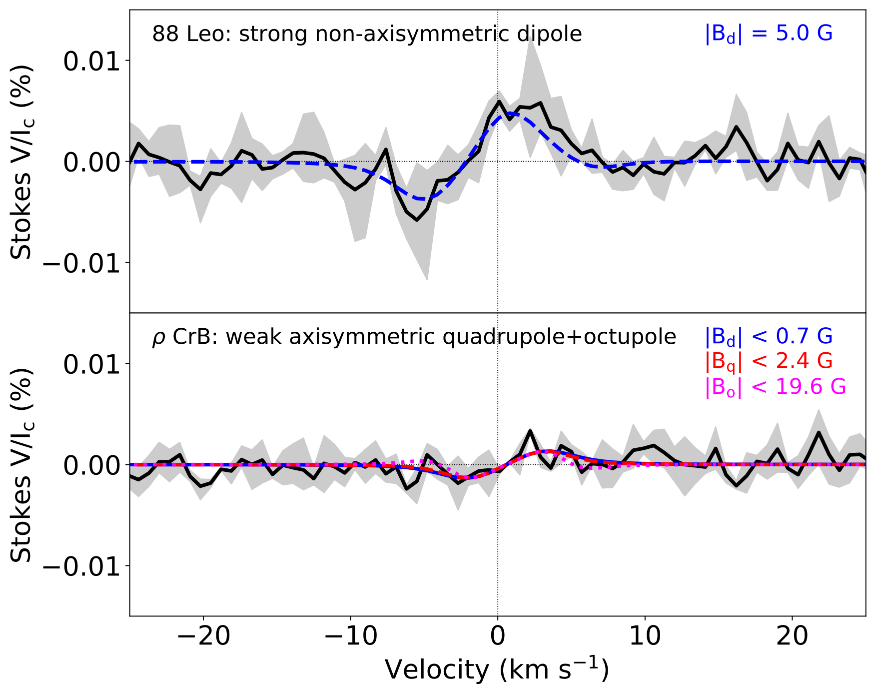

Figure 1: *LBT/PEPSI circular polarization profiles for 88 Leo (top) and ρ CrB (bottom). The gray shaded regions show the range of profiles from individual exposures, while the average profile is shown as a dark line. Models of the observed profiles with various assumptions about the field morphology are shown with colored lines. 88 Leo shows the clear signature of a dipole field, while ρ CrB shows a much weaker signal than the 3.2 G expected from its relative activity level.*

(post-transition) that was well below the 3.2 G expected from its relative activity level—suggesting that most of the field was concentrated in smaller spatial scales. Metcalfe et al. (2021) modeled the evolutionary change in magnetic braking torque between these two stars, and exploited additional constraints on the stellar properties to quantify the relative importance of various contributions to this change. They found that the magnetic braking torque for ρ CrB is more than an order of magnitude smaller than for 88 Leo, primarily due to a shift in morphology toward smaller spatial scales but reinforced by the evolutionary change in mass-loss rate and other properties. We aim to extend this successful test to additional pairs of stars covering a range of spectral types.

The objective of this proposal is to gather and interpret new spectropolarimetric observations that will directly test whether and how the complexity of magnetic field and the strength of magnetic braking changes for Sun-like stars beyond middle-age. After a detailed review of the evidence for a magnetic transition in middle-aged stars (**section 2**), we describe our plans to observe and model a carefully selected sample of a dozen stars that probe activity levels on opposite sides of the proposed magnetic transition (**section 3**). We discuss the involvement of graduate students in the research and their professional development (**section 4**), and we present a plan of work and metrics of success (**section 5**).

2 Evidence for a Magnetic Transition 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 constraint 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 Weakened 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 a Rossby number similar to the solar value ($\mathrm{Ro} \sim 2$ for 1D models that adopt mixing-length theory, but $\mathrm{Ro} \sim 1$ in 3D convection models; Brun et al., 2017). Although the Rossby number is a model-dependent quantity, it is strongly correlated with the observed chromospheric activity level (Noyes et al., 1984), so the critical Rossby number is equivalent to a critical activity level ($\log R'_{\mathrm{HK}} \approx -4.95$; Brandenburg et al., 2017).

The anomalous rotation highlighted by van Saders et al. (2016) is shown for F-type and G-type stars in **Figure 2**. A standard rotational evolution model (solid line) and a modified model that eliminates angular momentum loss beyond a critical Rossby number (dashed lines) are from the original paper, which also used a few cooler stars to constrain the fit. F-type stars are shown in blue, while G-type stars are shown in yellow. Asteroseismic ages for the Kepler sample have been updated with values from Creevey et al. (2017). 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 (for another perspective, see Lorenzo-Oliveira et al., 2019). The F-type stars are all Kepler targets, but two of them (labeled within brackets) are close analogs of the spectropolarimetric targets 88 Leo and ρ CrB, which we will discuss in section 2.3.

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.

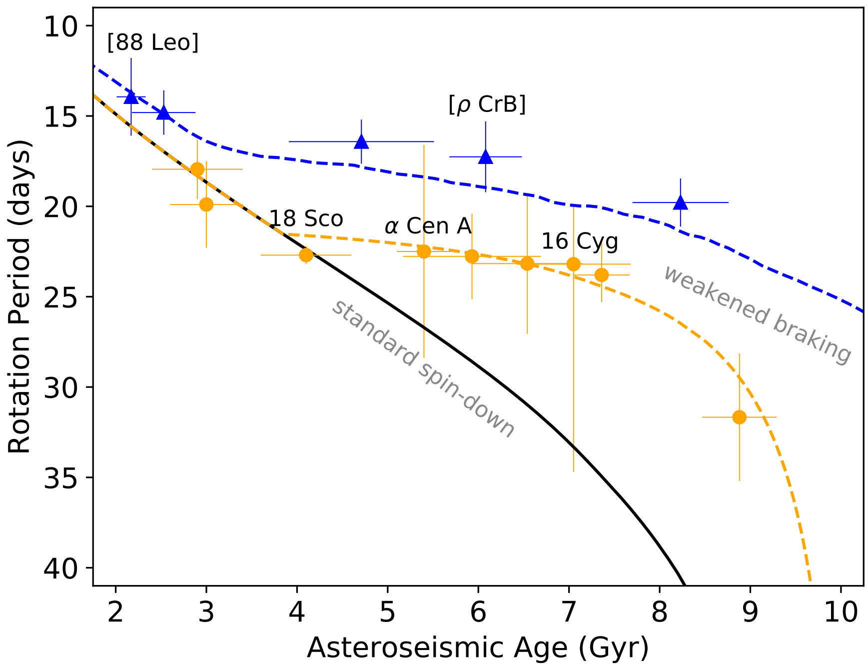

Figure 2: *Stellar evidence for weakened magnetic braking in F-type (blue) and G-type (yellow) stars. The solid line shows a standard rotational evolution model, which is calibrated using young star clusters and the Sun. The dashed lines show the modified model of van Saders et al. (2016), which eliminates angular momentum loss beyond a critical Rossby number determined from a fit to Kepler field stars with precise asteroseismic ages. A few bright solar analogs are labeled.*

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 complexity may be responsible for the onset of efficient magnetic braking in very young stars (Brown, 2014).

2.2 Disappearance of Sun-like Activity Cycles

If the disappearance of large-scale field is responsible for weakened braking, there may be a coincident shift in the underlying dynamo mechanism that can be seen in stellar activity cycles. An updated version of a diagram originally published by Böhm-Vitense (2007) is shown in **Figure 3**, using data from Brandenburg et al. (1998) and Saar & Brandenburg (1999). More recent data have been added from Hall et al. (2007), Bazot et al. (2007), Petit et al. (2008), Metcalfe et al. (2010, 2013), Ayres (2014), Egeland et al. (2015), Salabert et al. (2016), and Hempelmann et al. (2016).

The sequence of Sun-like cycles 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 (open points; see Boro Saikia et al., 2018). Many of the Mount Wilson targets in this 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

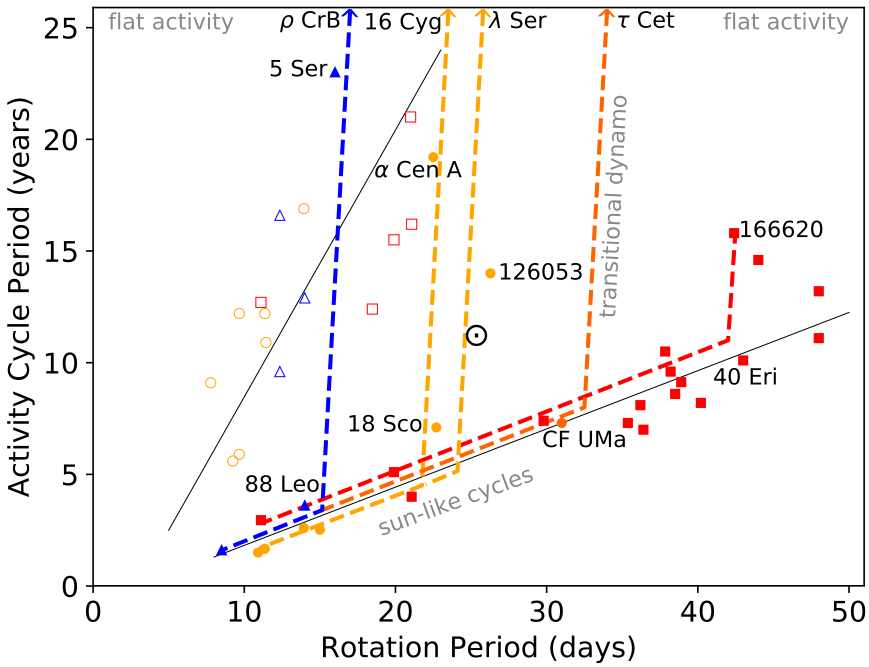

Figure 3: *Dependence of activity cycle period on rotation, showing two distinct sequences (solid lines). Points are colored by effective temperature, indicating F-type (blue triangles), G-type (yellow and orange circles), and K-type stars (red squares). Schematic evolutionary tracks are shown as dashed lines (Metcalfe & van Saders, 2017), leading to stars with constant activity that appear to have shut down their global dynamos (arrows along the top). Our targets are labeled.*

with well determined cycles. The oldest cycling F-type star in the Mount Wilson sample is 88 Leo (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 ρ CrB 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 of ρ CrB from gyrochronology is 2.5 ± 0.4 Gyr (Barnes, 2007), while both isochrone fitting and asteroseismology suggest an age of 8–10 Gyr (Metcalfe et al., 2021). No main-sequence F-type stars are observed to the right of the critical Rossby number (blue dashed line) because with weakened magnetic braking the rotation period subsequently evolves very slowly until the subgiant phase, when stars slow down from an increase in their moment of inertia as they expand and cool to become other spectral types (Metcalfe et al., 2020).

The transition across the critical Rossby number for G-type stars occurs at rotation periods comparable to the Sun ($P_{\rm rot} \sim$ 22–27 days). Before exceeding this threshold, magnetic braking continues in these stars and their cycle periods evolve along the two sequences in Figure 3 as their rotation slows. **Upon reaching the critical Rossby number, the surface rotation rate changes more slowly and the cycle grows longer and weaker before disappearing.** If we consider the evolutionary sequence defined by 18 Sco (4.1±0.5 Gyr; Mittag et al., 2016) and α Cen A (5.4±0.3 Gyr; Bazot et al., 2012), the data suggest that a normal activity cycle on the lower sequence may grow longer across the magnetic transition (left 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., 2007; Radick et al., 2018). The Sun falls to the right of this evolutionary sequence because it is 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 slightly slower. Considering other Sun-like stars, it appears 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).

All of the slowest rotators with cycles ($P_{\rm rot}$>35 days) are K-type stars, which is now understandable: magnetic braking appears to shut 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 40 days. The hottest cycling K-type star in Figure 3 is HD 166620, and it appears to be furthest along the magnetic transition (red dashed line). Most of the stars to the right of HD 166620 are significantly cooler, so they have not yet reached the critical Rossby number (Brandenburg et al., 2017). The long main-sequence lifetimes of K-type stars means that none of them have evolved enough to shut down their global dynamos. Constant activity stars in this range of periods (e.g. 31 Aql; Baliunas et al., 1995) are subgiants that evolved from hotter main-sequence progenitors (Metcalfe et al., 2020).

2.3 Shift in Magnetic Morphology

The most direct observational test for the disappearance of large-scale field can come from stellar spectropolarimetry. In the presence of a Sun-like magnetic field, photons emitted from the surface of a star become polarized (integrated signal less than 1 part in 10,000 as seen in **Figure 1**). Rotation imprints a relative velocity on each element of the surface, spreading the circular polarization signature across the spectral lines. The disk-integrated signature of an axisymmetric dipole field (viewed at some inclination) resembles a sinusoid with no polarization at line center and maximum polarization with opposite signs to either side. A phase offset of this pattern away from line center indicates non-axisymmetry (e.g. spherical harmonic with $m \neq 0$). The amplitude of the polarization signature reflects the strength and morphology of the global magnetic field. Geometric cancellation of opposite polarity regions on the surface means that a quadrupole field must be stronger to yield the same polarization amplitude as a dipole field. As the spatial scale becomes even smaller (octupole, hexadecapole, etc.), the disk-integrated polarization amplitude for a given field strength becomes vanishingly small. Thus, **stellar spectropolarimetry is like a spatial filter that is primarily sensitive to the largest-scale magnetic fields.**

Metcalfe et al. (2016) used results from existing spectropolarimetry to support the idea of a magnetic transition in middle-aged stars. For the young solar analog HD 76151, Petit et al. (2008) found that 93% of the magnetic energy was concentrated in poloidal field, with 79% in the dipole component and 18% in the quadrupole. More generally, they found that a growing fraction of the field was poloidal in solar analogs as rotation slowed. In flux-transport dynamo models, differential rotation is the mechanism that recycles poloidal field into the toroidal component (e.g., Dikpati & Gilman, 2009), so this trend can be interpreted as evidence of weak differential rotation. For the solar twin 18 Sco, they found more than 99% of the magnetic energy concentrated in poloidal field. Most interesting from the standpoint of weakened magnetic braking, only 34% of the 3.6 G poloidal field in 18 Sco was in the dipole component while 56% was in the quadrupole. So there are already indications of weakening differential rotation and a diminishing large-scale field in 18 Sco. On the opposite side of the magnetic transition, P. Petit (2011, private communication) found no detectable polarization in 16 Cyg A & B, despite a signal-to-noise ratio per pixel S/N>1000. A similar analysis of the transitional star α Cen A by Kochukhov et al. (2011) ruled out a global field stronger than 0.2 G. In short, the evolutionary sequence (18 Sco, α Cen A, 16 Cyg A & B) shows nearly constant rotation (Figure 2), a lengthening and ultimately vanishing stellar activity cycle (Figure 3), and a diminishing large-scale magnetic field from spectropolarimetry.

Motivated by the availability of a new spectropolarimeter on the LBT, Metcalfe et al. (2019) conducted an initial experiment to test for the disappearance of large-scale field across the magnetic transition. The focus was on stars hotter than the Sun because their shallower convection zones allow them to reach the critical Rossby number while they are still rotating relatively fast. The active star (88 Leo) served as a control for the positive detection of large-scale magnetic field at a given S/N. This ensured that a non-detection in the inactive star (ρ CrB) at even higher S/N could be attributed to the absence of large-scale field rather than a lack of sensitivity. The relative chromospheric activity levels of the two stars from long-term observations at Mount Wilson Observatory (Baliunas et al., 1995) set the expected amplitude of the polarization signal in the absence of a change in magnetic morphology, because chromospheric emission is produced by magnetic heating at all spatial scales. Scaling down the 5 G dipole field detected in 88 Leo to the 64% relative strength of chromospheric emission in ρ CrB, the expected polarization signature of 3.2 G should have been easily detectable. **The upper limit of 0.7 G on the dipole field and 2.4 G on the quadrupole field in ρ CrB (Figure 1) suggests that most of its magnetic field must be concentrated in smaller spatial scales, as predicted.**

Metcalfe et al. (2021) estimated the strength of magnetic braking for ρ CrB and 88 Leo by combining these constraints on magnetic morphology with the wind modeling prescription of Finley & Matt (2017, 2018). Given the polar strengths of an axisymmetric dipole, quadrupole, and/or octupole magnetic field, along with the mass-loss rate, rotation period, stellar mass, and radius, this prescription yields an estimate of the magnetic braking torque based on analytical fits to a set of detailed magnetohydrodynamic wind simulations. The results suggest that the magnetic braking torque for ρ CrB is more than an order of magnitude smaller than for 88 Leo. The largest factor that contributes to this reduction is the shift in magnetic morphology towards quadrupolar and higher-order fields (−67% when shifting the field from pure dipole to pure quadrupole), followed by the evolutionary change in mass-loss rate (−60%), with smaller contributions from the weaker magnetic field (up to −34%) and slower rotation (−26%). The slightly lower mass (+4%) and evolutionary change in the radius (+58%) for ρ CrB actually increases the relative magnetic braking torque, masking some of the other effects. The closest analogs of these two stars from the Kepler mission (labeled in Figure 2) follow the weakened braking model from van Saders et al. (2016).

3 Proposed Research: Intellectual Merit

We propose to obtain new spectropolarimetric observations for a carefully selected sample of a dozen stars, to test whether and how the complexity of magnetic field and the strength of magnetic braking changes beyond the middle of main-sequence lifetimes. Initial spectropolarimetric snapshots will be obtained with LBT/PEPSI, to demonstrate the sensitivity of the measurements to large-scale field in active stars and to probe the strength and morphology of magnetic fields for otherwise similar transitional and inactive stars (**section 3.1**). For non-detections of large-scale field in snapshot observations, it is always possible that the measurements could have sampled an inactive hemisphere. We will conduct resource-intensive follow-up spectropolarimetry with the ESPaDOnS instrument on the Canada-France-Hawaii Telescope (CFHT) to confirm the absence of large-scale fields at all longitudes for our inactive targets, and to provide global magnetic field maps for some of our active and transitional targets (**section 3.2**). Although an observed change in morphology across the transition is consistent with the hypothesis of weakened magnetic braking, it does not explicitly demonstrate that the morphology shift is responsible for the reduced rate of angular momentum loss. We will use a wind modeling prescription to estimate the change in magnetic braking torque that results from the observed changes in field morphology relative to other contributions, and we will forward model the rotation periods to assess the compatibility of observational constraints with either standard spin-down or weakened magnetic braking (**section 3.3**).

Table 1: Target List for the Spectropolarimetric Observing Program

		HD	Name	V	$P_{\rm rot}$(d)	$P_{\rm cyc}$(yr)	$\log R'_{\rm HK}$	$M(M_\odot)$	t(Gyr)	[Fe/H]
A	▲	100180	88 Leo	6.27	14	3.6	−4.92	1.11	2.0	+0.04
	●	146233	18 Sco	5.49	22	7.1	−4.93	1.03	4.1	+0.04
	●	103095	CF UMa	6.42	31	7.3	−4.90	0.72	4.1	−1.16
	■	26965	40 Eri	4.43	43	10.1	−4.87	0.79	6.3	−0.20
T	▲	136202	5 Ser	5.04	16	23.0	−5.09	1.34	3.9	+0.07
	●	126053	···	6.25	26	14.0	−4.96	0.91	6.5	−0.31
	■	166620	···	6.38	43	15.8	−4.96	0.78	12.4	−0.10
I	▲	143761	ρ CrB	5.39	17	flat	−5.04	1.00	8.4	−0.18
	●	186408	16 Cyg A	5.99	23	flat	−5.11	1.07	7.4	+0.09
	●	186427	16 Cyg B	6.25	23	flat	−5.09	1.04	7.1	+0.06
	●	141004	λ Ser	4.42	26	flat	−5.00	1.14	9.7	+0.04
	●	10700	τ Cet	3.49	34	flat	−5.18	0.78	12.4	−0.44

Notes: A = Active, T = Transitional, I = Inactive. Spectral type indicated with colored symbols.

3.1 Spectropolarimetric Snapshots with LBT/PEPSI

We selected the targets for our spectropolarimetry program using the previously identified evolutionary sequence (18 Sco, α Cen A, 16 Cyg A & B) as a template. We searched Baliunas et al. (1995, 1996) for pairs of targets with similar spectral types and rotation periods, including an active star with a clear magnetic cycle and an inactive star (below the critical activity level $\log R'_{\rm HK} \approx -4.95$) with constant activity on decadal timescales. We identified four pairs of stars covering a variety of spectral types from late-F to early-K, including a range of metallicities (which affects the convection zone depth and thus the Rossby number). Connecting each pair of stars with a schematic evolutionary track (Figure 3), we also identified a few stars (5 Ser, HD 126053, HD 166620) that appeared to be along the transition to a longer and weaker cycle like α Cen A. We adopted mass and age estimates from isochrone fitting (Brewer et al., 2016), updated with precise values from gyrochronology for active stars and asteroseismology for some transitional and inactive stars. If the identified sets of stars (**Table 1**) are representative of the magnetic morphology before, during, and after the transition proposed by Metcalfe & van Saders (2017), then spectropolarimetric snapshots should reveal the evolution of the large-scale magnetic field.

As summarized in section 2.3, we have already completed the first set of spectropolarimetric snapshots for a sequence of stars that are hotter and more rapidly rotating than the Sun (88 Leo, 5 Ser, and ρ CrB). We used the PEPSI instrument (Strassmeier et al., 2015) at the 2×8.4 m Large Binocular Telescope (LBT) on Mount Graham, Arizona. We collected Stokes V spectra because Zeeman signatures are the largest in this polarization state. The two polarized beams ($I + V$ and $I - V$) are coupled with 200 μm fibers ($1\farcs5$ on sky) to render the light into the spectrograph via an image slicer with 5 slices and a resolving power of R = 130,000. Zeeman polarization signatures are typically not detectable in the individual spectral lines of even the most active late-type stars. A direct detection and quantitative analysis of magnetic field in such cases requires the application of some multi-line polarization diagnostic method. We used the least-squares deconvolution (LSD; Donati et al., 1997; Kochukhov et al., 2010) technique, which derives high-quality mean intensity and polarization profiles by weighted co-addition of a large number of individual lines. The procedure was applied separately to the four observations of each star (two consecutive exposures with two telescopes) and the resulting profiles were inspected for consistency.

Historically, observations of magnetic activity in solar-type stars have relied on spectroscopic measurements of Ca H & K emission, a standard proxy for magnetic heating in the chromosphere (Leighton, 1959). Such observations are insensitive to magnetic polarity, and thus indicate the total magnetic field strength integrated over all spatial scales. By contrast, spectropolarimetry is sensitive to both the strength and polarity of magnetic field, so geometric cancellation effects make this technique most sensitive to the largest spatial scales (e.g. dipole field). We can estimate the relative activity levels for our pairs of targets by measuring the mean longitudinal magnetic field $\langle B_z \rangle$ from the first moment of the observed Stokes V profiles (Kochukhov et al., 2010). However, we will mitigate uncertainties about the relative activity levels by obtaining chromospheric activity measurements during the LBT observations, using the Network of Robotic Echelle Spectrographs (NRES) on the Las Cumbres Observatory global telescope (LCOGT) network. The PI has been using LCOGT for activity measurements since 2017, and all of our targets are already being observed monthly under a Key Project that is allocated 574 observing hours per year through 2023.

We propose to obtain LBT/PEPSI spectropolarimetric snapshots and contemporaneous LCOGT/NRES activity measurements for all of the targets listed in Table 1. We have already collected new observations in 2021A for the five early G-type targets, with collaborators who each have access to a 25% share of LBT time (M. Pinsonneault, Ohio State University and C. Clark, Northern Arizona University). We obtained higher S/N observations of 16 Cyg A & B to improve upon the unpublished null result from P. Petit (2011, private communication), and we acquired a new snapshot observation of 18 Sco as a control for the positive detection of large-scale field. The latter will also serve as the comparison for our snapshots of two additional solar analogs, including the transitional star HD 126053 and the inactive star λ Ser. A future student-led proposal for 2023A will target the active late G-type star CF UMa and the transitional K-type star HD 166620 (both observable in late spring), while a companion proposal for 2023B will focus on the inactive late G-type star τ Cet and the active K-type star 40 Eri (both observable in early fall). Data from these two runs will be aggregated to yield the comparisons for relevant pairs of stars.

3.2 Confirmation and Magnetic Field Maps with CFHT

After the spectropolarimetric snapshots with LBT establish the required S/N for detections (and statistically significant non-detections) of the extremely weak polarization signatures in our targets, resource-intensive follow-up observations with the CFHT will confirm the absence of large-scale field in our inactive targets and characterize the magnetic morphology of some active targets.

By sampling a random phase of the stellar rotation, snapshot observations are only sensitive to polarization signatures on one hemisphere of the star. For an axisymmetric magnetic field, a snapshot can be representative of the global strength and morphology, but additional measurements are needed to rule out a non-axisymmetric configuration with a stronger polarization signature on the unobserved hemisphere. To estimate the severity of this issue, consider the series of snapshot observations of the young solar analog HD 190771 by Petit et al. (2008), covering 10 unique rotational phases. Nearly all of the polarization profiles in the sequence are indicative of the star's strong non-axisymmetric field, but one of the snapshots yields a nearly flat profile similar to what we observed in ρ CrB (Figure 1). The magnetic field configuration observed at this specific rotational phase yielded almost complete cancellation of the disk-integrated polarization signature. Selecting one random snapshot from their series of observations, we would have a $\sim$10% chance of drawing the wrong conclusion about the strength and morphology of the magnetic field.

We can resolve this ambiguity by repeating the snapshot observation at other rotational phases. Rather than duplicating the spectropolarimetric snapshots with more expensive LBT time, we will obtain follow-up observations at the 3.6 m CFHT on Maunakea using the Echelle SpectroPolari-

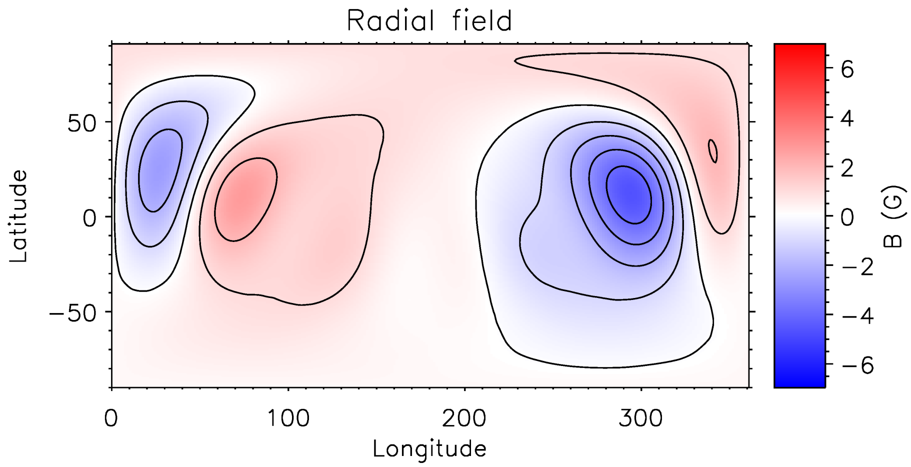

Figure 4: *Radial magnetic field map inverted from a series of spectropolarimetric snapshots. The inversion method simultaneously yields maps of the meridional and azimuthal field, but observations spanning at least 8–10 rotational phases are required for a unique result. Such maps not only verify the strength and complexity of the magnetic field, they also quantify the fraction of magnetic energy in poloidal and toroidal configurations to help constrain the underlying dynamo mechanism.*

metric Device for the Observation of Stars (ESPaDOnS). ESPaDOnS is a bench-mounted high-resolution echelle spectrograph / spectropolarimeter fiber-fed from a Cassegrain module. It was designed to obtain a nearly complete optical spectrum from 370 to 1050 nm in a single exposure with a resolving power of about R = 68,000. The total peak throughput is between 15–20% (telescope and detector included). With the required S/N known from the LBT snapshots, we can adjust the exposure time at CFHT to reach a comparable level of sensitivity. The facility is queue-scheduled, so for each of our inactive stars we will request four additional snapshots separated in time by a quarter rotation period. If we only get one additional snapshot (e.g. due to weather) it will reduce the odds of a spurious non-detection from ∼10% to ∼1%, and if we get two or more snapshots it will effectively rule out the possibility of a hidden large-scale field and confirm the results from LBT while providing useful limits on longer-term magnetic variability.

To characterize the detailed magnetic morphology of our active targets, we need to obtain a series of 8–10 spectropolarimetric snapshots spanning a full rotation. Zeeman Doppler Imaging (ZDI) is a technique for combining the information from such a series of snapshots to invert a complete magnetic field map of the stellar surface (**Figure 4**). Petit et al. (2008) produced ZDI maps (including the radial, meridional, and azimuthal field) for a series of solar analogs including 18 Sco, so we already have detailed information for one of our active targets. However, there may be important trends with spectral type that could be revealed with ZDI maps for 88 Leo, CF UMa, and/or 40 Eri, and if we detect large-scale field in our transitional targets there may be additional information that only ZDI maps can provide. Such maps not only verify the strength and complexity of the magnetic field, they also quantify the fraction of magnetic energy in poloidal and toroidal configurations to help constrain the underlying dynamo mechanism. **The evolution of magnetic complexity for younger stars was investigated by See et al. (2019a) using previously published ZDI maps. We will extend such studies beyond stellar middle-age for the first time.** The queue-scheduling of CFHT will facilitate the required series of spectropolarimetric snapshots even for the longest rotation period (43 days), but these observations are inherently more risky. The total time required for each star is relatively large, and gaps in the observing sequence due to interruptions from weather and other factors can create ambiguities in the inversion process.

We cannot predict how a Time Allocation Committee will evaluate the relative risks and benefits of ZDI maps, but we will attempt to obtain the necessary observations for at least four of our active and transitional targets, to be selected from the characteristics of LBT snapshots.

We propose to confirm our non-detections of large-scale field and construct complete magnetic field maps for selected targets from follow-up observations at CFHT. We obtained follow-up observations of our F-type targets from CFHT in 2021A, to confirm the non-detection of large-scale field in ρ CrB and for further characterization of the detected field in 88 Leo. Co-PI van Saders (University of Hawaii) has guaranteed access to all telescopes on Maunakea, with telescope time awarded by an internal Time Allocation Committee. We anticipate conducting CFHT observations after LBT measurements establish the required S/N for each target, so future proposals are planned for 2023A, 2024A, and 2024B. The frequency range of the ESPaDOnS instrument includes the Ca H & K lines, yielding simultaneous activity measurements.

3.3 Modeling the Magnetic Braking Torque and Rotational Evolution

Spectropolarimetric constraints on the strength and morphology of the large-scale magnetic fields in our pairs of targets can reveal evolutionary changes across a range of spectral types, but two kinds of modeling will help demonstrate that the observed changes are actually responsible for weakened magnetic braking: (1) If we leverage other observational constraints such as the X-ray flux, rotation period, stellar mass, and radius, we can forward model the magnetic braking torque and assess the relative importance of morphology changes compared to other contributions; (2) With additional constraints on the stellar age, metallicity, and effective temperature, we can forward model the rotation periods of our targets under various assumptions about the rate of angular momentum loss (e.g. standard spin-down, or weakened magnetic braking beyond middle-age).

As an example of the wind modeling prescription, Metcalfe et al. (2021) estimated the strength of magnetic braking for ρ CrB and 88 Leo by combining the analytical relations from Finley & Matt (2017, 2018) with the constraints on magnetic morphology from Metcalfe et al. (2019). Although 88 Leo exhibited a non-axisymmetric polarization profile, the amplitude of the signal could be reproduced with an axisymmetric dipole having a polar field strength $|B_{\rm d}| = 5$ G. For ρ CrB, Metcalfe et al. (2019) cited upper limits on the polar field strength assuming a pure axisymmetric dipole ($|B_{\rm d}| \leq 0.7$ G) or quadrupole field ($|B_{\rm q}| \leq 2.4$ G), with the latter being larger due to geometric cancellation effects. An identical analysis of the same LBT data yielded an upper limit on a pure axisymmetric octupole field of $|B_{\rm o}| \leq 19.6$ G. Observationally, the mass-loss rate is one of the least certain quantities required by the wind modeling prescription. Metcalfe et al. (2021) initially fixed the mass-loss rate to the solar value for both stars ($\dot{M}_\odot = 2 \times 10^{-14}\ M_\odot$/yr) and found that the magnetic braking torque for ρ CrB was $\lesssim$20% as strong as for 88 Leo. Empirically, the mass-loss rate is correlated with the X-ray flux. Adopting the scaling relation $\dot{M} \propto F_X^{0.77}$ from Wood et al. (2021), the mass-loss rate changes from $2.0\,\dot{M}_\odot$ to $0.36\,\dot{M}_\odot$ between the ages of these two stars, and the magnetic braking torque for ρ CrB becomes $\lesssim$8% as strong as for 88 Leo.

We propose to use a wind modeling prescription to estimate the change in magnetic braking torque between pairs of targets with the same spectral type, and to quantify the importance of morphology changes relative to other contributions. Aside from the spectropolarimetry, the observational constraints required for such modeling are already available for nearly all of our targets, and more precise masses and ages are expected when asteroseismic observations become available from TESS. Initial estimates of the masses and ages come from isochrone fitting (Brewer et al., 2016), supplemented with gyrochronology for active stars and asteroseismology for some transitional and inactive stars. Radius constraints come from fitting the broadband spectral energy distributions (SEDs) together with the Gaia EDR3 parallaxes following the procedures described in Stassun & Torres (2016) and Stassun et al. (2017, 2018). Archival X-ray measurements are available for all of our targets other than 5 Ser and HD 126053. Aside from 18 Sco (which has a ground-based asteroseismic detection; Bazot et al., 2011), all of our targets will be observed by TESS with 20-second cadence within the next year.

Wind modeling can reveal the current rate of angular momentum loss for each of our targets, but to understand how they reached their present configuration we need rotational evolution modeling. For this purpose, we will use the `rotevol` code (e.g., van Saders & Pinsonneault, 2013; van Saders et al., 2016, 2019; Somers et al., 2017). `rotevol` is a tracer code that runs separately on top of pre-existing grids of stellar evolution models, allowing us to compute rotational evolution tracks more than 1000 times faster than running a fully self-consistent rotating evolutionary model. It allows for departures from solid body rotation by approximating stars as "two-zone models" (e.g., MacGregor & Brenner, 1991), in which angular momentum transport between the convective envelope and the radiative interior occurs with a characteristic coupling timescale. For our spectropolarimetric targets, the tracer approach can be both fast and accurate because rotational feedback on the stellar structure is minimal. Adopting this approach also allows us to rapidly explore different prescriptions for the magnetic braking law without generating new evolutionary tracks for each set of braking law parameters.

As an example of the rotational evolution modeling, Metcalfe et al. (2021) attempted to match the rotation periods and other observational constraints for ρ CrB and 88 Leo with models that assumed either standard spin-down or weakened magnetic braking. They assumed solid body rotation, and used `rotevol` to track the angular momentum evolution as a function of time, given a set of YREC evolutionary tracks and interpolation tools in `kiauhoku` (Claytor et al., 2020). For 88 Leo they found excellent agreement with the observed rotation period for both standard and weakened braking prescriptions. The two cases are identical until the critical Rossby number is exceeded, and thus both predict the same rotation period for an active star like 88 Leo that is not yet beyond the critical Rossby number. By contrast, for ρ CrB the standard spin-down case predicted a rotation rate 2.6 times slower than observed, while a weakened braking case could successfully reproduce the observed rotation period within the uncertainties.

We propose to use rotational evolution modeling to assess the compatibility of the observational constraints for each of our targets with either standard spin-down or weakened magnetic braking. The `rotevol` code can currently evolve models using the braking laws of van Saders & Pinsonneault (2013), van Saders et al. (2016), or Kawaler (1988), but specification of alternate braking formulations is straightforward. In its current implementation, we can specify alternate scalings for the stellar mass-loss rate and magnetic field strength as functions of stellar mass and rotation rate. We will make the minor modifications required to incorporate the morphology-dependent braking law scalings from Finley & Matt (2017, 2018) so that we can explicitly include magnetic morphology in the rotational evolution modeling.

Summary of Intellectual Merit: The research program described above will establish an observational foundation for understanding how stellar magnetism and 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 stellar magnetism depend on rotation and mass beyond middle-age will have implications for theoretical models of angular momentum loss from magnetized stellar winds, the use of gyrochronology as a technique for inferring stellar ages, 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 development of a diverse, globally competitive STEM workforce through the participation of graduate students in the research. One graduate student has already become involved in the project (C. Clark, Northern Arizona University) by submitting an observing proposal on behalf of the collaboration for LBT time in 2021A. A companion proposal was submitted through Ohio State University, with the idea of spreading the required time across multiple LBT institutions. Involving Clark in this international collaboration has given her some professional development in instrumentation, and access to future postdoctoral opportunities. In addition, the research outlined in this proposal will comprise a substantial fraction of Ph.D. theses at the University of Colorado and the University of Hawaii. The students will be engaged in all aspects of the data reduction, analysis, and interpretation, and will take the lead on the resulting publications and presentations at scientific conferences. The PI has years of experience mentoring undergraduates, graduate students, and postdocs, and he will supplement the collaborative research experience by offering a professional development seminar during the award. While he was an NSF Astronomy & Astrophysics Postdoctoral Fellow, the PI developed the syllabus for "Survival Skills for Scientists" with weekly readings and group discussion, and he led the seminar at the University of Colorado in 2005 and 2009. The seminar attempts to prepare participants for academic jobs, while also exposing them to a broader range of perspectives from scientists with non-academic and private-sector backgrounds. The weekly discussion is guided by thought-provoking readings selected primarily from two short books: *"A Ph.D. Is Not Enough!"* by Peter Feibelman (2011 edition), and *"Put Your Science to Work"* by Peter Fiske. A current faculty member at the University of Colorado (Prof. Benjamin Brown) supports offering the seminar again, and has agreed to co-lead the informal weekly discussion. These activities fall outside the normal job responsibilities of the PI, who works as a full-time research scientist at an independent nonprofit organization.

The Co-PI will mentor a summer Research Experience for Teachers (RET) participant at the Institute for Astronomy (IfA) in two of the three summers during the award. The summer RET program was an experimental addition to the summer 2021 IfA REU program (funded through 6/30/2024), in which local Hawaii high school teachers were invited to participate in the REU program. RET participants experience the full complement of REU program activities, including talks from local scientists and cultural practitioners, a visit to Maunakea, and a final research presentation at the conclusion of the program. The RET program embeds high school teachers in a research environment, giving them first-hand experience in the process and people engaged in astronomy in Hawaii and knowledge that they can take back to their classrooms. More importantly, it establishes a working relationship between a practicing astronomer and a high school teacher, opens channels of communication, and lays the foundations for long-term, meaningful interactions between IfA astronomy and the local community. The RET program is a unique opportunity in the environment of Hawaii, where communities are particularly close-knit and centered around children and family, and where the future of astronomy requires buy-in from locals. The RET program specifically connects teachers, all of whom have close ties with the community, to IfA researchers. The Co-PI mentored one of two RET participants in the 2021 pilot program: science teacher Michelle Ramirez-Weinhouse based at the only elementary and high school on Lanai island. The Co-PI and Weinhouse met almost every day for the duration of the program. Weinhouse is still actively involved in the research group, and will be co-author on an upcoming paper that includes her contributions. During wrap discussions at the end of the program, Weinhouse reported that she would bring a new and positive perspective about astronomy to students in her classroom, many of whom had expressed skepticism about astronomy on the islands. The pilot RET program attracted $\sim$30 applicants across the islands, highlighting the interest in such an internship.

5 Plan of Work

Timeline: We obtained LBT spectropolarimetric snapshots for the three F-type targets in 2019A, and the resulting paper was published seven months later. We collected snapshots for five early G-type stars in 2021A, yielding definite detections in the active and transitional stars and statistically significant non-detections in the inactive stars. We will submit student-led LBT proposals for 2023A and 2023B to complete the observations for the four remaining late G-type and early K-type stars. An existing LCOGT Key Project provides 574 hours annually through 2023 for queue-scheduled stellar activity measurements with NRES, and all of the targets in Table 1 are observed regularly for that program. We will coordinate future measurements to repeat several times between ± 1 day of LBT observations. We obtained follow-up observations of our F-type targets from CFHT in 2021A, yielding tighter upper limits on the large-scale field strength for ρ CrB. We will submit future student-led CFHT proposals for 2023A, 2024A, and 2024B, after the LBT snapshots determine the required sensitivity levels. We will identify graduate students at the University of Colorado and the University of Hawaii to begin work on this project in the fall of 2022. With new LBT snapshots in hand for the early G-type stars, and the existing follow-up observations for F-type stars from CFHT, the students can begin work immediately. We will analyze and prepare these new data for publication in the first year, and we will submit LBT and CFHT proposals for 2023A and 2023B. In the second year we will analyze the LBT snapshots of late G-type and early K-type stars from 2023A and 2023B, and we will submit the final two CFHT proposals and analyze the new data from 2023A. In the fall of 2024 we will prepare the final LBT data for publication, and we will begin analyzing the final CFHT data. We will publish those data along with an overview of our findings from the entire observation program in the spring and summer of 2025.

Resources: We completed the LBT observations of three F-type stars with an allocation of 4 hours in 2019A, and five G-type stars with 7.5 hours in 2021A. Each of our targets require between 60–90 minutes to complete a Stokes V observation sequence, with longer integration times for the inactive stars to ensure that any non-detections are statistically significant. The complete observation program will require about 16 hours to execute, equivalent to two nights of LBT time spread over four semesters. The contemporaneous activity measurements with LCOGT will require about 3×30 minutes per target (including observation overhead), for a total of <8 additional hours spread over two semesters. The combination of smaller aperture at CFHT along with the lower resolution and higher efficiency of ESPaDOnS will require 4 hours to confirm the non-detections for each of our inactive targets. This amounts to 16 hours spread over three semesters. After we identify the most interesting active targets for magnetic maps, we will need an additional 8–10 hours per target to obtain the sequence of spectropolarimetric snapshots spanning a full rotation. We will attempt to gather such observations for at least four stars from our sample, for a total of 32–40 additional hours of CFHT time spread over three semesters.

Responsibilities: The LBT observations and wind modeling work will be carried out primarily by a graduate student at the University of Colorado and by the PI (Travis Metcalfe). The CFHT observations and rotational evolution modeling will be carried out primarily by a graduate student at the University of Hawaii and the Co-PI (Jennifer van Saders). Collectively, they will be responsible for writing proposals for telescope time (in collaboration with M. Pinsonneault), analyzing the observations to produce polarization profiles (in collaboration with O. Kochukhov) and chromospheric activity indices, preparing scientific findings for publication (with all of the collaborators), and presenting results at annual conferences. The graduate students will also have the opportunity to work with O. Kochukhov on the analysis of data sets from both LBT and CFHT, during sponsored visits and at scientific conferences. The PI will also be responsible for leading the professional development seminar at the University of Colorado, and the Co-PI will be responsible for mentoring RET participants at the University of Hawaii for two summers during the award.

Metrics of success: Because our observing program is a multi-year survey, we will initially judge progress by the number and quality of spectropolarimetric snapshots that we obtain for our sample. The individual observations do not depend on successful completion of the larger project. Each spectropolarimetric snapshot can provide useful constraints on the magnetic morphology shift, independently of any others. During the second year, the emphasis will shift to the number, quality, and intrinsic interest of conference talks and peer-reviewed publications. In the third year, we will be able to judge the significance of the results from the entire survey, and to evaluate the progress of the graduate students toward successful Ph.D. theses.

6 Results from Prior NSF Support

AST-1812634: "Magnetic Evolution of Sun-like Activity Cycles" (PI: Metcalfe, $225,545 9/1/2018–8/31/2021). **Intellectual merit:** The project obtained hundreds of new observations of chromospheric activity in two samples of stars, all of them are publicly available through the LCOGT science archive, and our software tools for data acquisition and analysis are available on Github. Initial results were presented by one of our summer students at an international workshop (Goga et al., 2019), and our new observations of ε Eri revealed some unexpected behavior during contemporaneous X-ray monitoring (Coffaro et al., 2020). While building up the archive of new magnetic activity measurements, we devised, executed, and published additional tests of our magnetic transition theory that rely on ground-based observations (Metcalfe et al., 2019, 2020, 2021). **Broader impacts:** The project directly contributed to the development of a diverse, globally competitive STEM workforce through the participation of undergraduate summer students (Sabrina Poulsen, Adam Goga) in the research. Goga continued working on the project to make additional improvements, and he released the software on Github for the benefit of other researchers. During the project, the PI wrote an award-winning monthly science column "Lab Notes" for the *Boulder Weekly* newspaper. The column highlighted the role of local scientists in research that captures the public imagination, and it promoted increased scientific literacy and public engagement with the science and technology topics covered by the series.

AST-1817215: "A New Spin on M Dwarf Ages and Evolution" (Co-PI: van Saders, $293,735 9/15/2018–8/31/2021, no-cost extension). **Intellectual Merit:** The investigators have been awarded a total of 95 hours for CFHT MegaPrime photometric monitoring of the open clusters Ruprecht 147 and M67 over the last 4 years. Ph.D. student Ryan Dungee is currently extracting light-curves, measuring periods in CFHT data, and modeling rotational sequences for M67. Publication in preparation. **Broader Impacts:** J.v.S., E.G., and R.D. were project leaders in the 2019, 2020, 2021 HI STAR summer camps, and J.v.S. was a 2019 science fair project mentor.

AST-1908723: "Collaborative Research: The Coeval Degenerates Survey" (PI: van Saders, $253,353 9/1/2019–8/31/2022, in progress). **Intellectual Merit:** We are calibrating cool star period-age relationships, using wide white-dwarf + M-dwarf binaries. University of Hawaii graduate student Alison Dugas has collected $\sim$2400 light-curves from public databases, and has designed and implemented a Gaussian Process period-finding algorithm. Collaborators at Boston University have provided white dwarf cooling ages for sample stars. Publication in preparation. **Broader Impacts:** J.v.S. is recruiting a HI STAR student for a fall 2021 science fair project, and supported summer Research Experience for Teachers (RET) participant Michelle Ramirez-Weinhouse (Lanai High & Elementary) in a literature search for rotation periods of binary system members.