Magnetic Evolution and the Disappearance of Sun-like Activity Cycles

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Abstract After decades of effort, the solar activity cycle is exceptionally well characterized but it remains poorly understood. Pioneering work at the Mount Wilson Observatory demonstrated that other sun-like stars also show regular activity cycles, and suggested two possible relationships between the rotation rate and the length of the cycle. Neither of these relationships correctly describe the properties of the Sun, a peculiarity that demands explanation. Recent discoveries have started to shed light on this issue, suggesting that the Sun’s rotation rate and magnetic field are currently in a transitional phase that occurs in all middle-aged stars. Motivated by these developments, we identify the manifestation of this magnetic transition in the best available data on stellar cycles. We propose a reinterpretation of previously published observations to suggest 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. Future tests of this hypothesis will come from ground-based activity monitoring of Kepler targets that span the magnetic transition, and from asteroseismology with the TESS mission to determine precise masses and ages for bright stars with known cycles.

Keywords: Magnetic fields, Chromosphere; Rotation; Solar Cycle, Observations

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1. Astrophysical Context

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 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 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 measured rotation rates and activity variations to help validate 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 ($Ro \equiv P_{\text{rot}}/\tau_c$, 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, Saar, and Turpin (1998) suggested that there were actually two distinct relationships between the rotation rate and the length of the cycle, with an upper sequence of stars showing a cycle every 300-500 rotations, and a lower 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. B"ohm-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. With a mean cycle period of 11 years and a sidereal rotation period of 25.4 days ($P_{\text{cyc}}/P_{\text{rot}} \sim 160$), the Sun falls between the two stellar sequences (B"ohm-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, Egeland, and van Saders, 2016). In the following section, we review the evidence for a magnetic transition and the underlying mechanisms. In Section 3, we examine previously published observations to identify the manifestation of this transition in stellar activity cycles, and we propose a new scenario for the evolution of the solar cycle. We discuss the potential for future observational tests of this hypothesis in Section 4.
2. Magnetic Metamorphosis

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 \( \frac{dJ}{dt} \propto \omega^3 \), 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 \( \sim 1 \) 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 tension 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 \( \sim 2-3 \) Gyr for hotter F-type stars and \( \sim 6-7 \) 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 \( R_\text{o} \sim 2 \). 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. 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 sun-like stars in Figure 1. A standard rotational evolution model (solid line) and the modified model that eliminates angular momentum loss beyond a critical
Figure 1. Stellar evidence for the shutdown of magnetic braking in sun-like 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) for solar metallicity and a zero age main-sequence (ZAMS) effective temperature of 5750 K, which eliminates angular momentum loss beyond a critical Rossby number ($\text{Ro} \sim 2$), determined from a fit to Kepler field stars with asteroseismic ages (black points and 16 Cyg). The shaded region represents the expected dispersion due to the range of masses and metallicities within the field star sample, encompassing ZAMS effective temperatures between 5600-5900 K. A few well-characterized solar analogs are shown with yellow points.

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 (black points and 16 Cyg) 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 sun-like Kepler stars. A few well-characterized solar analogs are shown with yellow points, including 18 Sco (Petit et al., 2008; Li et al., 2012; Mittag et al., 2016), α Cen A (Bazot et al., 2007; Bazot, Bourguignon, and Christensen-Dalsgaard, 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.

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, Drake, and Cohen, 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 increasing Alfvén radius, low-order fields consequently shed more angular momentum. The inverse of this process may be responsible for the onset of efficient magnetic braking in very young stars (Brown, 2014).

2.2. Triggering the Magnetic Transition

Metcalfe, Egeland, and van Saders (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 sun-like stars from the Mount Wilson survey (Baliunas, Sokoloff, and Soon, 1996; Donahue, Saar, and Baliunas, 1996). Such a comparison requires the Ca HK measurements to be converted to a chromospheric activity scale (log $R'_{HK}$) that accounts for the bolometric flux of different spectral types. The relationship between chromospheric activity and rotation is illustrated in Figure 2. The Kepler targets are plotted by spectral type, including F-type (triangles), G-type (circles), and K-type stars (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 and Hillenbrand (2008). The activity levels that correspond to key Rossby numbers are shown as shaded regions on either side of the Vaughan-Preston gap (dashed line; Vaughan and Preston, 1980). The dotted line connects some well-characterized solar analogs, including the same stars shown with yellow points in Figure 1.

The magnetic evolution of sun-like stars appears to change dramatically when they reach the critical Rossby number (Ro~2) identified by van Saders et al. (2016). The shutdown of magnetic braking near the activity level of 18Sco (log $R'_{HK}$=−4.93; Hall, Lockwood, and Skiff, 2007) keeps the rotation rate nearly constant as the activity level continues to decrease with age toward α Cen A (log $R'_{HK}$=−5.00; Henry et al., 1996) and 16 Cyg (log $R'_{HK}$=−5.09; Wright et al., 2004). A similar transition occurs at faster rotation rates for hotter stars like HD 143761 (blue triangle), and at slower rotation rates for cooler stars like HD 219834A (red square). The influence of this magnetic transition on stellar activity cycles is described in Section 3.

Metcalfe, Egeland, and van Saders (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
Figure 2. Relationship between rotation and chromospheric activity in field dwarfs and subgiants. The asteroseismic sample from Kepler is shown with black points, and a selection of targets from the Mount Wilson survey are shown as star symbols. The solar analogs discussed in Metcalfe, Egeland, and van Saders (2016) are connected with a dotted line, crossing the Vaughan-Preston gap (dashed line) before reaching the critical Rossby number (Ro∼2, shaded region) where magnetic braking becomes less efficient. The solar analogs from Figure 1 are again shown with yellow points, the F-type star HD 143761 is shown as a blue triangle, and the K-type star HD 219834A is shown as a red square.

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, again validating the asteroseismic age scale.

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 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).
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 in Böhm-Vitense (2007) is shown in Figure 3 using data from Brandenburg, Saar, and Turpin (1998). More recent data have been added from Hall, Henry, and Lockwood (2007), Bazot et al. (2007), Petit et al. (2008), DeWarf, Datin, and Guinan (2010), Metcalfe et al. (2010, 2013), Ayres (2014), Egeland et al. (2015), and Salabert et al. (2016). We do not include marginal detections of stellar cycles that may obscure the relationships suggested by the best available data (e.g., see Egeland, 2017).

The stellar sequence along the bottom of Figure 3 has three distinct regimes. For faster rotators ($P_{\text{rot}} < 22$ 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 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 $\sim 15$ 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 ($2.0 \pm 0.4$ Gyr; Barnes, 2007), which has $P_{\text{rot}} = 14$ days and shows normal cycles on both sequences. The more evolved star HD 143761 has $P_{\text{rot}} = 17$ days, and shows flat activity at $\log R'_{\text{HK}} = -5.04$ for 25 years (Baliunas et al., 1995). The age from gryochronology implied by this rotation period is $2.5 \pm 0.4$ Gyr (Barnes, 2007), which agrees with the age of F-type stars observed by Kepler that have reached the critical Rossby number (blue dashed line) where the rotation period subsequently evolves much more slowly (van Saders et al., 2016).

The transition across $R_o \sim 2$ for G-type stars occurs at rotation periods comparable to the Sun ($P_{\text{rot}} \sim 23$–30 days). Before reaching this threshold, magnetic braking continues in these stars and their cycle periods evolve along the two sequences as their rotation slows. When they reach the critical Rossby number, the 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 ($4.1 \pm 0.5$ Gyr; Li et al., 2012; Mittag et al., 2016), the Sun ($4.6$ Gyr), and $\alpha$ Cen A ($5.4 \pm 0.3$ Gyr; Bazot, Bourguignon, and Christensen-Dalsgaard, 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 ($P_{\text{rot}} \sim 23.5$ days at 7 Gyr; Davies et al., 2015; Metcalfe, Creevey, and Davies, 2015), where cyclic activity is no longer detected (Hall, Lockwood, and Skiff, 2007). 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
Figure 3. Updated version of a diagram originally published by Böhm-Vitense (2007), showing two different relationships between rotation rate and the length of the activity cycle. 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. Shaded regions indicate the fits of Brandenburg, Saar, and Turpin (1998) using a range of convective turnover times appropriate for G-type stars ($\tau = 7-14$ days) on the upper sequence and for K-type stars ($\tau = 17-23$ days) on the lower sequence.

timescales, and that the cycle might disappear sometime in the next 0.8-2.4 Gyr (between the ages of $\alpha$ Cen and 16 Cyg).

All of the slowest rotators with cycles ($P_{rot} > 30$ 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 our sample 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, Mathur, and Metcalfe, 2017). The slightly hotter star HD 182572 ($P_{rot} \sim 41$ days; Baliunas, Sokoloff, and Soon, 1996) appears to have already completed the magnetic transition like 16 Cyg A & B, showing flat activity at $\log R'_{HK} = -5.10$ for 13 years (Baliunas et al., 1995).

Although $\alpha$ 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 $\alpha$ Cen A is $\sim$35 years, much longer than the observed cycle (Brandenburg, Mathur, and Metcalfe, 2017). In addition, there is no evidence of a shorter cycle in $\alpha$ Cen A (see Ayres, 2014), even though 18 Sco shows a cycle on the lower sequence at essentially the same rotation period.

We can understand the evolution of the cycle toward longer periods during the magnetic transition by considering the variation of convective velocity with depth. The velocity is larger in the outer regions of the convection zone, and becomes progressively smaller in deeper layers (e.g., Miesch et al., 2012). Consequently, a star will initially exceed the critical Rossby number in the outer layers and the condition will only be met later in the deeper layers as the character of differential rotation shifts and the local rotation rate continues to slow (Metcalfe, Egeland, and van Saders, 2016). If the lower sequence in Figure 3 represents a dynamo operating closer to the surface, while the upper sequence is the result of a dynamo driven in deeper layers (e.g., Käpylä et al., 2016), we speculate that the cycle period may grow longer as the magnetic transition proceeds and pushes the dynamo into deeper layers. The size of the convection zone might then set the overall timescale for completing the transition, when cycles disappear (or become extremely long) as in HD 143761, 16 Cyg A & B and HD 182572. However, other identifications of the underlying dynamos that are responsible for the two stellar sequences may not support this interpretation.

4. Discussion and Future Outlook

Motivated by the recent discoveries of a rotational and magnetic transition in middle-aged stars (van Saders et al., 2016; Metcalfe, Egeland, and van Saders, 2016), we have identified the corresponding evolution of stellar activity cycles. A reinterpretation of previously published observations suggests that cycle periods grow longer along two sequences as magnetic braking slows the stellar rotation, but at a critical Rossby number (Ro $\sim$2) the surface rotation rate changes more slowly while the cycle gradually grows longer before disappearing. Evidence for this scenario exists for a range of spectral types, from the hotter F-type stars (HD 100180, HD 143761), to well-characterized solar analogs (18 Sco, $\alpha$ Cen A, 16 Cyg A & B), to the cooler K-type stars (HD 219834A, HD 182572). The Sun appears to have already started this transition, and the solar cycle is expected to grow longer on stellar evolutionary timescales before disappearing sometime in the next 0.8-2.4 Gyr (between the ages of $\alpha$ Cen and 16 Cyg).

The greatest obstacle to understanding how the magnetic 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 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 $\alpha$ Cen A; Li et al., 2012; Bazot, Bourguignon, and Christensen-Dalsgaard, 2012). This situation will soon
improve, after the Transiting Exoplanet Survey Satellite (TESS; Ricker et al., 2014) 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 stars down to $V \sim 12$ (Chaplin et al., 2011). Similar detections are expected from TESS down to $V \sim 7$ (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 stars are well-constrained from asteroseismology, chromospheric activity data have not been collected for long enough to detect stellar cycles. 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 hindered 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 $P_{\text{rot}} \sim 11$ days. Most of the Kepler sample has already made the transition across $R_\odot \sim 2$, so we might expect them to be “flat activity” stars like 16 Cyg A & B (Hall, Lockwood, and Skiff, 2007), but this remains to be seen. Future observations with the Las Cumbres Observatory (LCO) global telescope network promise to probe the onset and duration of the magnetic transition that drives the evolution and eventual disappearance of sun-like activity cycles.

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References

Angus, R., Aigrain, S., Foreman-Mackey, D., McQuillan, A.: 2015, Calibrating gyrochronology using Kepler asteroseismic targets. Mon. Not. Roy. Astron. Soc. 450, 1787. [DOI] [ADS]

Ayres, T.R.: 2014, The Ups and Downs of $\alpha$ Centauri. Astron. J. 147, 59. [DOI] [ADS]

Baliunas, S., Sokoloff, D., Soon, W.: 1996, Magnetic Field and Rotation in Lower Main-Sequence Stars: an Empirical Time-dependent Magnetic Bode’s Relation? Astrophys. J. Lett. 457, L99. [DOI] [ADS]

Baliunas, S.L., Donahue, R.A., Soon, W.H., Horne, J.H., Frazer, J., Woodard-Eklund, L., Bradford, M., Rao, L.M., Wilson, O.C., Zhang, Q., Bennett, W., Briggs, J., Carroll, S.M., Duncan, D.K., Figueroa, D., Lanning, H.H., Misch, T., Mueller, J., Noyes, R.W., Poppe, D., Porter, A.C., Robinson, C.R., Russell, J., Shelton, J.C., Szyma\-ner, T., Vaughan, A.H., Whitney, J.H.: 1995, Chromospheric variations in main-sequence stars. Astrophys. J. 438, 269. [DOI] [ADS]

Barnes, S.A.: 2007, Ages for Illustrative Field Stars Using Gyrochronology: Viability, Limita-
tions, and Errors. Astrophys. J. 669, 1167. [DOI] [ADS]

Bazot, M., Bourguignon, S., Christensen-Dalsgaard, J.: 2012, A Bayesian approach to the modelling of $\alpha$ Cen A. Mon. Not. Roy. Astron. Soc. 427, 1847. [DOI] [ADS]

Bazot, M., Bouchy, F., Kjeldsen, H., Charpinet, S., Laymand, M., Vauclair, S.: 2007, Astero-
seismology of $\alpha$ Centauri A. Evidence of rotational splitting. Astron. Astrophys. 470, 295. [DOI] [ADS]

Böhm-Vitense, E.: 2007, Chromospheric Activity in G and K Main-Sequence Stars, and What It Tells Us about Stellar Dynamos. Astrophys. J. 657, 486. [DOI] [ADS]
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Brandenburg, A., Mathur, S., Metcalfe, T.S.: 2017, Evolution of Coexisting Long and Short Period Stellar Activity Cycles. Astrophys. J., accepted (arXiv:1704.09009).

Brown, T.M.: 2014, The Metastable Dynamo Model of Stellar Rotational Evolution. Astrophys. J. 789, 101. DOI ADS

Chaplin, W.J., Kjeldsen, H., Christensen-Dalsgaard, J., Basu, S., Miglio, A., Appourchaux, T., Chaplin, W.J., Huber, D., Serenelli, A.M., Silva Aguirre, V., Sousa, S.G., Stello, D., Stevens, I.R., Suran, M.D., Uytterhoeven, K., White, T.R., Borucki, W.J., Brown, T.M., Jenkins, J.M., Kinemuchi, K., Van Cleve, J., Klaus, T.C.: 2011, Ensemble Asteroseismicology of Solar-Type Stars with the NASA Kepler Mission. Science 332, 213. DOI ADS

Creevey, O.L., Magalhaes, M., Schultheis, M., Salabert, D., Bazot, M., Thevenin, F., Mathur, S., Xu, H., Garcia, R.A.: 2017, Characterizing solar-type stars from full-length Kepler data sets using the Asteroseismic Modeling Portal. Astron. Astrophys. 601, A67. DOI ADS

Davies, G.R., Chaplin, W.J., Faer, W.M., Garcia, R.A., Lund, M.N., Mathis, S., Metcalfe, T.S., Appourchaux, T., Basu, S., Benomar, O., Campante, T.L., DeMink, E., Elsworth, Y., Handberg, R., Huber, D., Jimenez, A., Mathur, S., Mazumdar, A., Mosser, B., New, R., Pinsonneault, M.H., Pricopi, D., Quirion, P.-O., Régulo, C., Salabert, D., Serenelli, A.M., Silva Aguirre, V., Sousa, S.G., Stello, D., Stevens, I.R., Suran, M.D., Uytterhoeven, K., White, T.R., Borucki, W.J., Brown, T.M., Jenkins, J.M., Kinemuchi, K., Van Cleve, J., Klaus, T.C.: 2011, Ensemble Asteroseismicology of Solar-Type Stars with the NASA Kepler Mission. Astrophys. J. Supp. 210, 1. DOI ADS

Charbonneau, D.: 2010, Dynamo Models of the Solar. Living Reviews in Solar Physics 7, 3. DOI ADS

Creevey, O.L., Metcalfe, T.S., Schultheis, M., Salabert, D., Bazot, M., Thevenin, F., Mathur, S., Xu, H., Garcia, R.A.: 2017, Characterizing solar-type stars from full-length Kepler data sets using the Asteroseismic Modeling Portal. Astron. Astrophys. 601, A67. DOI ADS

DeWalt, L.E., Datin, K.M., Guinan, E.F.: 2010, X-ray, FUV, and UV Observations of α Centauri B: Determination of Long-term Magnetic Activity Cycle and Rotation Period. Astrophys. J. 722, 343. DOI ADS

Donahue, R.A., Saar, S.H., Ballman, S.L.: 1996, A Relationship between Mean Rotation Period in Lower Main-Sequence Stars and Its Observed Range. Astrophys. J. 466, 384. DOI ADS

Egeland, R.: 2017, Long-Term Variability of the Sun in the Context of Solar-Analog Stars. PhD thesis, Montana State University, Bozeman, Montana, USA. ADS

Egeland, R., Metcalfe, T.S., Hall, J.C., Henry, G.W.: 2015, Sun-like Magnetic Cycles in the Rapidly-rotating Young Solar Analog HD 30495. Astrophys. J. 812, 12. DOI ADS

Garraffo, C., Drake, J.J., Cohen, O.: 2016, The missing magnetic morphology term in stellar rotation evolution. Astron. Astrophys. 595, A110. DOI ADS

Gastine, T., Yadav, R.K., Morin, J., Reiners, A., Wicht, J.: 2014, From solar-like to antisolar differential rotation in cool stars. Mon. Not. Roy. Astron. Soc. 438, L76. DOI ADS
Hall, J.C., Henry, G.W., Lockwood, G.W.: 2007, The Sun-like Activity of the Solar Twin 18 Scorpii. *Astron. J.* 133, 2206. [DOI ADS](http://adsabs.harvard.edu/abs/2007AJ....133.2206H)

Hall, J.C., Lockwood, G.W., Skiff, B.A.: 2007, The Activity and Variability of the Sun and Sun-like Stars. I. Synoptic Ca ii H and K Observations. *Astron. J.* 133, 862. [DOI ADS](http://adsabs.harvard.edu/abs/2007AJ....133..862H)

Henry, T.J., Soderblom, D.R., Donahue, R.A., Baliunas, S.L.: 1996, A Survey of Ca ii H and K Chromospheric Emission in Southern Solar-Type Stars. *Astron. J.* 111. [DOI ADS](http://adsabs.harvard.edu/abs/1996AJ....111.1364H)

Käpylä, M.J., Käpylä, P.J., Olspert, N., Brandenburg, A., Warnecke, J., Karak, B.B., Pelt, J.: 2016, Multiple dynamo modes as a mechanism for long-term solar activity variations. *Astron. Astrophys.* 589, A56. [DOI ADS](http://adsabs.harvard.edu/abs/2016A&A...589A..56K)

Karoff, C., Metcalfe, T.S., Chaplin, W.J., Frandsen, S., Grundahl, F., Kjeldsen, H., Christensen-Dalsgaard, J., Nielsen, M.B., Friman, S., Thygesen, A.O., Arentoft, T., Amby, T.M., Sousa, S.G., Buzasi, D.L.: 2013, Sounding stellar cycles with Kepler - II. Ground-based observations. *Mon. Not. Roy. Astron. Soc.* 433, 3227. [DOI ADS](http://adsabs.harvard.edu/abs/2013MNRAS.433.3227K)

Kawaler, S.D.: 1988, Angular momentum loss in low-mass stars. *Astrophys. J.* 333, 236. [DOI ADS](http://adsabs.harvard.edu/abs/1988ApJ...333..236K)

Leighton, R.B.: 1959, Observations of Solar Magnetic Fields in Plage Regions. *Astrophys. J.* 130, 366. [DOI ADS](http://adsabs.harvard.edu/abs/1963ApJ...130..366L)

Li, T.D., Bi, S.L., Liu, K., Tian, Z.J., Shuai, G.Z.: 2012, Stellar parameters and seismological analysis of the star 18 Scorpii. *Astron. Astrophys.* 546, A89. [DOI ADS](http://adsabs.harvard.edu/abs/2012A&A...546A..89L)

Mamajek, E.E., Hillenbrand, L.A.: 2008, Improved Age Estimation for Solar-Type Dwarfs using Activity-Rotation Diagnostics. *Astrophys. J.* 687, 1264. [DOI ADS](http://adsabs.harvard.edu/abs/2012ApJ...687.1264M)

Metcalfe, T.S., Basu, S., Henry, T.J., Soderblom, D.R., Judge, P.G., Knöllker, M., Mathur, S., Čelik, Z., Antia, H.M., Benomar, O., Howe, R., Régulo, C., Salabert, D., Serenelli, A., Thompson, M.J., Trampedach, R., White, T.R., Ballot, J., Brandão, I.M., Molenda-Zakowicz, J., Kjeldsen, H., Twicken, J.D., Uddin, K., Wohler, B.: 2012, A Uniform Asteroseismic Analysis of 22 Solar-type Stars Observed by Kepler. *Astrophys. J.* 749, 152. [DOI ADS](http://adsabs.harvard.edu/abs/2012ApJ...749..152M)

Melis, S., Barnes, S.A., Latham, D.W., Batalha, N., Borucki, W.J., Koch, D.G., Basri, G., Walkowicz, L.M., Janes, K.A., Jenkins, J., Van Cleve, J., Haas, M.R., Bryson, S.T., Dupree, A.K., Furesz, G., Szcentgyorgyi, A.H., Buchhave, L.A., Clarke, B.D., Twicken, J.D., Quintana, E.V.: 2011, The Kepler Cluster Study: Stellar Rotation in NGC 6811. *Astrophys. J. Lett.* 733, L9. [DOI ADS](http://adsabs.harvard.edu/abs/2011ApJ...733L...9M)

Stellar parameters and seismological analysis of the star 18 Scorpii. *Astron. Astrophys.* 546, A89. [DOI ADS](http://adsabs.harvard.edu/abs/2012A&A...546A..89L)

Metcalfe, T.S., Basu, S., Henry, T.J., Soderblom, D.R., Judge, P.G., Knöllker, M., Mathur, S., Rempel, M.: 2010, A spin-down clock for cool stars from observations of a 2.5-billion-year-old cluster. *Nature* 517, 589. [DOI ADS](http://adsabs.harvard.edu/abs/2010Natur.517..589M)

Metcalfe, T.S., Creevey, O.L., Davies, G.R.: 2015, Asteroseismic Modeling of 16 Cyg A & B using the Complete Kepler Data Set. *Astrophys. J. Lett.* 811, L37. [DOI ADS](http://adsabs.harvard.edu/abs/2015ApJ...811L..37M)

Metcalfe, T.S., Egeland, R., van Saders, J.: 2016, Stellar Evidence That the Solar Dynamo May Be in Transition. *Astrophys. J. Lett.* 826, L2. [DOI ADS](http://adsabs.harvard.edu/abs/2016ApJ...826L...2M)

Metcalfe, T.S., Basu, S., Henry, T.J., Soderblom, D.R., Judge, P.G., Knöllker, M., Mathur, S., Rempel, M.: 2010, Discovery of a 1.6 Year Magnetic Activity Cycle in the Exoplanet Host Star ε Eridani. *Astrophys. J. Lett.* 723, L213. [DOI ADS](http://adsabs.harvard.edu/abs/2010ApJ...723L.213M)

Metcalfe, T.S., Chaplin, W.J., Appourchaux, T., García, R.A., Basu, S., Brandão, I., Creevey, O.L., Deheuvels, S., Doğan, G., Egggenberger, P., Karoff, C., Miglio, A., Stello, D., Yildiz, M., Čelik, Z., Antia, H.M., Benomar, O., Howe, R., Régulo, C., Salabert, D., Stahn, T., Bedding, T.R., Davies, G.R., Elsworth, Y., Gizon, L., Hekker, S., Mathur, S., Mosser, B., Bryson, S.T., Still, M.D., Christensen-Dalsgaard, J., Gilliland, R.L., Kawaler, S.D., Kjeldsen, H., Ibrahim, K.A., Klaus, T.C., Li, J.: 2012, Asteroseismology of the Solar Analogs 16 Cyg A and B from Kepler Observations. *Astrophys. J. Lett.* 748, L10. [DOI ADS](http://adsabs.harvard.edu/abs/2012ApJ...748L..10M)

Metcalfe, T.S., Buccino, A.P., Brown, B.P., Mathur, S., Soderblom, D.R., Henry, T.J., Mauas, P.J.D., Petrucci, R., Hall, J.C., Basu, S.: 2013, Magnetic Activity Cycles in the Exoplanet Host Star ε Eridani. *Astrophys. J. Lett.* 763, L26. [DOI ADS](http://adsabs.harvard.edu/abs/2013ApJ...763L..26M)
Disappearance of Sun-like Cycles

Soran, M.D., Yildiz, M., Askoz, C., Elsworth, Y., Gruberbauer, M., Guenther, D.B., Lebreton, Y., Molaverdikhani, K., Pricopi, D., Simoniello, R., White, T.R.: 2014, Properties of 42 Solar-type Kepler Targets from the Asteroseismic Modeling Portal. *Astrophys. J. Supp.* 214, 27. [DOI] [ADS]

Miesch, M.S., Featherstone, N.A., Rempel, M., Trampedach, R.: 2012, On the Amplitude of Convective Velocities in the Deep Solar Interior. *Astrophys. J.* 757, 128. [DOI] [ADS]

Mittag, M., Schröder, K.-P., Hempelmann, A., González-Pérez, J.N., Schmitt, J.H.M.M.: 2016, Chromospheric activity and evolutionary age of the Sun and four solar twins. *Astron. Astrophys.* 591, A89. [DOI] [ADS]

Noyes, R.W., Hartmann, L.W., Baliunas, S.L., Duncan, D.K., Vaughan, A.H.: 1984, Rotation, convection, and magnetic activity in lower main-sequence stars. *Astrophys. J.* 279, 763. [DOI] [ADS]

Pace, G., Meléndez, J., Pasquini, L., Carraro, G., Danziager, J., François, P., Matteucci, F., Santos, N.C.: 2009, An investigation of chromospheric activity spanning the Vaughan-Preston gap: impact on stellar ages. *Astron. Astrophys.* 499, L9. [DOI] [ADS]

Petit, P., Dintrans, B., Solanki, S.K., Donati, J.-F., Aurière, M., Lignières, F., Morin, J., Paletou, F., Ramirez Velez, J., Catala, C., Fares, R.: 2008, Toroidal versus poloidal magnetic fields in Sun-like stars: a rotation threshold. *Mon. Not. Roy. Astron. Soc.* 388, 80. [DOI] [ADS]

Pinsonneault, M.H., Kawalet, S.D., Sofia, S., Demarque, P.: 1989, Evolutionary models of the rotating sun. *Astrophys. J.* 338, 424. [DOI] [ADS]

Réville, V., Brun, A.S., Matt, S.P., Strugarek, A., Pinto, R.F.: 2015, The Effect of Magnetic Topology on Thermally Driven Wind: Toward a General Formulation of the Braking Law. *Astrophys. J.* 798, 116. [DOI] [ADS]

Ricker, G.R., Winn, J.N., Vanderspek, R., Latham, D.W., Balos, G.A., Bean, J.L., Berta-Thompson, Z.K., Brown, T.M., Buchhave, L., Butler, R.P., Chaplin, W.J., Charbonneau, D., Christensen-Dalsgaard, J., Clamimp, M., Deming, D., Doty, J., De Lee, N., Dressing, C., Dunham, E.W., Endl, M., Fressin, F., Ge, J., Henning, T., Holman, M.J., Howard, A.W., Ida, S., Jenkins, J., Jernigan, G., Johnson, J.A., Kane, L., Kawai, N., Kjeldsen, H., Laughlin, G., Levine, A.M., Lin, D., Lissauer, J.J., MacQueen, P., Marcy, G., McCullough, P.R., Morton, T.D., Narita, N., Paegert, M., Palle, E., Pepe, F., Pepper, J., Quirrenbach, A., Rinehart, S.A., Sasson, D., Sato, B., Seager, S., Sozzetti, A., Stassun, K.G., Sullivan, P., Szyszko, I., Torres, G., Udry, S., Villasenor, J.: 2014, Transiting Exoplanet Survey Satellite (TESS). In: *Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave*. Proc. SPIE 9143, 914320. [DOI] [ADS]

Salabert, D., Régulo, C., García, R.A., Beck, P.G., Ballot, J., Creevey, O.L., Pérez Hernández, F., do Nascimento, J.-D. Jr., Corsaro, E., Egeland, R., Mathur, S., Metcalfe, T.S., Bigot, L., Ceillier, T., Pallé, P.L.: 2016, Magnetic variability in the young solar analog KIC 10644253. Observations from the Kepler satellite and the HERMES spectrograph. *Astron. Astrophys.* 589, A118. [DOI] [ADS]

Schwabe, M.: 1844, Sonnenbeobachtungen im Jahre 1843. Von Herrn Hofrath Schwabe in Dessau. *Astronomische Nachrichten* 21, 232. [ADS]

Skumanich, A.: 1972, Time Scales for Ca II Emission Decay, Rotational Braking, and Lithium Depletion. *Astrophys. J.* 171, 565. [DOI] [ADS]

Thompson, M.J., Toomre, J., Anderson, E.R., Antia, H.M., Berthomieu, G., Burtonclay, D., Chitre, S.M., Christensen-Dalsgaard, J., Corbard, T., De Rosa, M., Genovese, C.R., Gough, D.O., Haber, D.A., Harvey, J.W., Hill, F., Howe, R., Korzennik, S.G., Kosovichev, A.G., Leibacher, J.W., Pipers, F.P., Provost, J., Rhodes, E.J.R., Schou, J., Sekii, T., Stark, P.B., Wilson, P.R.: 1996, Differential Rotation and Dynamics of the Solar Interior. *Science* 272, 1300. [DOI] [ADS]

van Saders, J.L., Ceillier, T., Metcalfe, T.S., Silva Aguirre, V., Pinsonneault, M.H., García, R.A., Mathur, S., Davies, G.R.: 2016, Weakened magnetic braking as the origin of anomalously rapid rotation in old field stars. *Nature* 529, 181. [DOI] [ADS]

Vaughan, A.H., Preston, G.W.: 1980, A survey of chromospheric Ca II H and K emission in field stars of the solar neighborhood. *Pub. Astron. Soc. Pacific* 92, 385. [DOI] [ADS]

White, T.R., Benomar, O., Silva Aguirre, V., Ball, W.H., Bedding, T.R., Chaplin, W.J., Christensen-Dalsgaard, J., García, R.A., Gizon, L., Stello, D., Aigrain, S., Antia, H.M., Appourchaux, T., Bazot, M., Campante, T.L., Creevey, O.J., Davies, G.R., Elsworth, Y.P., Gaulme, P., Handberg, R., Hekker, S., Houdek, G., Howe, R., Huber, D., Karoff, C., Marques, J.P., Mathur, S., McQuillan, A., Metcalfe, T.S., Mosser, B., Nielsen, M.B.,
Régulo, C., Salabert, D., Stahn, T.: 2017, Kepler observations of the asteroseismic binary HD 176465. *Astron. Astrophys.* **601**, A82. [DOI](10.1051/0004-6361/201630387) [ADS](http://adsabs.harvard.edu/abs/2017A&A...601A..82R)

Wilson, O.C.: 1978, Chromospheric variations in main-sequence stars. *Astrophys. J.* **226**, 379. [DOI](10.1086/156005) [ADS](http://adsabs.harvard.edu/abs/1978ApJ...226..379W)

Wright, J.T., Marcy, G.W., Butler, R.P., Vogt, S.S.: 2004, Chromospheric Ca II Emission in Nearby F, G, K, and M Stars. *Astrophys. J. Supp.* **152**, 261. [DOI](10.1086/384447) [ADS](http://adsabs.harvard.edu/abs/2004ApJS..152..261W)