Stellar Activity Cycles

Sandra V. Jeffers[1*], René Kiefer[2] and Travis S. Metcalfe[3]

[1*]Max Planck Institut für Sonnensystemforschung,
Justus-von-Liebig-Weg 3, Göttingen, 37077, Germany.
[2]Leibniz Institute for Solar Physics (KIS), Schöneckstraße 6,
Freiburg, 79104, Germany.
[3]White Dwarf Research Corporation, 9020 Brumm Trail, Golden,
Colorado 80403, USA.

*Corresponding author(s). E-mail(s): jeffers@mps.mpg.de;
Contributing authors: kiefer@leibniz-kis.de; travis@wdrc.org;

Abstract

The magnetic field of the Sun is generated by internal dynamo process with a cyclic period of 11 years or a 22 year magnetic cycle. The signatures of the Sun's magnetic cycle are observed in the different layers of its atmosphere and in its internal layers. In this review, we use the same diagnostics to understand the magnetic cycles of other stars with the same internal structure as the Sun. We review what is currently known about mapping the surface magnetic fields, chromospheric and coronal indicators, cycles in photometry and asteroseismology. We conclude our review with an outlook for the future.

Keywords: stars: activity cycles, stars: photospheres, stars: chromospheres, stars: corona, stars:interiors

1 Introduction

Magnetic fields on the Sun are well characterised with observations at both high spatial and temporal resolutions. The signatures of the solar dynamo are observable in the different layers of the Sun's atmosphere using multi-wavelength observations and through seismology that allows us to directly probe beneath the Sun's surface. For a comprehensive review of the solar dynamo we refer to the recent review of Charbonneau (2020). For stars with

masses ranging from slightly higher than the Sun down to about one-third of the Sun's mass, they are known to have a comparable internal structure as the Sun, in the form of an internal radiative zone and an convective envelope. Since the presence of an outer convective envelope is a key ingredient in the generation of the Solar dynamo, we also expect to see comparable signatures of magnetic activity on other solar-type stars. While it is unfortunately not possible to observe other stars with the same spatial resolution or temporal cadence as the Sun, they do allow us to understand how key components of the solar dynamo, such as stellar mass and rotation rate, impact the internal dynamo processes.

A key component of the solar dynamo is that the dynamo mechanism produces a balance between the amounts of magnetic flux generated and lost over its 11-year activity cycle. At the beginning of the cycle, magnetic flux emerges at mid-latitudes on the Sun's surface. Over the course of the cycle, the latitude of flux emergence decreases, reflecting the changing nature of the Sun's internal magnetic field, and finally reaches the Sun's equator. This winged pattern of flux emergence is commonly depicted in a solar butterfly diagram (Maunder, 1904). The importance of the surface magnetic fields in the dynamo process has been recently reviewed by Cameron and Schüssler (2023). The first detection of a magnetic field in sunspots was reported by Hale (1908). The evolution of the Sun's large-scale magnetic field over its cycle has been monitored by regular polarimetric observations since the 1970s (Cameron et al, 2018). For each 11-year cycle, the magnetic field changes polarity, leading to a 22-year magnetic cycle (Hathaway, 2015). Higher up in the Sun's atmosphere, chromospheric diagnostics are commonly used such as the S index. The S index is a measure of the emission in the cores of the Ca II H and K lines, at 396.6 nm and 393.4 nm respectively, relative to nearby spectral continuum regions (Wilson, 1968). Another key feature of the solar dynamo is that the Sun's S index is co-incident with the evolution of the geometry of the solar large-scale magnetic field, where a complex geometry occurs at S index activity maximum and a more simple dipole at S index activity minimum. Similarly, the Sun's coronal emission variations, as observed in X-rays, are also co-incident with the evolution of the Sun's large-scale magnetic field (Ayres, 2020). While Radick et al (2018) reported that the photometric variations of the Sun are co-incident with variations in its Ca II emission and the total solar irradiance.

Probing the internal structure of the Sun using the technique of helioseismology allows us to understand how the internal layers of the Sun are impacted by its magnetic cycle. The primary diagnostic is via globally resonant acoustic waves, or p-modes. The specific way in which the p-modes' parameters vary as a consequence of the changing levels of magnetic activity and magnetic field strength, in particular the p-mode frequencies, encodes information about the perturbation causing these changes. In the Sun, the frequencies of p-modes are correlated with the level of magnetic activity, whereas p-mode amplitudes are anti-correlated with the level of magnetic activity. While there are many more indicators to characterise the magnetic cycle of the Sun, these are the main

seismic diagnostics that can be searched for in the photometric time series of other stars and can yield insights into their magnetic cycles.

One of the challenges in observing and characterising stellar cycles is the long timespans that are needed to acquire definitive results. The longest data sets are those of the S index for the Sun and for other stars. The longest continuous sets of S index chromospheric activity measurements were obtained over 35 years at the Mount Wilson observatory[1] between 1968 and 2003 (Oláh et al, 2016), although most of the published datasets end in 1992 (Baliunas et al, 1995). Additional long-term observations are available from Lowell Observatory (1992–2020; Hall et al, 2007), Keck Observatory (1996–present; Baum et al, 2022), the TIGRE telescope (2013–present; González-Pérez et al, 2022), ESPaDOnS (Echelle SpectroPolarimetric Device for the Observation of STARS) (2006–present; Brown et al, 2022) and NARVAL (2007–present; Brown et al, 2022) in the northern hemisphere, and from ESO (2003–present; Lovis et al, 2011) and SMARTS (2007–2013; Metcalfe et al, 2009) in the southern hemisphere.

In terms of understanding stellar cycles, there has recently been significant progress in understanding how the geometry of a star's large-scale magnetic field varies over its magnetic cycle. This is due to the development of instrumentation to reconstruct, and dedicated telescopes to monitor, the large-scale magnetic fields of many stars. The main instruments used to observe the magnetic fields of stars are: (1) ESPaDOnS at the 3.6 m Canada France Hawaii telescope (Donati et al, 2006a), its twin (2) NARVAL at the 2.2 m Telescope Bernard Lyot (TBL; Aurière, 2003), and (3) HARPSpol (Snik et al, 2008; Piskunov et al, 2011). The advantage of ESPaDOnS and NARVAL is that they were specifically designed with the purpose of monitoring the magnetic fields of stars. For example, their long wavelength ranges cover wavelengths from the far-UV to the nIR and are capable of observing many thousands of lines that can be combined to increase the information content using techniques such as least-squares deconvolution (LSD; Donati et al, 1997; Kochukhov et al, 2010). Additionally, NARVAL is the only instrument at the TBL allowing detailed monitoring of the large-scale magnetic field of stars on short to long timescales. Even though these instrumental developments were commissioned more than 15 years ago, it is only now that we have a sufficiently long time span of data to understand the intrinsic variability of these stars on timescales of the order of the solar cycle.

Furthermore, the field of asteroseismology has rapidly advanced over the last 15 years with the advent of high-precision photometric missions such as CoRoT (Baglin et al, 2006; Auvergne et al, 2009), *Kepler* (Borucki et al, 2010; Koch et al, 2010) and currently TESS (Ricker et al, 2014). Data from these space missions secured with a high cadence has allowed us to put the Sun in the context of other stars and to monitor the impact of stellar magnetic fields on the stars' internal layers.

---

[1]For publicly available data, see https://dataverse.harvard.edu/dataverse/mwo_hk_project

In this review article, we focus on the observational diagnostics of stellar magnetic cycles of F, G and K dwarfs. We first address photospheric signatures of stellar cycles in Section 2, and then observations of cycles in the stellar chromosphere and corona in Section 3. Finally, we present cycles in terms of the internal layers of stars via astroseismology in Section 4. For completeness we also briefly summarise what is known about photometric cycles in Section 5. We then discuss the future prospects in Section 6.

2 Photospheric diagnostics

To reconstruct the large-scale magnetic field of stars other than the Sun, a commonly used method is Zeeman-Doppler Imaging (ZDI). This technique can measure the net magnetic field from a non-homogeneous distribution of circularly polarised light as a function of stellar rotation phase. As previously mentioned, the information content of thousands of spectral lines is combined using the technique of LSD. From a time series of LSD Stokes V observations covering not more than a few stellar rotation periods, the ZDI technique inverts the observed circularly polarised profiles into the strength, polarisation and distribution on the stellar surface in terms of the poloidal, toroidal and meridional magnetic fields (via spherical harmonics expansion Donati et al, 2006b; Folsom et al, 2018). An example of the time series of Stokes V LSD profiles and the corresponding ZDI map is shown in Figure 1 for the K dwarf ϵ Eri in October 2015. In this review we specifically focus on the results from ZDI as these are many times more numerous than the tentative results from Doppler imaging alone (for example Jeffers et al, 2007; Hackman et al, 2012, for the long-term brightness monitoring of AB Dor and II Peg).

A key diagnostic of the solar magnetic cycle is that the Sun's chromospheric cycle, or S index cycle, is in phase with its magnetic cycle meaning that its large-scale magnetic field switches polarity at activity maximum. The first star reported to show a solar-like magnetic cycle is the K dwarf 61 Cyg A (Boro Saikia et al, 2016, 2018). 61 Cyg A is an old K5 dwarf, with a very slow rotation rate and a S index cycle of 7.3 yr. It shows polarity switches of its large-scale magnetic field in phase with its S index activity maximum. Similar to the Sun, the large-scale field geometry is complex at activity maximum and dipolar at activity minimum. A summary of 61 Cyg A's magnetic cycle is shown in Figure 2. Another K dwarf with an extensive time span of magnetic maps is the young, rapidly rotating K dwarf, ϵ Eri which has been shown by Metcalfe et al (2013) to have two S index cycles of 2.95 yr and 12.7 yr. In contrast to 61 Cyg A and the Sun, ϵ Eri's large-scale magnetic field geometry shows a high degree of complexity at the minimum of the shorter $\sim$3-year S index cycle (Jeffers et al, 2022). It also does not show a change in polarity with every S index maximum (Jeffers et al, 2014; Petit et al, 2021). However, Jeffers et al (2022) recently showed that this could be explained if ϵ Eri's shorter $\sim$3-year cycle is a modulation of its longer $\sim$13-year cycle and that a polarity switch in its large-scale magnetic field should occur in phase with the longer
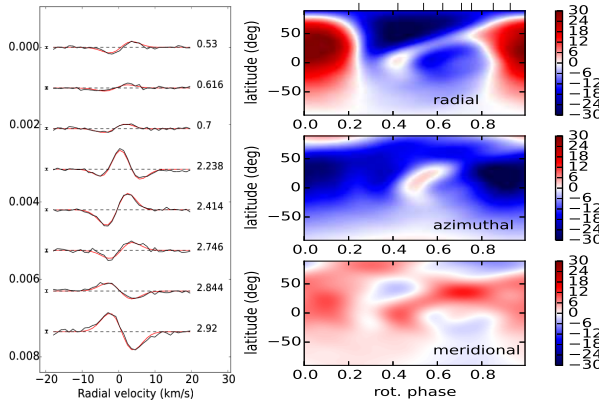
Fig. 1 Time-series of Stokes *V* profiles for ϵ Eri in October 2015 (*left panel*) with the reconstructed large-scale magnetic field geometry shown in the three panels on the right. For the Stokes *V* profiles, the black lines represent the data and red dotted lines correspond to synthetic profiles of our magnetic model and where successive profiles are shifted vertically for display clarity. Rotational phases of observations are indicated in the right part of the Stokes V LSD profiles and as vertical ticks at the top of the ZDI map. Data is from the NARVAL spectropolarimeter at the 2.2m Telescope Bernard Lyot secured as part of the BCool collaboration.

S index cycle (Figure 3). Indications of third cycle period has been recently been presented by Fuhrmeister et al (2023), though long-term observations of ϵ Eri's S-index are needed to confirm this additional cycle. Other young K dwarfs that have been monitored using multi-epoch ZDI observations include the very young stars AB Dor and LQ Hya (Donati et al, 2003), though no clear cyclic behaviour was identified. More recently, Lehtinen et al (2022) reported a polarity reversal in LQ Hya, that is coincident with a possible S-index activity minimum.

For G dwarfs that are approximately within 10 % of the Sun's mass, we have a long timespan of magnetic maps for HD 171488 (Marsden et al, 2006; Jeffers and Donati, 2008; Jeffers et al, 2011; Willamo et al, 2022), HN Peg (Boro Saikia et al, 2015), EK Dra (Waite et al, 2017), HD 190771 (Petit et al, 2009; Morgenthaler et al, 2011) and κ Cet (Boro Saikia et al, 2022). However, we are yet to observe a solar-like magnetic cycle where the large-scale magnetic field switches polarity at *S* index maximum on another early-G dwarf. This is .epsly because the G dwarfs that have been investigated with multi-epoch maps all are much younger than the Sun. For the three young stars EK Dra, HD 171488, and HN Peg the large-scale magnetic field evolves rapidly with little evidence of polarity switches in either the poloidal or toroidal fields. In particular, for HN Peg, the toroidal field appears and disappears again without any correlation with other activity indicators such as the *S* index. Polarity reversals have been observed in the G2 dwarf HD 190771 (Petit et al, 2009; Morgenthaler et al, 2011), however, they appear first in the azimuthal field (Petit et al, 2009) but are not observed in subsequent observations (Morgenthaler et al, 2011). Somewhat surprisingly, Morgenthaler
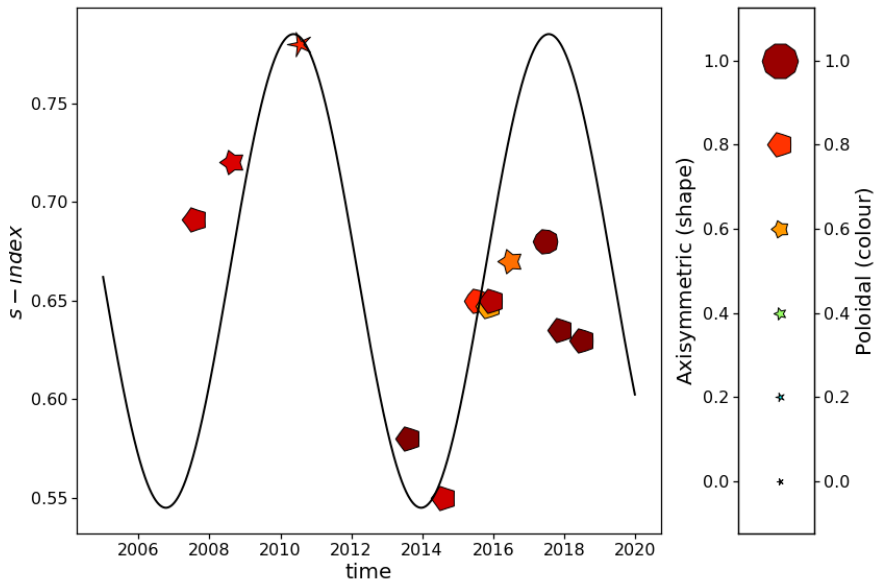
Fig. 2 Magnetic and S index cycle of 61 Cyg A as a function of time. The solid black line is a sinusoid with the period 61 Cyg A's S index cycle of 7.3 yr. Each of the coloured data points summarises the magnetic field geometry of one magnetic map. Data points are coloured depending on whether the large-scale field is poloidal (dark red) or toroidal (blue). The shape of the points indicates the dipolar fraction of the poloidal field, with decagon shaped symbols having a high degree of axisymmetry. Data is from the NARVAL spectropolarimeter at the 2.2m Telescope Bernard Lyot secured as part of the BCool collaboration.

et al (2011) report a polarity reversal in subsequent epochs of HD 190771's radial field. Recently, Boro Saikia et al (2022) reported a potential ~ 10-year magnetic cycle for the G5 V star κ Cet, a moderately active star with a rotation period of 9.2 d. κ Cet is also slightly older than EK Dra, HD 171488, and HN Peg with an age of ~ 750 Myrs. Similar to the K2 dwarf ϵ Eri, κ Cet shows evidence for having two chromospheric cycle periods of 3.1 yr and 6 yr, respectively. The longer period dominates for most of the data set analysed by Boro Saikia et al (2022). Interestingly, the shorter period is present at the beginning and end of the dataset, when the longer period disappears. Additional spectropolarimetric observations that densely sample κ Cet's S index cycle periods will help to resolve the intriguing case of the cyclic evolution of κ Cet's magnetic field.

The first star to show successive polarity switches in its large-scale magnetic field geometry is the planet-hosting late-F dwarf τ Boo (Catala et al, 2007; Donati et al, 2008; Fares et al, 2009, 2013). With a rotation period of only 3.3 d, τ Boo is more massive and has a much faster rotation than 61 Cyg A. The first results indicated a polarity switch occurring between June 2006 and June 2007, and then again between June 2007 and July 2008 from which Fares et al (2013) concluded that the magnetic cycle was 2 yr long. Subsequent
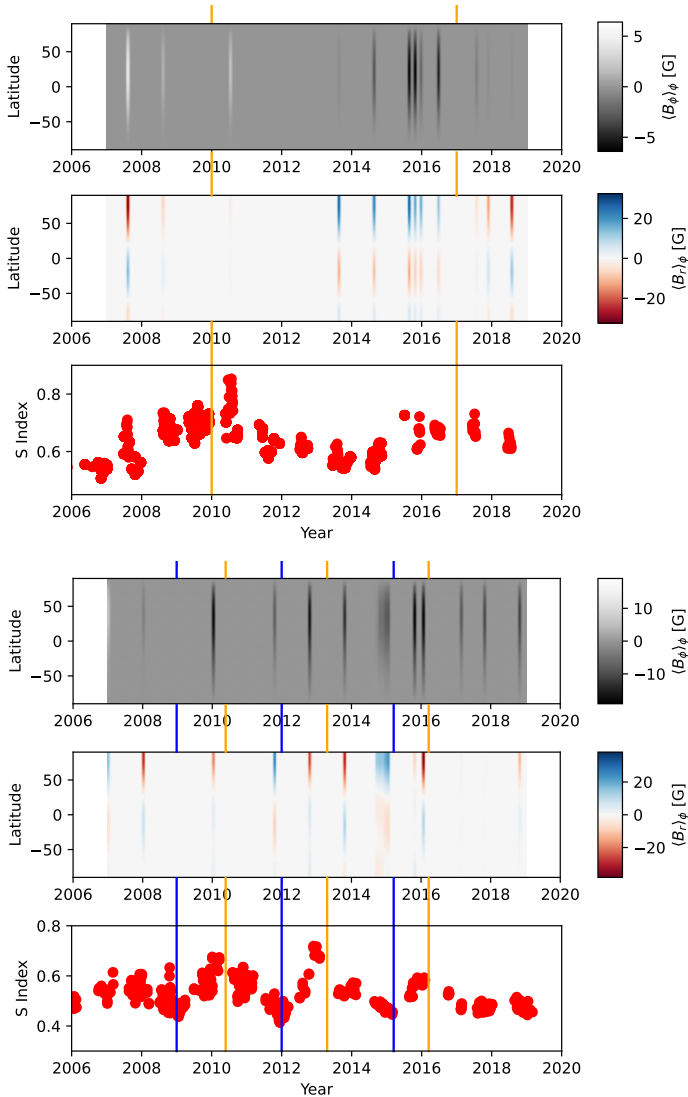
Fig. 3 Butterfly diagrams for 61 Cyg A (upper three panels) and ϵ Eri (lower three panels). The vertical blue and orange lines indicate the S index minima and maxima, respectively. Taken from Jeffers et al (2022).

work by Mengel et al (2016) presented additional epochs of τ Boo's large-scale magnetic field and reported that τ Boo has an S index cycle length of 120 d. More recently, the densely sampled observations by Jeffers et al (2018) over τ Boo's S index cycle showed that τ Boo's magnetic cycle is indeed co-incident with its S index cycle and with a polarity reversal at S index activity maximum. This makes τ Boo one of the shortest magnetic cycles with a length of 240 d. τ Boo's giant ~ 6 Jupiter-mass planet, which orbits at a distance of

~ 0.5 AU, has been considered to play a role in its internal dynamo processes via tidal locking, similar to the increased activity of stars in binary systems (see Fares et al, 2013). Recent work by Brown et al (2021) showed that similar levels of activity and polarity reversals also exist on HD 75332 a star with a similar mass and rotation rate as τ Boo. Using 12 epochs of magnetic maps, Brown et al (2021) showed that HD 75332 has a rapid 1.06 yr cycle and that a polarity reversal at activity maximum is consistent with polarity switches at activity maximum but a repeated polarity switch is required to confirm the cyclic nature of HD 75332's large-scale magnetic field. Another late-F star that shows evidence for a potential 3-year cycle is HD 78366 (Morgenthaler et al, 2011), where the radial field shows polarity reversals with a possible 3-year cycle. In contrast, the recently work of Marsden et al (2023) showed that the large-scale magnetic field of the old F7 dwarf Chi Dra is stable over a 5 year time span and does not show indications of cyclic behaviour. The results from these stars show the that rapid cyclic nature of the large-scale magnetic field of late F-stars could be an intrinsic feature of young to middle aged stars with a shallow convective zone, and that more stable patterns emerge as these stars evolve off the .eps-sequence.

While the observational data is not yet conclusive on several targets, the dense phase coverage of 61 Cyg A and ϵ Eri allow a more detailed comparison with the workings of the solar dynamo processes. In the case of the Sun, it is well established that the axisymmetric component of the toroidal field $\langle B_\phi \rangle$ (Cameron et al, 2018) is a proxy for flux emergence of the global dynamo and follows the Sun's S index. Recent work by Jeffers et al (2022) shows that this relation still holds at the resolution of the magnetic maps reconstructed with ZDI. Applying this to 61 Cyg A shows that the flux emergence also follows its S index, while for ϵ Eri it shows two cycles and the potential onset of an extended inactive period. The work of Jeffers et al (2022) concludes that surface magnetic fields play a crucial role in the dynamos of 61 Cyg A, ϵ Eri, and the Sun. For further discussion on the nature of the stellar dynamo from a modelling perspective we refer to Brun et al (2022); Käpylä et al (2023) and references therein.

3 Chromospheric and Coronal Diagnostics

Most of the available data on stellar activity cycles come from observations of the Ca II H (396.6 nm) and K (393.4 nm) spectral lines (hereafter Ca HK). Emission in the cores of these lines is a well-established proxy for magnetic heating in the chromosphere (Leighton, 1959). Time series observations with an appropriate cadence can probe both the long-term variations due to magnetic activity cycles (Wilson, 1978), as well as shorter-term modulation due to stellar rotation (Baliunas et al, 1983). Considering the 11-year sunspot cycle, decades of observations are typically required to measure activity cycles in other stars. A list of stars with currently known chromospheric cycles was recently compiled by Mittag et al (2023) (see their Table 1).
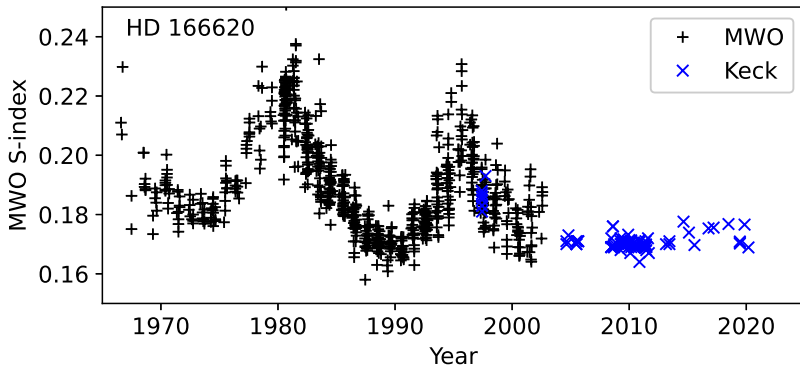
Fig. 4 Stellar activity measurements for the old K-type star HD 166620 spanning more than 50 years, including observations from Mount Wilson (black points) and Keck (blue points). This is the first unambiguous example of a Sun-like star entering a grand magnetic minimum (data from Oláh et al, 2016; Baum et al, 2022).

As an illustration of what we can learn from multi-decadal time series measurements, the combined datasets from Mount Wilson and Keck for the old K-type star HD 166620 are shown in Fig. 4. The Mount Wilson Observatory (MWO) S index is one of the standard proxies for magnetic activity, measuring emission in the Ca HK line cores relative to nearby pseudo-continuum bands. The first few decades of observations from Mount Wilson (black points in Fig. 4; Oláh et al, 2016) reveal a regular activity cycle with a period $P_{cyc} \sim 15$ yr. Higher-cadence observations beginning in the 1980s reveal rotational modulation with a mean period $P_{rot} \sim 42$ d, and significant differential rotation from seasonal variations (33.4–50.8 d), presumably as active regions migrate to different latitudes through the cycle (Donahue et al, 1996). In addition, the apparent correlation between cycle amplitude and the rise time for individual cycles has been used to examine whether the Waldmeier Effect in the Sun (Waldmeier, 1935) is also observed for other Sun-like stars (Garg et al, 2019; Willamo et al, 2020). Most notably, the continued observations from Keck (blue points in Fig. 4; Baum et al, 2022) reveal a smooth transition from cycling to constant activity, the first unambiguous example of a Sun-like star entering a grand magnetic minimum (Luhn et al, 2022). The high-cadence observations around 2010 coincide with the next expected maximum of the cycle, which is clearly absent. This may support the idea that stellar cycles can become intermittent as stars evolve through the critical activity level where weakened magnetic braking appears to begin (van Saders et al, 2016; Metcalfe et al, 2022).

Some stellar cycles have also been observed at X-ray wavelengths. The magnetic processes that heat the chromosphere also heat the corona, which has a much higher temperature ($\sim 10^6$ K, emitting at X-ray wavelengths) and fills a larger volume around the star. Variations around the mean X-ray luminosity are substantially larger than variations around the mean Ca HK emission, providing a higher contrast for the detection of magnetic cycles. For example,

the young solar-type star ι Hor shows fractional variations that are 3–4 times larger in X-ray luminosity than in Ca HK emission (Sanz-Forcada et al, 2013). The .eps challenge is that X-ray measurements must be obtained from above the Earth's atmosphere, so the cadence and duration of the observations are limited by competition for time on space telescopes and the longevity of X-ray missions (for instrument stability). These challenges have effectively forced studies of coronal activity cycles to rely on measurements from two long-lived X-ray missions, *XMM-Newton* and *Chandra*.

Most observations of coronal activity cycles have focused on stars with previously known activity cycles from Ca HK measurements. The earliest detections included the 7.3-year cycle in 61 Cyg A (Hempelmann et al, 2006; Robrade et al, 2012) and the 8.2-year cycle in HD 81809 (Favata et al, 2008; Orlando et al, 2017), both of which appeared to be approximately in phase with chromospheric variations. The discovery of substantially shorter chromospheric activity cycles in the young solar-type stars ι Hor (Metcalfe et al, 2010; Alvarado-Gómez et al, 2018) and ϵ Eri (Metcalfe et al, 2013) provided new opportunities to study coronal activity cycles on shorter timescales (Sanz-Forcada et al, 2013; Coffaro et al, 2020), and revealed some fascinating incongruities between chromospheric and coronal variations. Discoveries of previously unknown activity cycles are currently limited to the southern hemisphere stars α Cen A & B (Robrade et al, 2012), which were inaccessible to the Mount Wilson survey. Characterization of the coronal activity cycle in the 5.4 Gyr solar analog α Cen A is of particular interest as a constraint on the future of the 11-year solar cycle. The amplitude of its 19.2-year X-ray cycle is about one-third that of the Sun (Ayres, 2020), suggesting that the solar cycle may be growing longer and weaker (Metcalfe and van Saders, 2017).

With high-quality measurements of stellar activity cycles and rotation periods, it is natural to ask whether there is any discernible relationship between these observables, as expected from dynamo theory. This question was examined empirically by Erika Böhm-Vitense in 2007 (Böhm-Vitense, 2007). In the first figure of her thought-provoking paper, she simply plotted P_{cyc} against P_{rot} for stars in the Mount Wilson survey with the most reliable measurements (Saar and Brandenburg, 1999). An updated version of this plot is shown in Fig. 5, which reveals two distinct relationships between these two observables (solid lines). There is an upper sequence of long-period cycles (open points; but see Boro Saikia et al, 2018), and a lower sequence of short-period cycles (solid points), with the solar cycle falling curiously in between. Some of the stars exhibit cycles on both branches simultaneously, leading Böhm-Vitense to suggest that the two branches may represent two distinct dynamos operating in different regions of the star. Considering other properties of the stellar sample, she suggested that cycles on the long-period sequence may be driven in the near-surface shear layer, while the cycles on the short-period sequence may be driven at the base of the convection zone.

The first explanation for the peculiar position of the Sun in Fig. 5 came ten years later (Metcalfe and van Saders, 2017). The updated version of
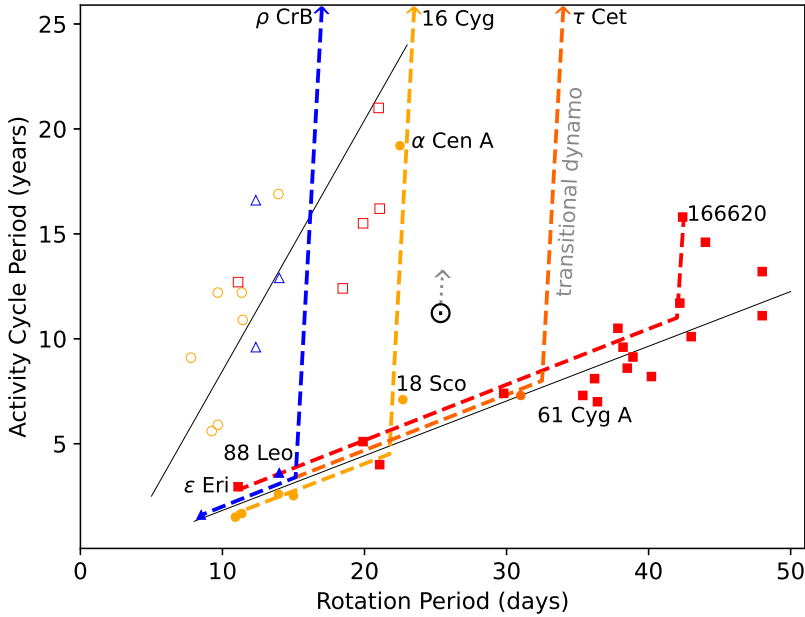
Fig. 5 Dependence of activity cycle period on rotation, showing two distinct sequences (solid lines). Points are coloured by effective temperature, indicating F-type (blue triangles), G-type (yellow and orange circles), and K-type stars (red squares). Schematic evolutionary tracks are shown as dashed lines, leading to stars with constant activity that appear to have shut down their global dynamos (arrows along top). Several notable stars are labelled.

the diagram coloured the points by spectral type, indicating hotter F-type (blue triangles), Sun-like G-type (yellow circles), and cooler K-type stars (red squares). The authors added several stars with measured rotation periods but no activity cycles (arrows along top) and included schematic evolutionary tracks (dashed lines) to indicate where rotation periods became nearly constant for different spectral types, apparently due to weakened magnetic braking (van Saders et al, 2016; Metcalfe et al, 2016). According to this interpretation, activity cycles initially grow longer along each sequence as the stellar rotation period slows over time. However, when stars reach a critical Rossby number (the rotation period normalised by the convective turnover time), the rotation period re.epss nearly constant while the cycle gradually grows longer and weaker before disappearing entirely. This explains why hotter stars are confined to the left side of the diagram, while progressively cooler stars (with longer convective turnover times) continue to evolve further towards the right side. It also suggests that the Sun may be in a transitional evolutionary phase and that the solar cycle may represent a special case of dynamo theory. These conclusions still hold even with the more recent results of Boro Saikia et al (2018) who confirm the lower sequence but question the presence of the upper sequence in Figure 5. Linking chromospheric cycles with the photospheric large-scale magnetic field (see Section 2), See et al (2016) reported

that there are indications that stars on the upper sequence have highly variable toroidal fields, while stars on the lower branch have stable poloidal fields. However, more stars with both chromospheric cycles and ZDI maps are needed to confirm this conclusion at short rotation periods.

An analysis contemporaneous to Metcalfe and van Saders (2017) by Axel Brandenburg and collaborators relied on a different representation of the measurements, more closely connected to dynamo theory (Brandenburg et al, 2017). Rather than plot P_{cyc} against P_{rot}, the authors plotted $\log(P_{\mathrm{rot}}/P_{\mathrm{cyc}})$ (related to the strength of the α effect) against $\log R'_{\mathrm{HK}}$ (related to the strength of the magnetic field; Brandenburg et al, 1998). The latter is the chromospheric emission from the MWO S index, corrected for a small photospheric contribution and normalised by the bolometric luminosity of the star, allowing meaningful comparisons of stars with different spectral types. In this representation, a constant slope in a plot of P_{cyc} against P_{rot} becomes a horizontal line. However, the stellar data actually show a slope, indicating a weaker α effect as the magnetic field grows weaker. The solar cycle and HD 166620 both appear closer to the short-period sequence in this analysis, but the old solar analog α Cen A (Judge et al, 2017) and the K-type subgiant 94 Aqr A (Metcalfe et al, 2020) remain significant outliers.

4 Seismology: insight into the internal structure

As the Sun and the stars pass through their activity cycles, the physical conditions in the regions in which the magnetic concentrations are located change over time. Solar and stellar oscillations propagating in these regions[2] are sensitive to these changes. The specific way in which the modes parameters consequently vary, in particular the mode frequencies, contains valuable information about the perturbation causing these changes, i.e., the varying magnetic field. Therefore, helio- and asteroseismology enable us to probe the interior and atmospheric magnetic structure of the Sun and the stars.

4.1 On the Sun

For the Sun, essentially all fundamental p-mode parameters are observed to vary over the solar activity cycle. The first parameter for which this was noticed, was the mode frequencies of low-degree modes (Woodard and Noyes, 1985). This detection has been confirmed and expanded over the following decades (Elsworth et al, 1990; Libbrecht and Woodard, 1990; Jiménez-Reyes et al, 1998; Howe et al, 1999; Chaplin et al, 2001; Salabert et al, 2015; Tripathy et al, 2015). Now, the cyclic shift of p-mode frequencies, which is tightly in phase with the activity cycle for p-modes below the acoustic cut-off frequency, has been confirmed for a wide range of frequencies and harmonic degrees (e.g., Broomhall, 2017). In the context of stellar cycles, it is important to note that – in contrast to p-mode frequencies, which are, as mentioned, correlated with the

---

[2]p-, g-, and mixed modes; consult, e.g., the review by Hekker and Christensen-Dalsgaard, 2017 for more details about the different types of modes.

level of magnetic activity – solar p-mode amplitudes are indeed anti-correlated with the level of magnetic activity (e.g., Komm et al, 2000a; Jiménez et al, 2002; Jiménez-Reyes et al, 2003; Jiménez-Reyes et al, 2004; Salabert et al, 2004; Burtseva et al, 2009; Broomhall et al, 2014, 2015; Kiefer et al, 2018). Also mode linewidths, which are related to mode damping (e.g., Jefferies et al, 1991; Chaplin et al, 2000), mode energies (e.g., Komm et al, 2000b; Kiefer et al, 2018), mode energy supply rates (Kiefer and Broomhall, 2021), and mode parameters of pseudomodes above the acoustic cut-off frequency (Kosak et al, 2022) vary through the solar cycle.

The sensitivity of p-modes to perturbations depends on their frequency as well as on their harmonic degree, increasing with both. This behaviour is largely due to the modes' inertia decreasing with both frequency and harmonic degree (see, e.g., Christensen-Dalsgaard and Berthomieu, 1991; Komm et al, 2000b; Chaplin et al, 2001 and for a more in-depth discussion and more references consult the review article by Basu, 2016). In contrast to the Sun, for stars, only the lowest harmonic degrees $l = 0, 1, 2$ of p-modes can be measured, as the stellar photometric time series integrate the light of the full stellar disk. For these low harmonic degrees, the mode inertia does not differ very much between them. Any detected variation in the frequency shifts between modes of different harmonic degrees can be utilised to infer the latitudinal distribution of magnetic activity (Moreno-Insertis and Solanki, 2000; Chaplin et al, 2007; Thomas et al, 2021). Further, mode frequency shifts, which increase with mode frequency, can be attributed to magnetic perturbations that are located very close to the surface, as higher frequency modes are concentrated to shallower layers (e.g., Basu et al, 2012; Salabert et al, 2015; Broomhall, 2017).

4.2 Asteroseismic detections of stellar magnetic activity (cycles)

It is the tight anti-correlation between the activity-related variations in p-mode frequencies and p-mode amplitudes that is a tell-tale seismic signature for varying levels of stellar magnetic activity in solar-like oscillators. This signature can be searched for in high-quality photometric time series that were delivered to us by the satellite missions CoRoT (Baglin et al, 2006; Auvergne et al, 2009), *Kepler* (Borucki et al, 2010; Koch et al, 2010), and currently TESS (Ricker et al, 2014). If a stellar activity cycle is not fully covered by the data, the measured p-mode parameter variation generally presents a lower boundary on each star's cycle variability. In contrast, short activity cycles with periods of weeks or a few months may be missed by seismology: The length of the time series segments, that are needed to achieve the required frequency resolution to detect p-mode frequency variation on the order of a few tenths of µHz, is typically around 100 d.

Chaplin et al (2007) and Karoff et al (2009) investigated which types of stars ought to be observed and what characteristics the data must have if stellar activity cycles are to be detected and characterised seismically. Karoff et al (2009) also include ground-based observations of chromospheric activity
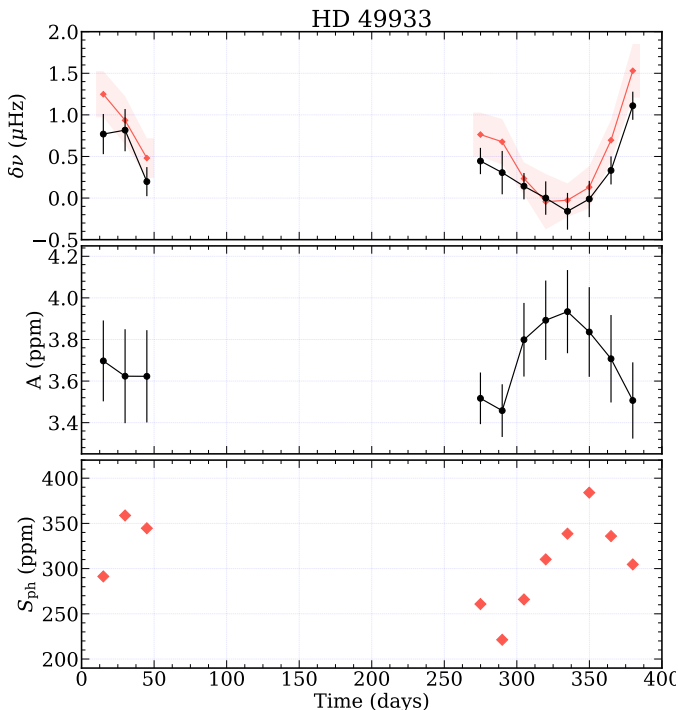
Fig. 6 First detection of the asteroseismic fingerprint of stellar magnetic activity on the CoRoT target HD 49933 by García et al (2010). *Top panel:* p-mode frequency shifts $\delta\nu$ as measured via the cross-correlation (red diamonds) and the peak bagging approaches (black circles). *Middle panel:* Mean p-mode amplitudes A obtained from peak-bagging. *Bottom panel:* Starspot proxy S_{ph} measured from the standard deviation of segments of the time series. This figure is a reproduction of Fig. 1 from García et al (2010) based on their original data.

in their considerations. They found that, most importantly, the photometric time series as well as the ground-based observations need to be sufficiently long – at least several consecutive months – and the amplitude of the acoustic modes of the observed stars should be large enough so they protrude the noise (also see Chaplin et al, 2011a,b; Campante et al, 2016b; Ball et al, 2018; Schofield et al, 2019). An in-depth review of the inferences asteroseismology can yield on stellar activity and activity cycles was also provided by Chaplin and Basu (2014).

The first detection of activity-related p-mode parameter variations was achieved by García et al (2010) for the F-type dwarf star HD 49933 with CoRoT data. Their main results are reproduced in Fig. 6. The p-mode frequency shifts are depicted in the top panel as measured with two different methods (p-mode peak bagging in black circles, cross-correlation of the periodogram as red diamonds). The middle panel shows the p-mode amplitudes and the bottom panel shows a "starspot proxy", which is the standard deviation of segments of the photometric time series. Indeed, the temporal changes

in mode frequencies and mode amplitudes are clearly anti-correlated, pointing towards magnetic activity being the cause of these variations. As for the Sun, also HD 49933's frequency shifts increase with mode frequency, as Salabert et al (2011) found. This indicates that the magnetic perturbation is located close to the star's surface.

Using *Kepler* data of 24 solar-like stars with a length of at least 960 d, Kiefer et al (2017a) found significant frequency shifts ($> 1\sigma$) on 23 stars, showing that p-mode frequency variations are a very widespread phenomenon in solar-like oscillators. For six of these stars, the variation of p-mode amplitudes is also strongly anti-correlated (Spearman rank correlation coefficient $\rho < -0.5$) with the observed shifts of their frequencies. Shortly before, Salabert et al (2016) already found that the young solar analog KIC 10644253 exhibits activity-related p-mode frequency shifts. Based on spectroscopic observations with the HERMES spectrograph, they also demonstrated that this star is more active than the Sun.

The search for seismically detected magnetic activity (cycles) was then further expanded by Santos et al (2018) to 87 solar-like stars, including the 66 stars from the *Kepler* LEGACY sample (Lund et al, 2017; Aguirre et al, 2017) and 25 solar-like KOI targets (Campante et al, 2016a). They used a Bayesian peak-bagging technique on 90-day segments of the photometric time series to measure the shifts of individual p-mode peaks in the periodogram enabling them to analyse different harmonic degrees and even azimuthal orders for variations in their parameters. The results of two of the stars in their sample are shown in Fig. 7. The two top panels show the frequency shifts of KIC 8006161 in the top panel and the logarithm of the mode amplitudes obtained from Bayesian peak-bagging in the bottom panel. The results of KIC 5184732, a more typical example from the analysed sample regarding the magnitude of the uncertainties and amplitude of the variations, are shown in the two bottom panels. In both cases, there are significant and systematic variations in p-mode frequencies as well as in mode amplitudes. What is more, these variations are anti-correlated (as measured by Pearson's correlation coefficient r) with one another, at a level of $r = -0.791$ for KIC 8006161 and $r = -0.482$ for KIC 5184732, signifying magnetic activity is likely causing these variations.

Indeed, KIC 8006161 is probably one of the most intensively studied stars from the *Kepler* seismic sample due to its very significant asteroseismic signature of magnetic activity. This star is very similar to the Sun in mass and radius but has a metallicity which is about twice the solar value. Karoff et al (2018) analysed spectroscopic observations from the MWO program of KIC 8006161 spanning almost 20 years. This uncovered an activity cycle with a period of approximately 7.4 yr. Through its cycle, KIC 8006161 has a significantly higher variability in its photospheric activity proxy S_{ph} and its S index than the Sun. Karoff et al (2018) postulated the star's higher metallicity brings about a deeper convective envelope compared to the Sun. This, in turn, then causes stronger levels of activity. The authors also show that the *Kepler* era of observations is coincident with the rising period of magnetic activity for
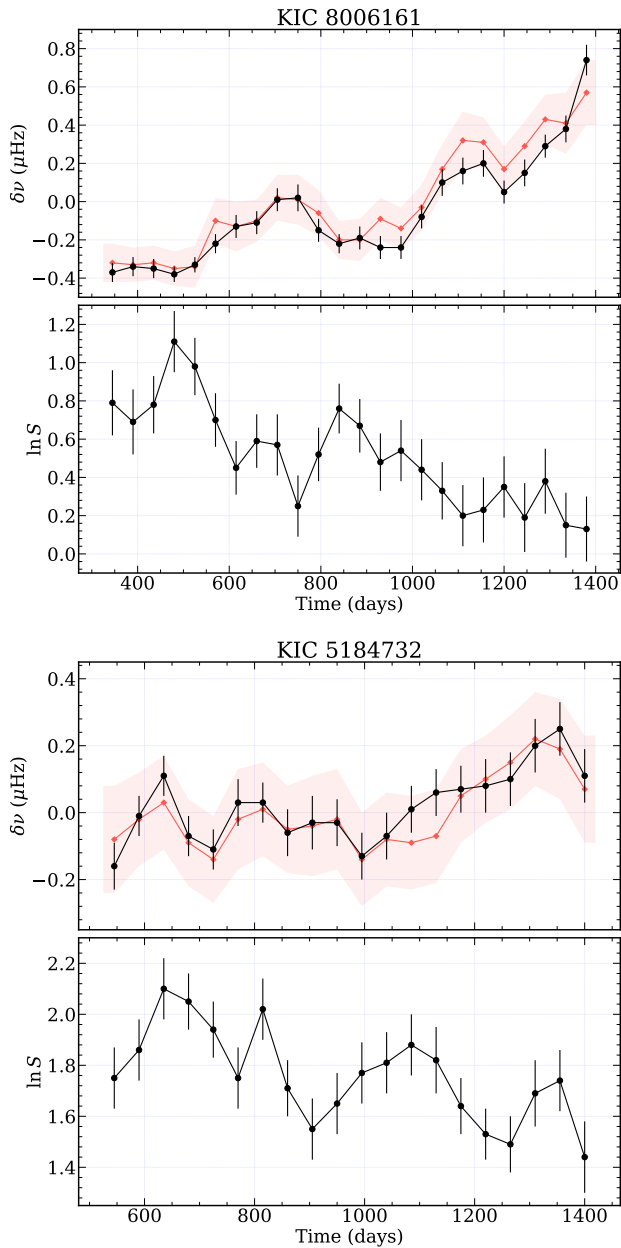
Fig. 7 Asteroseismic detection of magnetic activity in the two solar-like *Kepler* targets KIC 8006161 and KIC 5184732. *Top panel for each star:* Mean frequency shifts $\delta\nu$ averaged over all available p-modes as a function of time as measured by Bayesian peak-bagging (black circles) and as measured with the cross-correlation technique (red diamonds). *Bottom panel for each star:* Logarithmic mode height $\ln S$ of the p-modes obtained from peak-bagging. This figure was produced based on the original data from Santos et al (2018).

KIC 8006161. This lends further support to activity being the root cause of the measured p-mode parameter variations. Due to the exquisite quality of the *Kepler* data and the very good signal-to-noise ratio of the p-mode peaks in the periodogram of KIC 8006161, Thomas et al (2019) were able to constrain its latitudinal distribution of active regions by remapping the observed frequency shift to the stellar surface. Their technique utilises that modes of different harmonic degrees differ in their sensitivity to the latitudinal distribution of the perturbation causing the frequencies to shift (Moreno-Insertis and Solanki, 2000; Chaplin et al, 2007). The authors determined that KIC 8006161's active regions are distributed over a wider band of latitudes and are located at higher latitudes than for the Sun. Based on a model of the rotation profile and the rotational modulation of this star's *Kepler* time series, Bazot et al (2018) constructed a butterfly diagram. In their result, KIC 8006161 exhibits spots at both low latitudes close to the equator and, during some periods, at higher latitudes around $40°$.

Following the advice of Karoff et al (2009), Karoff et al (2013) observed 20 Sun-like stars in the *Kepler* field-of-view with the Nordic Optical Telescope (NOT) and determined their excess flux (surface flux arising from magnetic sources) and S index. From the stars' *Kepler* light curves, they measured the rotation periods and the small frequency separation, which they used to guide the target selection for their program. The stellar fundamental parameters were obtained using an asteroseismic modelling code. Karoff et al (2013) found that the ten stars from their sample which have independent measurements of asteroseismic ages, rotation periods and excess flux follow the Skumanich relations (Skumanich, 1972) reasonably well. Further and interestingly, they obtained a much stronger relation between asteroseismically determined stellar properties and the stars' excess flux than with their S index. Karoff et al (2019) subsequently analysed the full four years of NOT spectroscopic data (covering the complete *Kepler* main mission 2009–2013) as well as the photometric variability and p-mode frequency shifts of these 20 stars. They detected a strong correlation between the different activity proxies only for a few targets, most notably for KIC 8006161. The authors attribute this to the rather sparse sampling of spectroscopic data and the relative shortness of the photometric time series compared to the expected length of activity cycles. While Karoff et al (2013, 2019) did not specifically look for or find new asteroseismic detections of stellar activity cycles, they showed how asteroseismology – in conjunction with ground-based spectroscopic data – can usefully inform research on stellar activity, activity cycles, and the investigation of age–rotation–activity relations of solar-like oscillators.

4.3 p-mode frequency variations and their relations to fundamental stellar parameters

Santos et al (2019) investigated whether the amplitudes of the mean frequency shifts $\delta\nu_{\max}$ given by Santos et al (2018) depend on fundamental stellar parameters. Parts of their results are reproduced in Fig. 8. They found that there
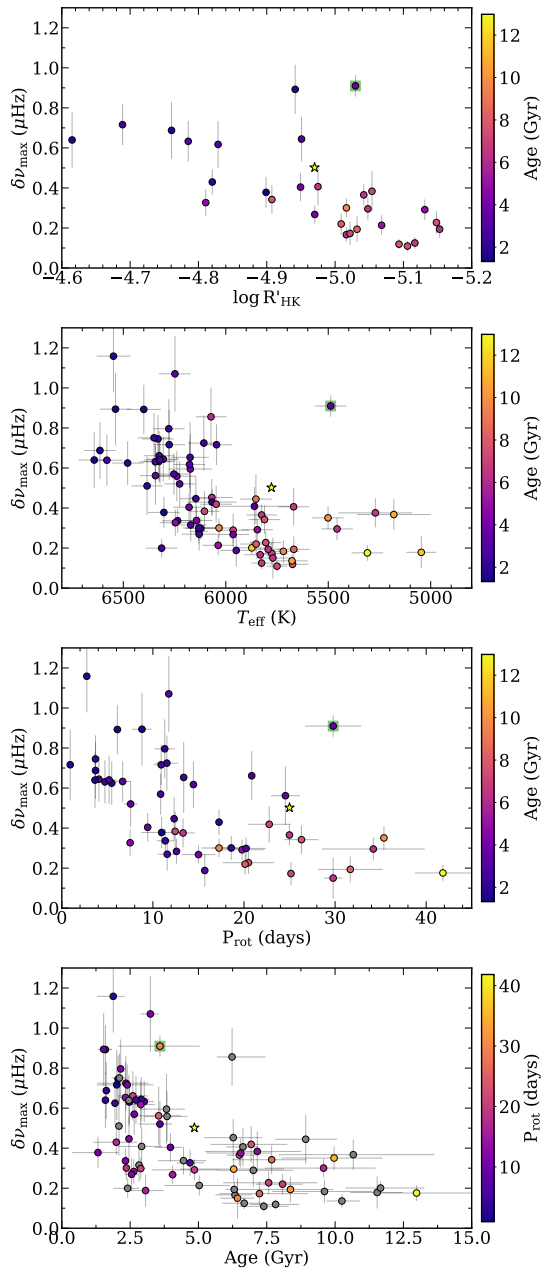
Fig. 8 Frequency shift amplitudes $\delta\nu_{\mathrm{max}}$ of 75 *Kepler* stars as a function of different stellar parameters: chromospheric activity level $\log R'_{\mathrm{HK}}$ (*first panel*), effective Temperature T_{eff} (*second panel*), rotation period P_{rot} (*third panel*), and age (*fourth panel*). The colours of the data points indicate the stars' ages, except for the bottom panel, where they encode rotation period. KIC 8006161 and the Sun are highlighted by the light green square and yellow star, respectively. This figure was produced based on the original data from Santos et al (2019).

is a strong correlation between the amplitude of the frequency shifts and the chromospheric activity level as measured by the $\log R'_{\rm HK}$ index with a Spearman rank correlation coefficient of $\rho = 0.69$ (first panel of Fig. 8), supporting magnetic activity as the root cause of the measured shifts. As a function of effective temperature $T_{\rm eff}$, $\delta\nu_{\rm max}$ increases. This is not necessarily caused by an increase in the strength of magnetic activity with $T_{\rm eff}$ but is most likely caused by the increased mode sensitivity. Both, Metcalfe et al (2007) (based on work done by Dziembowski and Goode 2004) and Kiefer et al (2019) used a simple scaling model for the frequency shifts, assuming that they are proportional to the depth of the perturbation causing them (magnetic activity), the p-modes' inertia, and the strength of the activity. The relations which they deducted reproduce the course of $\delta\nu_{\rm max}$ seen in the second panel of Fig. 8 reasonably well. As can be seen in the bottom two panels of Fig. 8, $\delta\nu_{\rm max}$ decreases as rotation period $P_{\rm rot}$ increases and as stars age. This is expected, as stellar activity as well as stellar rotation is known to decay as stars get older (see, e.g, Skumanich, 1972; Vaughan et al, 1981; Noyes et al, 1984).

As the frequencies of p-modes of unequal harmonic degrees are variably susceptible to perturbations, also the frequency separation ratios are subject to magnetic activity-induced variations. Thomas et al (2021) investigated the bias caused by activity-perturbed separation ratios on the estimates for fundamental stellar parameters through stellar modelling pipelines. They determined that, for solar-like stars with activity levels similar to the Sun, the bias is typically less than $0.5\,\%$ for mass, but can affect estimates of stellar age by up to $5\,\%$ and core hydrogen content by up to $3\,\%$. Stronger than solar activity levels consequently increases these errors, as will extreme inclination angles, because the separation ratios are more strongly perturbed in such a scenario. Similarly, Pérez Hernández et al (2019) found that the activity-induced variation of the small frequency separation, i.e., the frequency separation of consecutive quadrupole and radial modes, can cause misdetermination of stellar age by up to $10\,\%$ and of mass and radius by a few percent. However, they also find this variation can often be masked by filtering out surface effects from the mode frequencies.

As all p-mode frequencies shift with activity, the frequency of maximum oscillation amplitude $\nu_{\rm max}$ follows suit. In their study of the temporal variation of the solar $\nu_{\rm max,\odot}$, Howe et al (2020) indeed found that it is positively correlated with the level of solar magnetic activity and that it changes by as much as $\simeq 25\,\mu{\rm Hz}$ between solar activity minimum and maximum. As $\nu_{\rm max,\odot}$ is used in asteroseismic scaling relations, this shift can incur an error of up to $0.8\,\%$ and $2.4\,\%$ in the estimates of stellar radius and mass, respectively.

4.4 Theoretical groundwork and recent detection of interior magnetic fields

Before the advent of asteroseismology, there have been a number of theoretical developments in helioseismology dealing with the effects of internal magnetic field on the oscillation frequencies of the Sun. Gough and Thompson (1990)

used perturbation theory for the calculation of the frequency shifts of p-mode multiplets caused by buried magnetic field distributions. Their framework was later expanded by Antia et al (2000) and Baldner et al (2009) for the investigation of long time series of solar p-mode splitting coefficients to yield information on magnetic field concentrations in the solar convective envelope. Utilizing another flavour of perturbation theory, Lavely and Ritzwoller (1992) applied a quasi-degenerate perturbational ansatz to deduct a theoretical framework for the calculation of the effect of convection and elastic-gravitational asphericities on p-modes. This was later expanded to include the effect of sub-surface magnetic field concentrations by Kiefer et al (2017b) and Kiefer and Roth (2018). Similarly, Hanasoge (2017) and Das et al (2020) deduct expressions describing the effect of Lorentz stresses on the coupling of solar oscillations.

These theories can also be applied to other solar-like stars – albeit in a more limited fashion due to the spatially unresolved nature of stellar observations – and as long as the physical boundary conditions with which the theory has been developed are respected. Using stellar structural and oscillation models, these theories can emulate the fingerprint of cyclic variations of magnetic field strengths and configurations in the stellar oscillation frequencies.

Over the last few years, several groups have pushed forward the theoretical description of and, consequently, the search for signatures of the interplay of internal magnetic fields and stellar oscillation. These recent studies largely focused on the impact of internal magnetic field on gravity or mixed-mode frequencies: Van Beeck et al (2020) calculated frequency shifts in gravity-mode pulsators at the end of the main-sequence and find that axisymmetric poloidal-toroidal fields stronger than 10^6 G should be detectable from *Kepler* time series, if these fields exist. Prat et al (2020) predicted that oblique dipolar magnetic fields leave detectable signatures in the gravity mode periods by applying their theory to a magnetic, rapidly rotating and slowly pulsating B-type star. Several recent studies investigated the effects of magnetic field distributions of various configurations on mixed modes in red giants (Gomes and Lopes, 2020; Mathis et al, 2021; Bugnet et al, 2021; Bugnet, 2022; Loi, 2020, 2021) and γ Dor and SPB stars (Dhouib et al, 2022).

In the wake of this flurry of recent theoretical studies, the existing data sets were reanalysed, looking for the predicted signatures of magnetic fields in the oscillation frequencies. Using *Kepler* data, Li et al (2022) detected strong magnetic fields in the cores of giant stars. For three hydrogen-shell burning giants, they measured asymmetries in the (mixed-mode) oscillation multiplets, which translate into magnetic field strengths of 102 ± 12 kG for KIC 8684542, 98 ± 24 kG for KIC 7518143, and an upper limit of 41 kG for KIC 11515377. Recently, building on the technique presented by Li et al (2022), Deheuvels et al (2023) seismically detected strong magnetic fields in the cores of 11 red giants, again using *Kepler* data. These observational studies are thus far restricted to static magnetic fields, i.e., one data point in time without the detection of cyclic activity. However, they clearly show that – given long enough data sets

– variable or cyclic magnetic field concentrations can be detected in the stellar interiors using asteroseismology.

5 Activity cycles in photometric time series

Stellar activity cycles can also reveal themselves as periodic variations of stellar brightness (see, e.g., Baliunas and Vaughan, 1985), just as the Sun's total irradiance varies slightly over the solar 11-year cycle (see, e.g., Yeo et al, 2014). Using long-term observations of the V-band magnitude, Oláh et al (2000) were able to detect starspot cycles for nine out of the ten stars in their sample of rapidly-rotating active stars (a mix of K and G stars, including mainsequence stars, subgiants, and giants) with data lengths between 11–30 yr. They found that the detected photometric cycle lengths agree with those from other activity proxies found by other authors. Later, Oláh and Strassmeier (2002) expanded this study to a baseline of up to 34 yr and could confirm that cycle period depends on rotation rate.

Evaluating four-year-long photometric light curves from the *Kepler* satellite, Vida et al (2014) presented evidence for activity cycles for nine of the 39 fast-rotating late-type active stars they investigated. The cycles they detected have periods between 300–900 d. Vida et al (2014) used the temporal variation of the stars' rotation period as an indicator for the cycles. Using multi-decadal ground-based photometric data, this approach enabled Oláh et al (2009) to detect activity cycles in at least 15 of the 20 active stars in their sample. Ferreira Lopes et al (2015) found evidence for stellar cycles in the photometric data of 16 CoRoT FGK main sequence stars. These cycles follow the earlier-found relations between the length of the activity cycles and the stars' rotation periods. Further, in addition to the active and inactive branches in the $P_{\rm rot}$-$P_{\rm cyc}$ diagram proposed by Böhm-Vitense (2007), they detected hints for a possible third branch for short cycles.

With between 16 and 27 years of Johnson B- and V-band photometry from the Automatic Photoelectric Telescope (APT) at the Fairborn Observatory in Arizona, Lehtinen et al (2016) investigated differential photometry from 21 young solar-type stars. They detected photometric activity cycles in nearly all of the targeted stars. Populating the $\log \frac{P_{\rm rot}}{P_{\rm cyc}}$-$\log {\rm Ro}^{-1}$ diagram as defined in Saar and Brandenburg (1999), they could confirm the active and transitional activity branches and found that the transitional branch merges with the active branch at $\approx \log {\rm Ro}^{-1} = 1.42$, similar to what was reported by Boro Saikia et al (2018). Using time-frequency analysis, Soon et al (2019) investigated the temporal variations in chromospheric (S index) and photometric (differential photometry in b- and y-bands) of decades-long time series. They found that activity of the young rapidly rotating solar analogue HD 30495 (also see Egeland et al, 2015 for a detailed analysis of this star), as measured with these two time series are strongly correlated. They detected activity cycles in the 'midterm' regime with a length of 1.6–1.8 yr and confirmed a longer cycle with a period of $\approx$11 yr.

Mathur et al (2014) defined two simple measures of photometric activity levels: S_{ph} is the standard deviation of the complete time series and thus reflects an average level of activity. With $\langle S_{\mathrm{ph,k}} \rangle$, the standard deviation of the time series is calculated over $k \times P_{\mathrm{rot}}$. They identified $k = 5$ to be a good value, which smoothes out variations by rotation sufficiently, while still leaving longer-cycle variations intact. These measures are both often-used in the investigation of space-photometry for activity (e.g., Salabert et al, 2016; Karoff et al, 2018; Mathur et al, 2019). Distefano and Lanzafame (2020) show that stellar activity cycles can also be detected in Gaia photometric time series. For two Gaia targets, they present evidence of cyclic photometric variations with cycle lengths of $P_{\mathrm{cyc}} \approx 500\,\mathrm{d}$ for Gaia DR2 2925085041699059712 and of $P_{\mathrm{cyc}} = 3262 \pm 125\,\mathrm{d}$ for Gaia DR2 3246069594362282752.

The as-of-yet largest number of detections of photometric activity cycles was achieved by Reinhold et al (2017). They analysed the long-cadence *Kepler* times series of 23601 stars. As a signature for photometric variability, and hence for varying levels of magnetic activity, they measured the variability amplitude within each *Kepler* quarter ($\approx 90\,\mathrm{d}$) as the difference between the 5th and 95th percentiles of the light curve. They found amplitude periodicities in 3203 stars with cycle periods between $0.5\,\mathrm{yr} < P_{\mathrm{cyc}} < 6\,\mathrm{yr}$ with stellar rotation periods between $1\,\mathrm{d} < P_{\mathrm{rot}} < 40\,\mathrm{d}$. Interestingly, they confirmed, by folding all of the detected cycles, that the average shape of the stellar activity cycle deviates from a perfect sine, in particular during epochs of maximal and minimal activity. No dependence on stellar effective temperature was detected for this behaviour. The detections are scattered around the inactive (I) branch in the P_{cyc}-P_{rot} diagram (cf., Saar and Brandenburg, 1999; Böhm-Vitense, 2007) with only few detections on the active (A) and short-cycle (S) branches. The authors propose that this may be due to the strong sensitivity of *Kepler* photometry to spots and plages in the photosphere, while other studies, which have detected the A and S branches, used chromospheric activity indicators.

The *Kepler* satellite recorded 53 full-frame images (FFIs) over the course of its main mission. Montet et al (2017) used these FFIs to investigate a set of 3845 stars (F7 to G4) for signs of long-term photometric variability. For approximately $10\,\%$ of their targets, 463 stars, Montet et al (2017) observed significant ($> 3\sigma$) brightness variations over the *Kepler* mission. By eye, they detected apparently complete cycles for 28 stars. Further, they identified the range of rotation periods during which the transition from spot- to facula-dominated variability occurs, to lie between $15\,\mathrm{d} < P_{\mathrm{rot}} < 25\,\mathrm{d}$. Also, the detected cycles appear to follow the A and I branches in the P_{cyc}-P_{rot} diagram.

Basri and Shah (2020) generated a large number of light curves based on starspot models in order to understand degeneracies in these light curves affected by starspots with varying lifetimes and distributions as well as underlying global and differential rotation. In light of their study, caution must be taken when interpreting short-term cyclic behavior in photometric light curves as the signature of possible activity cycles: such cycle-like behaviour can be

the result of random fluctuations. The authors urge to reconsider past identifications of short-term activity cycles, such as those reported by, e.g., Vida et al (2014); Reinhold et al (2017), and encourage to scrutinize detections of cycles, which are solely based on variations in photometric time series, more carefully in future analyses.

6 Summary and future prospects

In this review, we have presented the latest results on understanding stellar magnetic cycles on stars other than the Sun using the same diagnostics as are commonly used to quantify the solar cycle. Over the 11-year solar cycle, changes in the internal structure of the Sun are observed in acoustic oscillations (p-modes), while on the Sun's surface or the photosphere, the 11-year evolution of activity is evident from the patterns of spot emergence with ever decreasing latitudes as the cycle progresses. At solar activity maximum there is the largest number of starspots, and the Sun's large-scale magnetic field geometry is complex. In the Sun's outer atmospheric layers, for example in the chromosphere and corona, variations in its S index and X-rays are co-incident with activity maximum.

While the spatial resolution and time cadence of stellar observations is several orders of magnitude lower than observations of the Sun, we can use the same multi-wavelength diagnostics to quantify stellar magnetic activity. These are namely Doppler and Zeeman-Doppler imaging to map photospheric features such as dark, bright and magnetic spots, the S index and X-ray observations as diagnostics of the stellar chromosphere and corona. In particular, we now have the capability to observe stars over time bases that are comparable to the length of the solar cycle.

Observations of solar-like cycles have been observed on other stars, where the large-scale magnetic field geometry, including polarity reversals, is co-incident with S index activity minimum and X-ray variations. For stars that have the same mass but are very much younger than the Sun, having just arrived on the zero-age main-sequence, they show more extreme levels of activity without any cyclic behaviour. As the stars age, the variations in magnetic activity start to become more cyclic like what we observe on the Sun, and could even have superimposed cycles. Long timespans of S-index monitoring show that cycles on solar-mass stars older than the Sun start to become lower in amplitude before eventually disappearing as the stars evolve off the main-sequence. This is consistent with the recent results of Brown et al (2022) where chromospheric activity and variability is shown to decrease together with the toroidal field strength as stars evolve through their main-sequence lifetimes. This is also in agreement with the results of Radick et al (2018) where they report that young stars have an inverse correlation between photometric brightness and Ca II emission, while more evolved main-sequence stars tend to show a direct correlation. Looking to the future, more long-term monitoring of the large-scale magnetic field geometry and S-index of stars that are

both younger and older than the Sun, but with a similar mass, will provide us with an important insight into exactly when activity patterns start to become more regular and when they disappear. Similarly, the systematic observations of young, middle-aged and old stars with masses lower than the Sun will also provide us with an insight into how crucial stellar mass is for the stars' internal dynamo generation mechanisms.

Asteroseismology of stellar activity and activity cycles will take the next step forward with ESA's exoplanet-finding PLATO mission (Rauer et al, 2014). PLATO will observe two Long-duration Observation Phase (LOP) fields for two years each. The exact position of these fields will be fixed two years before the targeted 2026 launch (Nascimbeni et al, 2022). At least 15000 dwarf and subgiant stars in the spectral type range F5–K7 with magnitudes $V \leq 11$ will be observed in the stellar sample with the highest priority at a time cadence of $25\,s$ (sample P1, see Goupil, 2017; Montalto et al, 2021). Another at least 1000 stars (dwarfs and subgiants, F5–K7) with $V \leq 8.5$ will be observed during a LOP (sample P2). This sample's higher brightness increases the feasibility of ground-based follow-up observations. Additional ≥ 245000 stars (sample P5, dwarfs and subgiants, F5–K7) with $V \leq 13$ will be observed with a lower signal-to-noise ratio than those in P1. The duration of two consecutive years is not optimal for seismic studies of complete activity cycles, as shown in Sect. 4. PLATO will still most likely expand the number of seismic targets with detected signatures of magnetic activity considerably and thus help improve our understanding of stellar dynamos, cycles, and how these depend on fundamental stellar parameters. If the PLATO mission should be extended and the same LOP be revisited, this would substantially increase the potential of the seismic detection and probing of activity cycles.

References

Aguirre VS, Lund MN, Antia HM, et al (2017) Standing on the shoulders of Dwarfs: the Kepler asteroseismic LEGACY sample II - radii, masses, and ages. The Astrophysical Journal 835(2):173. https://doi.org/10.3847/1538-4357/835/2/173, https://arxiv.org/abs/1611.08776

Alvarado-Gómez JD, Hussain GAJ, Drake JJ, et al (2018) Far beyond the Sun - I. The beating magnetic heart in Horologium. Mon. Not. Roy. Astron. Soc.473(4):4326–4338. https://doi.org/10.1093/mnras/stx2642, https://arxiv.org/abs/1710.02438 [astro-ph.SR]

Antia HM, Chitre SM, Thompson MJ (2000) The Sun's acoustic asphericity and magnetic fields in the solar convection zone. Astronomy & Astrophysics 360:335–344

Aurière M (2003) Stellar Polarimetry with NARVAL. In: Arnaud J, Meunier N (eds) EAS Publications Series, p 105

Auvergne M, Bodin P, Boisnard L, et al (2009) The CoRoT satellite in flight: description and performance. Astronomy & Astrophysics 506(1):411–424. https://doi.org/10.1051/0004-6361/200810860

Ayres TR (2020) In the Trenches of the Solar-Stellar Connection. I. Ultraviolet and X-Ray Flux-Flux Correlations across the Activity Cycles of the Sun and Alpha Centauri AB. Astrophys. J. Supplement250(1):16. https://doi.org/10.3847/1538-4365/aba3c6

Baglin A, Auvergne M, Barge P, et al (2006) Scientific Objectives for a Minisat: CoRoT. In: Fridlund M, Baglin A, Lochard J, et al (eds) The CoRoT Mission Pre-Launch Status - Stellar Seismology and Planet Finding, Noordwijk, The Netherlands, p 33

Baldner CS, Antia HM, Basu S, et al (2009) Solar Magnetic Field Signatures in Helioseismic Splitting Coefficients. The Astrophysical Journal 705(2):1704–1713. https://doi.org/10.1088/0004-637X/705/2/1704

Baliunas SL, Vaughan AH (1985) Stellar activity cycles. Annual Review of Astron. and Astrophys.23:379–412. https://doi.org/10.1146/annurev.aa.23.090185.002115

Baliunas SL, Hartmann L, Noyes RW, et al (1983) Stellar rotation in lower main-sequence stars measured from time variations in H and K emission-line fluxes. II. Detailed analysis of the 1980 observing season data. Astrophys. J.275:752–772. https://doi.org/10.1086/161572

Baliunas SL, Donahue RA, Soon WH, et al (1995) Chromospheric Variations in Main-Sequence Stars. II. Astrophys. J.438:269. https://doi.org/10.1086/175072

Ball WH, Chaplin WJ, Schofield M, et al (2018) A Synthetic Sample of Short-cadence Solar-like Oscillators for TESS. The Astrophysical Journal Supplement Series 239(2):34. https://doi.org/10.3847/1538-4365/aaedbc

Basri G, Shah R (2020) The Information Content in Analytic Spot Models of Broadband Precision Light Curves. II. Spot Distributions and Lifetimes and Global and Differential Rotation. Astrophys. J.901(1):14. https://doi.org/10.3847/1538-4357/abae5d, https://arxiv.org/abs/2008.04969 [astro-ph.SR]

Basu S (2016) Global Seismology of the Sun. Living Reviews in Solar Physics 13:2. https://doi.org/10.1007/s41116-016-0003-4, https://arxiv.org/abs/1606.07071

Basu S, Broomhall AM, Chaplin WJ, et al (2012) Thinning of the Sun's magnetic layer: The peculiar solar minimum could have been predicted. The Astrophysical Journal 758(1):43. https://doi.org/10.1088/0004-637X/758/

1/43, https://arxiv.org/abs/1208.5493

Baum AC, Wright JT, Luhn JK, et al (2022) Five Decades of Chromospheric Activity in 59 Sun-like Stars and New Maunder Minimum Candidate HD 166620. Astron. J.163(4):183. https://doi.org/10.3847/1538-3881/ac5683, https://arxiv.org/abs/2203.13376 [astro-ph.SR]

Bazot M, Nielsen MB, Mary D, et al (2018) Butterfly diagram of a Sun-like star observed using asteroseismology. Astron. Astrophys.619:L9. https://doi.org/10.1051/0004-6361/201834251, https://arxiv.org/abs/1810.08630 [astro-ph.SR]

Böhm-Vitense E (2007) Chromospheric Activity in G and K Main-Sequence Stars, and What It Tells Us about Stellar Dynamos. Astrophys. J.657(1):486–493. https://doi.org/10.1086/510482

Boro Saikia S, Jeffers SV, Petit P, et al (2015) Variable magnetic field geometry of the young sun HN Pegasi (HD 206860). Astron. Astrophys.573:A17. https://doi.org/10.1051/0004-6361/201424096, https://arxiv.org/abs/1410.8307 [astro-ph.SR]

Boro Saikia S, Jeffers SV, Morin J, et al (2016) A solar-like magnetic cycle on the mature K-dwarf 61 Cygni A (HD 201091). Astron. Astrophys.594:A29. https://doi.org/10.1051/0004-6361/201628262, https://arxiv.org/abs/1606.01032 [astro-ph.SR]

Boro Saikia S, Lueftinger T, Jeffers SV, et al (2018) Direct evidence of a full dipole flip during the magnetic cycle of a sun-like star. Astron. Astrophys.620:L11. https://doi.org/10.1051/0004-6361/201834347, https://arxiv.org/abs/1811.11671 [astro-ph.SR]

Boro Saikia S, Lüftinger T, Folsom CP, et al (2022) Time evolution of magnetic activity cycles in young suns: The curious case of κ Ceti. Astron. Astrophys.658:A16. https://doi.org/10.1051/0004-6361/202141525, https://arxiv.org/abs/2110.06000 [astro-ph.SR]

Borucki WJ, Koch D, Basri G, et al (2010) Kepler Planet-Detection Mission: Introduction and First Results. Science 327(5968):977–980. https://doi.org/10.1126/science.1185402

Brandenburg A, Saar SH, Turpin CR (1998) Time Evolution of the Magnetic Activity Cycle Period. Astrophys. J. Lett.498(1):L51–L54. https://doi.org/10.1086/311297

Brandenburg A, Mathur S, Metcalfe TS (2017) Evolution of Co-existing Long and Short Period Stellar Activity Cycles. Astrophys. J.845(1):79. https://doi.org/10.3847/1538-4357/aa7cfa, https://arxiv.org/

abs/1704.09009 [astro-ph.SR]

Broomhall AM (2017) A Helioseismic Perspective on the Depth of the Minimum Between Solar Cycles 23 and 24. Solar Phys.292:67. https://doi.org/10.1007/s11207-017-1068-5

Broomhall AM, Chatterjee P, Howe R, et al (2014) The Sun's Interior Structure and Dynamics, and the Solar Cycle. Space Sci. Rev.186:191–225. https://doi.org/10.1007/s11214-014-0101-3

Broomhall AM, Pugh C, Nakariakov V (2015) Solar cycle variations in the powers and damping rates of low-degree solar acoustic oscillations. Advances in Space Research 56(12):2706–2712. https://doi.org/10.1016/j.asr.2015.04.018

Brown EL, Marsden SC, Mengel MW, et al (2021) Magnetic field and chromospheric activity evolution of HD 75332: a rapid magnetic cycle in an F star without a hot Jupiter. Mon. Not. Roy. Astron. Soc.501(3):3981–4003. https://doi.org/10.1093/mnras/staa3878, https://arxiv.org/abs/2012.05407 [astro-ph.SR]

Brown EL, Jeffers SV, Marsden SC, et al (2022) Linking chromospheric activity and magnetic field properties for late-type dwarf stars. Mon. Not. Roy. Astron. Soc.514(3):4300–4319. https://doi.org/10.1093/mnras/stac1291, https://arxiv.org/abs/2205.03108 [astro-ph.SR]

Brun AS, Strugarek A, Noraz Q, et al (2022) Powering Stellar Magnetism: Energy Transfers in Cyclic Dynamos of Sun-like Stars. Astrophys. J.926(1):21. https://doi.org/10.3847/1538-4357/ac469b, https://arxiv.org/abs/2201.13218 [astro-ph.SR]

Bugnet L (2022) Magnetic signatures on mixed-mode frequencies. II. Period spacings as a probe of the internal magnetism of red giants. Astron. Astrophys.667:A68. https://doi.org/10.1051/0004-6361/202243167, https://arxiv.org/abs/2208.14954 [astro-ph.SR]

Bugnet L, Prat V, Mathis S, et al (2021) Magnetic signatures on mixed-mode frequencies. I. An axisymmetric fossil field inside the core of red giants. Astron. Astrophys.650:A53. https://doi.org/10.1051/0004-6361/202039159, https://arxiv.org/abs/2102.01216 [astro-ph.SR]

Burtseva O, Hill F, Kholikov S, et al (2009) Lifetimes of High-Degree p Modes in the Quiet and Active Sun. Solar Phys.258(1):1–11. https://doi.org/10.1007/s11207-009-9399-5, https://arxiv.org/abs/0902.2016

Cameron R, Schüssler M (2023) Observationally guided models for the solar dynamo and the role of the surface field. arXiv e-prints arXiv:2305.02253. https://doi.org/10.48550/arXiv.2305.02253, https://arxiv.org/abs/2305.02253 [astro-ph.SR]

Cameron RH, Duvall TL, Schüssler M, et al (2018) Observing and modeling the poloidal and toroidal fields of the solar dynamo. Astron. Astrophys.609:A56. https://doi.org/10.1051/0004-6361/201731481, https://arxiv.org/abs/1710.07126 [astro-ph.SR]

Campante TL, Lund MN, Kuszlewicz JS, et al (2016a) Spin-Orbit Alignment of Exoplanet Systems: Ensemble Analysis Using Asteroseismology. The Astrophysical Journal 819(1):85. https://doi.org/10.3847/0004-637x/819/1/85, https://arxiv.org/abs/1601.06052

Campante TL, Schofield M, Kuszlewicz JS, et al (2016b) The Asteroseismic Potential of TESS: Exoplanet-host Stars. The Astrophysical Journal 830(2):138. https://doi.org/10.3847/0004-637X/830/2/138

Catala C, Donati JF, Shkolnik E, et al (2007) The magnetic field of the planet-hosting star τ Bootis. Mon. Not. Roy. Astron. Soc.374(1):L42–L46. https://doi.org/10.1111/j.1745-3933.2006.00261.x, https://arxiv.org/abs/astro-ph/0610758 [astro-ph]

Chaplin W, Appourchaux T, Elsworth Y, et al (2001) The phenomenology of solar-cycle-induced acoustic eigenfrequency variations: a comparative and complementary analysis of GONG, BiSON and VIRGO/LOI data. Mon. Not. Roy. Astron. Soc.324(4):910–916. https://doi.org/10.1046/j.1365-8711.2001.04357.x

Chaplin WJ, Basu S (2014) Inferences on Stellar Activity and Stellar Cycles from Asteroseismology. Space Science Reviews 186(1-4):437–456. https://doi.org/10.1007/s11214-014-0090-2

Chaplin WJ, Elsworth Y, Isaak GR, et al (2000) Variations in the excitation and damping of low- solar p modes over the solar activity cycle. Mon. Not. Roy. Astron. Soc.313(1):32–42. https://doi.org/10.1046/j.1365-8711.2000.03176.x

Chaplin WJ, Elsworth Y, Houdek G, et al (2007) On prospects for sounding activity cycles of Sun-like stars with acoustic modes. Monthly Notices of the Royal Astronomical Society 377(1):17–29. https://doi.org/10.1111/j.1365-2966.2007.11581.x

Chaplin WJ, Bedding TR, Bonanno A, et al (2011a) Evidence for the impact of stellar activity on the detectability of solar-like oscillations observed by Kepler. The Astrophysical Journal Letters 732(1):L5. https://doi.org/10.

1088/2041-8205/732/1/L5, https://arxiv.org/abs/1103.5570

Chaplin WJ, Kjeldsen H, Bedding TR, et al (2011b) Predicting the detectability of oscillations in solar-type stars observed by Kepler. The Astrophysical Journal 732(1):54. https://doi.org/10.1088/0004-637X/732/1/54

Charbonneau P (2020) Dynamo models of the solar cycle. Living Reviews in Solar Physics 17(1):4. https://doi.org/10.1007/s41116-020-00025-6

Christensen-Dalsgaard J, Berthomieu G (1991) Theory of solar oscillations. In: Cox AN, Livingston WC, Matthews M (eds) Solar interior and atmosphere. University of Arizona Press, p 401–478

Coffaro M, Stelzer B, Orlando S, et al (2020) An X-ray activity cycle on the young solar-like star ϵ Eridani. Astron. Astrophys.636:A49. https://doi.org/10.1051/0004-6361/201936479, https://arxiv.org/abs/2002.11009 [astro-ph.SR]

Das SB, Chakraborty T, Hanasoge S, et al (2020) Sensitivity Kernels for Inferring Lorentz Stresses from Normal-mode Frequency Splittings in the Sun. The Astrophysical Journal 897(1):38. https://doi.org/10.3847/1538-4357/ab8e3a

Deheuvels S, Li G, Ballot J, et al (2023) Strong magnetic fields detected in the cores of 11 red giant stars using gravity-mode period spacings. arXiv e-prints arXiv:2301.01308. https://arxiv.org/abs/2301.01308 [astro-ph.SR]

Dhouib H, Mathis S, Bugnet L, et al (2022) Detecting deep axisymmetric toroidal magnetic fields in stars - The traditional approximation of rotation for differentially rotating deep spherical shells with a general azimuthal magnetic field. Astron. Astrophys.661:A133. https://doi.org/10.1051/0004-6361/202142956, https://arxiv.org/abs/2202.10026

Distefano E, Lanzafame A (2020) Detection and characterization of stellar magnetic activity with Gaia. Astronomische Nachrichten 341(5):508–512. https://doi.org/10.1002/asna.202013732

Donahue RA, Saar SH, Baliunas SL (1996) A Relationship between Mean Rotation Period in Lower Main-Sequence Stars and Its Observed Range. Astrophys. J.466:384. https://doi.org/10.1086/177517

Donati JF, Semel M, Carter BD, et al (1997) Spectropolarimetric observations of active stars. Mon. Not. Roy. Astron. Soc.291(4):658–682. https://doi.org/10.1093/mnras/291.4.658

Donati JF, Collier Cameron A, Semel M, et al (2003) Dynamo processes and activity cycles of the active stars AB Doradus, LQ Hydrae and HR 1099.

Mon. Not. Roy. Astron. Soc.345(4):1145–1186. https://doi.org/10.1046/j.1365-2966.2003.07031.x

Donati JF, Catala C, Landstreet JD, et al (2006a) ESPaDOnS: The New Generation Stellar Spectro-Polarimeter. Performances and First Results. In: Casini R, Lites BW (eds) Solar Polarization 4, p 362

Donati JF, Howarth ID, Jardine MM, et al (2006b) The surprising magnetic topology of τ Sco: fossil remnant or dynamo output? Mon. Not. Roy. Astron. Soc.370(2):629–644. https://doi.org/10.1111/j.1365-2966.2006.10558.x, https://arxiv.org/abs/astro-ph/0606156 [astro-ph]

Donati JF, Moutou C, Farès R, et al (2008) Magnetic cycles of the planet-hosting star τ Bootis. Mon. Not. Roy. Astron. Soc.385(3):1179–1185. https://doi.org/10.1111/j.1365-2966.2008.12946.x, https://arxiv.org/abs/0802.1584 [astro-ph]

Dziembowski WA, Goode PR (2004) Helioseismic Probing of Solar Variability: The Formalism and Simple Assessments. The Astrophysical Journal 600(1):464–479. https://doi.org/10.1086/379708, https://arxiv.org/abs/0310095 [astro-ph]

Egeland R, Metcalfe TS, Hall JC, et al (2015) Sun-like Magnetic Cycles in the Rapidly-rotating Young Solar Analog HD 30495. Astrophys. J.812(1):12. https://doi.org/10.1088/0004-637X/812/1/12, https://arxiv.org/abs/1507.03611 [astro-ph.SR]

Elsworth Y, Howe R, Isaak GR, et al (1990) Variation of low-order acoustic solar oscillations over the solar cycle. Nature345(6273):322–324. https://doi.org/10.1038/345322a0

Fares R, Donati JF, Moutou C, et al (2009) Magnetic cycles of the planet-hosting star τ Bootis - II. A second magnetic polarity reversal. Mon. Not. Roy. Astron. Soc.398(3):1383–1391. https://doi.org/10.1111/j.1365-2966.2009.15303.x, https://arxiv.org/abs/0906.4515 [astro-ph.SR]

Fares R, Moutou C, Donati JF, et al (2013) A small survey of the magnetic fields of planet-host stars. Mon. Not. Roy. Astron. Soc.435(2):1451–1462. https://doi.org/10.1093/mnras/stt1386, https://arxiv.org/abs/1307.6091 [astro-ph.SR]

Favata F, Micela G, Orlando S, et al (2008) The X-ray cycle in the solar-type star HD 81809. XMM-Newton observations and implications for the coronal structure. Astron. Astrophys.490(3):1121–1126. https://doi.org/10.1051/0004-6361:200809694, https://arxiv.org/abs/0806.2279 [astro-ph]

Ferreira Lopes CE, Leão IC, de Freitas DB, et al (2015) Stellar cycles from photometric data: CoRoT stars. Astron. Astrophys.583:A134. https://doi.org/10.1051/0004-6361/20142490010.48550/arXiv.1508.06194, https://arxiv.org/abs/1508.06194 [astro-ph.SR]

Folsom CP, Bouvier J, Petit P, et al (2018) The evolution of surface magnetic fields in young solar-type stars II: the early main sequence (250-650 Myr). Mon. Not. Roy. Astron. Soc.474(4):4956–4987. https://doi.org/10.1093/mnras/stx3021, https://arxiv.org/abs/1711.08636 [astro-ph.SR]

Fuhrmeister B, Coffaro M, Stelzer B, et al (2023) A multi-wavelength view of the multiple activity cycles of ϵ Eridani. Astron. Astrophys.672:A149. https://doi.org/10.1051/0004-6361/202245201, https://arxiv.org/abs/2303.08487 [astro-ph.SR]

García RA, Mathur S, Salabert D, et al (2010) CoRoT reveals a magnetic activity cycle in a Sun-like star. Science 329(5995):1032. https://doi.org/10.1126/science.1191064

Garg S, Karak BB, Egeland R, et al (2019) Waldmeier Effect in Stellar Cycles. Astrophys. J.886(2):132. https://doi.org/10.3847/1538-4357/ab4a17, https://arxiv.org/abs/1909.12148 [astro-ph.SR]

Gomes P, Lopes I (2020) Core magnetic field imprint in the non-radial oscillations of red giant stars. Mon. Not. Roy. Astron. Soc.496(1):620–628. https://doi.org/10.1093/mnras/staa1585, https://arxiv.org/abs/2007.09632 [astro-ph.SR]

González-Pérez JN, Mittag M, Schmitt JHMM, et al (2022) Eight Years of TIGRE Robotic Spectroscopy: Operational Experience and Selected Scientific Results. Frontiers in Astronomy and Space Sciences 9:912546. https://doi.org/10.3389/fspas.2022.912546, https://arxiv.org/abs/2206.02832 [astro-ph.IM]

Gough DO, Thompson MJ (1990) The effect of rotation and a buried magnetic field on stellar oscillations. Monthly Notices of the Royal Astronomical Society 242(1):25–55. https://doi.org/10.1093/mnras/242.1.25

Goupil M (2017) Expected asteroseismic performances with the space project PLATO. In: European Physical Journal Web of Conferences, p 01003, https://doi.org/10.1051/epjconf/201716001003

Hackman T, Mantere MJ, Lindborg M, et al (2012) Doppler images of II Pegasi for 2004-2010. Astron. Astrophys.538:A126. https://doi.org/10.1051/0004-6361/201117603, https://arxiv.org/abs/1106.6237 [astro-ph.SR]

Hale GE (1908) On the Probable Existence of a Magnetic Field in Sun-Spots. Astrophys. J.28:315. https://doi.org/10.1086/141602

Hall JC, Lockwood GW, Skiff BA (2007) The Activity and Variability of the Sun and Sun-like Stars. I. Synoptic Ca II H and K Observations. Astron. J.133(3):862–881. https://doi.org/10.1086/510356

Hanasoge SM (2017) Seismic sensitivity of normal-mode coupling to Lorentz stresses in the Sun. Monthly Notices of the Royal Astronomical Society 470(3):2780–2790. https://doi.org/10.1093/mnras/stx1342, https://arxiv.org/abs/1705.09431

Hathaway DH (2015) The Solar Cycle. Living Reviews in Solar Physics 12(1):4. https://doi.org/10.1007/lrsp-2015-4, https://arxiv.org/abs/1502.07020 [astro-ph.SR]

Hekker S, Christensen-Dalsgaard J (2017) Giant star seismology. Astronomy and Astrophysics Review 25:1. https://doi.org/10.1007/s00159-017-0101-x, https://arxiv.org/abs/1609.07487

Hempelmann A, Robrade J, Schmitt JHMM, et al (2006) Coronal activity cycles in 61 Cygni. Astron. Astrophys.460(1):261–267. https://doi.org/10.1051/0004-6361:20065459

Howe R, Komm R, Hill F (1999) Solar Cycle Changes in GONG P-Mode Frequencies, 1995-1998. Astrophys. J.524(2):1084–1095. https://doi.org/10.1086/307851

Howe R, Chaplin WJ, Basu S, et al (2020) Solar cycle variation of νmax in helioseismic data and its implications for asteroseismology. Monthly Notices of the Royal Astronomical Society: Letters 493(1):L49–L53. https://doi.org/10.1093/MNRASL/SLAA006

Jefferies SM, Pomerantz MA, Duvall, T. L. J, et al (1991) Characteristics of intermediate-degree solar p-mode line widths. Astrophys. J.377:330–336. https://doi.org/10.1086/170362

Jeffers SV, Donati JF (2008) High levels of surface differential rotation on the young G0 dwarf HD171488. Mon. Not. Roy. Astron. Soc.390(2):635–644. https://doi.org/10.1111/j.1365-2966.2008.13695.x

Jeffers SV, Donati JF, Collier Cameron A (2007) Magnetic activity on AB Doradus: temporal evolution of star-spots and differential rotation from 1988 to 1994. Mon. Not. Roy. Astron. Soc.375(2):567–583. https://doi.org/10.1111/j.1365-2966.2006.11154.x, https://arxiv.org/abs/astro-ph/0610259 [astro-ph]

Jeffers SV, Donati JF, Alecian E, et al (2011) Observations of non-solar-type dynamo processes in stars with shallow convective zones. Mon. Not. Roy. Astron. Soc.411(2):1301–1312. https://doi.org/10.1111/j.1365-2966.2010.17762.x

Jeffers SV, Petit P, Marsden SC, et al (2014) ϵ Eridani: an active K dwarf and a planet hosting star?. The variability of its large-scale magnetic field topology. Astron. Astrophys.569:A79. https://doi.org/10.1051/0004-6361/201423725

Jeffers SV, Mengel M, Moutou C, et al (2018) The relation between stellar magnetic field geometry and chromospheric activity cycles - II The rapid 120-day magnetic cycle of τ Bootis. Mon. Not. Roy. Astron. Soc.479(4):5266–5271. https://doi.org/10.1093/mnras/sty1717, https://arxiv.org/abs/1805.09769 [astro-ph.SR]

Jeffers SV, Cameron RH, Marsden SC, et al (2022) The crucial role of surface magnetic fields for stellar dynamos: ϵ Eridani, 61 Cygni A, and the Sun. Astron. Astrophys.661:A152. https://doi.org/10.1051/0004-6361/202142202, https://arxiv.org/abs/2201.07530 [astro-ph.SR]

Jiménez A, Roca Cortés TR, Jiménez-Reyes J (2002) Variation of the low-degree solar acoustic mode parameters over the solar cycle. Solar Phys.209(2):247–263. https://doi.org/10.1023/A:1021226503589

Jiménez-Reyes SJ, Régulo C, Pallé PL, et al (1998) Solar activity cycle frequency shifts of low-degree p-modes. Astron. Astrophys.329:1119–1124

Jiménez-Reyes SJ, García RA, Jiménez A, et al (2003) Excitation and Damping of Low-Degree Solar p-Modes during Activity Cycle 23: Analysis of GOLF and VIRGO Sun Photometer Data. Astrophys. J.595(1):446–457. https://doi.org/10.1086/377304

Jiménez-Reyes SJ, Chaplin WJ, Elsworth Y, et al (2004) Tracing the "Acoustic" Solar Cycle: A Direct Comparison of BiSON and GOLF Low-l p-Mode Variations. Astrophys. J.604(2):969–976. https://doi.org/10.1086/381936

Judge PG, Egeland R, Metcalfe TS, et al (2017) The Magnetic Future of the Sun. Astrophys. J.848(1):43. https://doi.org/10.3847/1538-4357/aa8d6a, https://arxiv.org/abs/1710.05088 [astro-ph.SR]

Käpylä PJ, Browning MK, Brun AS, et al (2023) Simulations of solar and stellar dynamos and their theoretical interpretation. arXiv e-prints arXiv:2305.16790. https://doi.org/10.48550/arXiv.2305.16790, https://arxiv.org/abs/2305.16790 [astro-ph.SR]

Karoff C, Metcalfe TS, Chaplin WJ, et al (2009) Sounding stellar cycles with Kepler - I. Strategy for selecting targets. Monthly Notices of the Royal Astronomical Society 399(2):914–923. https://doi.org/10.1111/j.1365-2966.2009.15323.x

Karoff C, Metcalfe TS, Chaplin WJ, et al (2013) Sounding stellar cycles with Kepler - II. Ground-based observations. Monthly Notices of the Royal Astronomical Society 433(4):3227–3238. https://doi.org/10.1093/mnras/stt964

Karoff C, Metcalfe TS, Santos ÂRG, et al (2018) The Influence of Metallicity on Stellar Differential Rotation and Magnetic Activity. The Astrophysical Journal 852(1):46. https://doi.org/10.3847/1538-4357/aaa026, https://arxiv.org/abs/1711.07716

Karoff C, Metcalfe TS, Montet BT, et al (2019) Sounding stellar cycles with Kepler - III. Comparative analysis of chromospheric, photometric and asteroseismic variability. Monthly Notices of the Royal Astronomical Society 485(4):5096–5104. https://doi.org/10.1093/mnras/stz782, https://arxiv.org/abs/1902.02172

Kiefer R, Broomhall AM (2021) They do change after all: 25 yr of GONG data reveal variation of p-mode energy supply rates. Mon. Not. Roy. Astron. Soc.500(3):3095–3110. https://doi.org/10.1093/mnras/staa3198, https://arxiv.org/abs/2010.06287 [astro-ph.SR]

Kiefer R, Roth M (2018) The Effect of Toroidal Magnetic Fields on Solar Oscillation Frequencies. The Astrophysical Journal 854(1):74. https://doi.org/10.3847/1538-4357/aaa3f7

Kiefer R, Schad A, Davies G, et al (2017a) Stellar magnetic activity and variability of oscillation parameters: An investigation of 24 solar-like stars observed by Kepler. Astronomy & Astrophysics 598:A77. https://doi.org/10.1051/0004-6361/201628469

Kiefer R, Schad A, Roth M (2017b) The Direct Effect of Toroidal Magnetic Fields on Stellar Oscillations: An Analytical Expression for the General Matrix Element. The Astrophysical Journal 846(2):162. https://doi.org/10.3847/1538-4357/aa8634, https://arxiv.org/abs/1709.02454

Kiefer R, Komm R, Hill F, et al (2018) GONG p-Mode Parameters Through Two Solar Cycles. Solar Phys.293(11):151. https://doi.org/10.1007/s11207-018-1370-x

Kiefer R, Broomhall AM, Ball WH (2019) Seismic Signatures of Stellar Magnetic Activity—What Can We Expect From TESS? Frontiers in Astronomy and Space Sciences 6:52. https://doi.org/10.3389/fspas.2019.00052

Koch DG, Borucki WJ, Basri G, et al (2010) Kepler Mission Design, Realized Photometric Performance, and Early Science. The Astrophysical Journal Letters 713(2):L79–L86. https://doi.org/10.1088/2041-8205/713/2/L79, https://arxiv.org/abs/1001.0268

Kochukhov O, Makaganiuk V, Piskunov N (2010) Least-squares deconvolution of the stellar intensity and polarization spectra. Astron. Astrophys.524:A5. https://doi.org/10.1051/0004-6361/201015429, https://arxiv.org/abs/1008.5115 [astro-ph.SR]

Komm RW, Howe R, Hill F (2000a) Solar-Cycle Changes in Gong p-Mode Widths and Amplitudes 1995–1998. Astrophys. J.531(2):1094–1108. https://doi.org/10.1086/308518

Komm RW, Howe R, Hill F (2000b) Width and Energy of Solar p-Modes Observed by Global Oscillation Network Group. The Astrophysical Journal 543(1):472–485. https://doi.org/10.1086/317101

Kosak K, Kiefer R, Broomhall AM (2022) A multi-instrument investigation of the frequency stability of oscillations above the acoustic cut-off frequency with solar activity. Mon. Not. Roy. Astron. Soc.512(4):5743–5754. https://doi.org/10.1093/mnras/stac647, https://arxiv.org/abs/2203.03685 [astro-ph.SR]

Lavely EM, Ritzwoller MH (1992) The effect of global-scale, steady-state convection and elastic-gravitational asphericities on helioseismic oscillations. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 339(1655):431–496. https://doi.org/10.1098/rsta.1992.0048

Lehtinen J, Jetsu L, Hackman T, et al (2016) Activity trends in young solar-type stars. Astron. Astrophys.588:A38. https://doi.org/10.1051/0004-6361/20152742010.48550/arXiv.1509.06606, https://arxiv.org/abs/1509.06606 [astro-ph.SR]

Lehtinen JJ, Käpylä MJ, Hackman T, et al (2022) Topological changes in the magnetic field of LQ Hya during an activity minimum. Astron. Astrophys.660:A141. https://doi.org/10.1051/0004-6361/201936780, https://arxiv.org/abs/1909.11028 [astro-ph.SR]

Leighton RB (1959) Observations of Solar Magnetic Fields in Plage Regions. Astrophys. J.130:366. https://doi.org/10.1086/146727

Li G, Deheuvels S, Ballot J, et al (2022) Magnetic fields of 30 to 100 kG in the cores of red giant stars. Nature610(7930):43–46. https://doi.org/10.1038/s41586-022-05176-0, https://arxiv.org/abs/2208.09487 [astro-ph.SR]

Libbrecht KG, Woodard MF (1990) Solar-cycle effects on solar oscillation frequencies. Nature345(6278):779–782. https://doi.org/10.1038/345779a0

Loi ST (2020) Effect of a strong magnetic field on gravity-mode period spacings in red giant stars. Monthly Notices of the Royal Astronomical Society 496(3):3829–3840. https://doi.org/10.1093/MNRAS/STAA1823, https://arxiv.org/abs/2006.08635

Loi ST (2021) Topology and obliquity of core magnetic fields in shaping seismic properties of slowly rotating evolved stars. Mon. Not. Roy. Astron. Soc.504(3):3711–3729. https://doi.org/10.1093/mnras/stab991, https://arxiv.org/abs/2104.03112 [astro-ph.SR]

Lovis C, Dumusque X, Santos NC, et al (2011) The HARPS search for southern extra-solar planets. XXXI. Magnetic activity cycles in solar-type stars: statistics and impact on precise radial velocities. arXiv e-prints arXiv:1107.5325. https://arxiv.org/abs/1107.5325 [astro-ph.SR]

Luhn JK, Wright JT, Henry GW, et al (2022) HD 166620: Portrait of a Star Entering a Grand Magnetic Minimum. Astrophys. J. Lett.936(2):L23. https://doi.org/10.3847/2041-8213/ac8b13, https://arxiv.org/abs/2207.00612 [astro-ph.SR]

Lund MN, Aguirre VS, Davies GR, et al (2017) Standing on the Shoulders of Dwarfs: the Kepler Asteroseismic LEGACY Sample. I. Oscillation Mode Parameters. The Astrophysical Journal 835(2):172. https://doi.org/10.3847/1538-4357/835/2/172

Marsden SC, Donati JF, Semel M, et al (2006) Surface differential rotation and photospheric magnetic field of the young solar-type star HD 171488 (V889 Her). Mon. Not. Roy. Astron. Soc.370(1):468–476. https://doi.org/10.1111/j.1365-2966.2006.10503.x

Marsden SC, Evensberget D, Brown EL, et al (2023) The magnetic field and stellar wind of the mature late-F star χ Draconis A. Mon. Not. Roy. Astron. Soc.522(1):792–810. https://doi.org/10.1093/mnras/stad925

Mathis S, Bugnet L, Prat V, et al (2021) Probing the internal magnetism of stars using asymptotic magneto-asteroseismology. Astron. Astrophys.647:A122. https://doi.org/10.1051/0004-6361/202039180, https://arxiv.org/abs/2012.11050 [astro-ph.SR]

Mathur S, Salabert D, García RA, et al (2014) Photometric magnetic-activity metrics tested with the Sun: application to Kepler M dwarfs. Journal of Space Weather and Space Climate 4:A15. https://doi.org/10.1051/swsc/201401110.48550/arXiv.1404.3076, https://arxiv.org/abs/1404.3076 [astro-ph.SR]

Mathur S, García RA, Bugnet L, et al (2019) Revisiting the Impact of Stellar Magnetic Activity on the Detectability of Solar-Like Oscillations by Kepler. Frontiers in Astronomy and Space Sciences 6:46. https://doi.org/10.3389/fspas.2019.00046, https://arxiv.org/abs/1907.01415

Maunder EW (1904) Note on the Distribution of Sun-spots in Heliographic Latitude, 1874-1902. Mon. Not. Roy. Astron. Soc.64:747–761. https://doi.org/10.1093/mnras/64.8.747

Mengel MW, Fares R, Marsden SC, et al (2016) The evolving magnetic topology of τ Boötis. Mon. Not. Roy. Astron. Soc.459(4):4325–4342. https://doi.org/10.1093/mnras/stw828, https://arxiv.org/abs/1604.02501 [astro-ph.SR]

Metcalfe TS, van Saders J (2017) Magnetic Evolution and the Disappearance of Sun-Like Activity Cycles. Solar Phys.292(9):126. https://doi.org/10.1007/s11207-017-1157-5, https://arxiv.org/abs/1705.09668 [astro-ph.SR]

Metcalfe TS, Dziembowski WA, Judge PG, et al (2007) Asteroseismic signatures of stellar magnetic activity cycles. Monthly Notices of the Royal Astronomical Society: Letters 379(1):L16–L20. https://doi.org/10.1111/j.1745-3933.2007.00325.x

Metcalfe TS, Judge PG, Basu S, et al (2009) Activity Cycles of Southern Asteroseismic Targets. arXiv e-prints arXiv:0909.5464. https://arxiv.org/abs/0909.5464 [astro-ph.SR]

Metcalfe TS, Basu S, Henry TJ, et al (2010) Discovery of a 1.6 Year Magnetic Activity Cycle in the Exoplanet Host Star ι Horologii. Astrophys. J. Lett.723(2):L213–L217. https://doi.org/10.1088/2041-8205/723/2/L213, https://arxiv.org/abs/1009.5399 [astro-ph.SR]

Metcalfe TS, Buccino AP, Brown BP, et al (2013) Magnetic Activity Cycles in the Exoplanet Host Star epsilon Eridani. Astrophys. J. Lett.763(2):L26. https://doi.org/10.1088/2041-8205/763/2/L26, https://arxiv.org/abs/1212.4425 [astro-ph.SR]

Metcalfe TS, Egeland R, van Saders J (2016) Stellar Evidence That the Solar Dynamo May Be in Transition. Astrophys. J. Lett.826(1):L2. https://doi.org/10.3847/2041-8205/826/1/L2, https://arxiv.org/abs/1606.01926 [astro-ph.SR]

Metcalfe TS, van Saders JL, Basu S, et al (2020) The Evolution of Rotation and Magnetic Activity in 94 Aqr Aa from Asteroseismology with TESS. Astrophys. J.900(2):154. https://doi.org/10.3847/1538-4357/aba963, https://arxiv.org/abs/2007.12755 [astro-ph.SR]

Metcalfe TS, Finley AJ, Kochukhov O, et al (2022) The Origin of Weakened Magnetic Braking in Old Solar Analogs. Astrophys. J. Lett.933(1):L17. https://doi.org/10.3847/2041-8213/ac794d, https://arxiv.org/abs/2206.08540 [astro-ph.SR]

Mittag M, Schmitt JHMM, Schröder KP (2023) Revisiting the cycle-rotation connection for late-type stars. Astron. Astrophys.674:A116. https://doi.org/10.1051/0004-6361/202245060, https://arxiv.org/abs/2306.05866 [astro-ph.SR]

Montalto M, Piotto G, Marrese PM, et al (2021) The all-sky PLATO input catalogue. Astron. Astrophys.653:A98. https://doi.org/10.1051/0004-6361/202140717, https://arxiv.org/abs/2108.13712 [astro-ph.EP]

Montet BT, Tovar G, Foreman-Mackey D (2017) Long-term Photometric Variability in Kepler Full-frame Images: Magnetic Cycles of Sun-like Stars. Astrophys. J.851(2):116. https://doi.org/10.3847/1538-4357/aa9e0010.48550/arXiv.1705.07928, https://arxiv.org/abs/1705.07928 [astro-ph.SR]

Moreno-Insertis F, Solanki SK (2000) Distribution of magnetic flux on the solar surface and low-degree p-modes. Monthly Notices of the Royal Astronomical Society 313(2):411–422. https://doi.org/10.1046/j.1365-8711.2000.03246.x

Morgenthaler A, Petit P, Morin J, et al (2011) Direct observation of magnetic cycles in Sun-like stars. Astronomische Nachrichten 332:866. https://doi.org/10.1002/asna.201111592, https://arxiv.org/abs/1109.3982 [astro-ph.SR]

Nascimbeni V, Piotto G, Börner A, et al (2022) The PLATO field selection process. I. Identification and content of the long-pointing fields. Astron. Astrophys.658:A31. https://doi.org/10.1051/0004-6361/202142256, https://arxiv.org/abs/2110.13924 [astro-ph.EP]

Noyes RW, Hartmann LW, Baliunas SL, et al (1984) Rotation, convection, and magnetic activity in lower main-sequence stars. The Astrophysical Journal 279(1):763–777. https://doi.org/10.1086/161945

Oláh K, Strassmeier KG (2002) Starspot cycles from long-term photometry. Astronomische Nachrichten 323:361–366. https://doi.org/10.1002/1521-3994(200208)323:3/4⟨361::AID-ASNA361⟩3.0.CO;2-1

Oláh K, Kolláth Z, Strassmeier KG (2000) Multiperiodic light variations of active stars. Astron. Astrophys.356:643–653

Oláh K, Kolláth Z, Granzer T, et al (2009) Multiple and changing cycles of active stars. II. Results. Astron. Astrophys.501(2):703–713. https://doi.

org/10.1051/0004-6361/200811304, https://arxiv.org/abs/0904.1747 [astro-ph.SR]

Oláh K, Kővári Z, Petrovay K, et al (2016) Magnetic cycles at different ages of stars. Astron. Astrophys.590:A133. https://doi.org/10.1051/0004-6361/201628479, https://arxiv.org/abs/1604.06701 [astro-ph.SR]

Orlando S, Favata F, Micela G, et al (2017) Fifteen years in the high-energy life of the solar-type star HD 81809. XMM-Newton observations of a stellar activity cycle. Astron. Astrophys.605:A19. https://doi.org/10.1051/0004-6361/201731301, https://arxiv.org/abs/1707.06437 [astro-ph.SR]

Pérez Hernández F, García RA, Mathur S, et al (2019) Influence of Magnetic Activity on the Determination of Stellar Parameters Through Asteroseismology. Frontiers in Astronomy and Space Sciences 6:41. https://doi.org/10.3389/fspas.2019.00041, https://arxiv.org/abs/1906.10569

Petit P, Dintrans B, Morgenthaler A, et al (2009) A polarity reversal in the large-scale magnetic field of the rapidly rotating sun HD 190771. Astron. Astrophys.508(1):L9–L12. https://doi.org/10.1051/0004-6361/200913285, https://arxiv.org/abs/0909.2200 [astro-ph.SR]

Petit P, Folsom CP, Donati JF, et al (2021) Multi-instrumental view of magnetic fields and activity of ϵ Eridani with SPIRou, NARVAL, and TESS. Astron. Astrophys.648:A55. https://doi.org/10.1051/0004-6361/202040027, https://arxiv.org/abs/2101.02643 [astro-ph.SR]

Piskunov N, Snik F, Dolgopolov A, et al (2011) HARPSpol — The New Polarimetric Mode for HARPS. The Messenger 143:7–10

Prat V, Mathis S, Neiner C, et al (2020) Period spacings of gravity modes in rapidly rotating magnetic stars. Astron. Astrophys.636:A100. https://doi.org/10.1051/0004-6361/201937398

Radick RR, Lockwood GW, Henry GW, et al (2018) Patterns of Variation for the Sun and Sun-like Stars. Astrophys. J.855(2):75. https://doi.org/10.3847/1538-4357/aaaae3

Rauer H, Catala C, Aerts C, et al (2014) The PLATO 2.0 mission. Experimental Astronomy 38(1-2):249–330. https://doi.org/10.1007/s10686-014-9383-4, https://arxiv.org/abs/1310.0696 [astro-ph.EP]

Reinhold T, Cameron RH, Gizon L (2017) Evidence for photometric activity cycles in 3203 Kepler stars. Astron. Astrophys.603:A52. https://doi.org/10.1051/0004-6361/20173059910.48550/arXiv.1705.03312, https://arxiv.org/abs/1705.03312 [astro-ph.SR]

Ricker GR, Winn JN, Vanderspek R, et al (2014) Transiting Exoplanet Survey Satellite. Proceedings of the SPIE 9143:914,320. https://doi.org/10.1117/1.JATIS.1.1.014003, https://arxiv.org/abs/1406.0151

Robrade J, Schmitt JHMM, Favata F (2012) Coronal activity cycles in nearby G and K stars. XMM-Newton monitoring of 61 Cygni and α Centauri. Astron. Astrophys.543:A84. https://doi.org/10.1051/0004-6361/201219046, https://arxiv.org/abs/1205.3627 [astro-ph.SR]

Saar SH, Brandenburg A (1999) Time Evolution of the Magnetic Activity Cycle Period. II. Results for an Expanded Stellar Sample. Astrophys. J.524(1):295–310. https://doi.org/10.1086/307794

Salabert D, Fossat E, Gelly B, et al (2004) Solar p modes in 10 years of the IRIS network. Astron. Astrophys.413(3):1135–1142. https://doi.org/10.1051/0004-6361:20031541

Salabert D, Régulo C, Ballot J, et al (2011) About the p-mode frequency shifts in HD 49933. Astronomy & Astrophysics 530:A127. https://doi.org/10.1051/0004-6361/201116633

Salabert D, García RA, Turck-Chièze S (2015) Seismic sensitivity to subsurface solar activity from 18 yr of GOLF/SoHO observations. Astron. Astrophys.578:A137. https://doi.org/10.1051/0004-6361/201425236

Salabert D, García RA, Beck PG, et al (2016) Photospheric and chromospheric magnetic activity of seismic solar analogs. Observational inputs on the solar-stellar connection from Kepler and Hermes. Astron. Astrophys.596:A31. https://doi.org/10.1051/0004-6361/20162858310.48550/arXiv.1608.01489, https://arxiv.org/abs/1608.01489 [astro-ph.SR]

Salabert D, Régulo C, García RA, et al (2016) Magnetic variability in the young solar analog KIC 10644253. Astronomy & Astrophysics 589:A118. https://doi.org/10.1051/0004-6361/201527978

Santos ARG, Campante TL, Chaplin WJ, et al (2018) Signatures of Magnetic Activity in the Seismic Data of Solar-type Stars Observed by Kepler. The Astrophysical Journal Supplement Series 237(1):17. https://doi.org/10.3847/1538-4365/aac9b6

Santos ÂRG, Campante TL, Chaplin WJ, et al (2019) Signatures of Magnetic Activity: On the Relation between Stellar Properties and p-mode Frequency Variations. The Astrophysical Journal 883(1):65. https://doi.org/10.3847/1538-4357/ab397a

Sanz-Forcada J, Stelzer B, Metcalfe TS (2013) ιHorologi, the first coronal activity cycle in a young solar-like star. Astron. Astrophys.553:L6.

https://doi.org/10.1051/0004-6361/201321388, https://arxiv.org/abs/1305.1132 [astro-ph.SR]

Schofield M, Chaplin WJ, Huber D, et al (2019) The Asteroseismic Target List (ATL) for solar-like oscillators observed in 2-minute cadence with the Transiting Exoplanet Survey Satellite (TESS). The Astrophysical Journal Supplement Series 241(1):12. https://doi.org/10.3847/1538-4365/ab04f5, https://arxiv.org/abs/1901.10148

See V, Jardine M, Vidotto AA, et al (2016) The connection between stellar activity cycles and magnetic field topology. Mon. Not. Roy. Astron. Soc.462(4):4442–4450. https://doi.org/10.1093/mnras/stw2010, https://arxiv.org/abs/1610.03737 [astro-ph.SR]

Skumanich A (1972) Time Scales for CaII Emission Decay, Rotational Braking, and Lithium Depletion. The Astrophysical Journal 171:565–567. https://doi.org/10.1086/151310

Snik F, Jeffers S, Keller C, et al (2008) The upgrade of HARPS to a full-Stokes high-resolution spectropolarimeter. In: McLean IS, Casali MM (eds) Ground-based and Airborne Instrumentation for Astronomy II, p 70140O, https://doi.org/10.1117/12.787393

Soon W, Velasco Herrera VM, Cionco RG, et al (2019) Covariations of chromospheric and photometric variability of the young Sun analogue HD 30495: evidence for and interpretation of mid-term periodicities. Mon. Not. Roy. Astron. Soc.483(2):2748–2757. https://doi.org/10.1093/mnras/sty3290

Thomas AE, Chaplin WJ, Basu S, et al (2021) Impact of magnetic activity on inferred stellar properties of main-sequence Sun-like stars. Monthly Notices of the Royal Astronomical Society 502(4):5808–5820. https://doi.org/10.1093/MNRAS/STAB354, https://arxiv.org/abs/2102.02566

Thomas AEL, Chaplin WJ, Davies GR, et al (2019) Asteroseismic constraints on active latitudes of solar-type stars: HD 173701 has active bands at higher latitudes than the Sun. Mon. Not. Roy. Astron. Soc.485(3):3857–3868. https://doi.org/10.1093/mnras/stz672, https://arxiv.org/abs/1903.04998 [astro-ph.SR]

Tripathy SC, Jain K, Hill F (2015) Variations in High Degree Acoustic Mode Frequencies of the Sun during Solar Cycle 23 and 24. Astrophys. J.812(1):20. https://doi.org/10.1088/0004-637X/812/1/20, https://arxiv.org/abs/1509.05474

Van Beeck J, Prat V, Van Reeth T, et al (2020) Detecting axisymmetric magnetic fields using gravity modes in intermediate-mass stars. Astron. Astrophys.638:A149. https://doi.org/10.1051/0004-6361/201937363, https:

//arxiv.org/abs/2005.02411 [astro-ph.SR]

van Saders JL, Ceillier T, Metcalfe TS, et al (2016) Weakened magnetic braking as the origin of anomalously rapid rotation in old field stars. Nature529(7585):181–184. https://doi.org/10.1038/nature16168, https://arxiv.org/abs/1601.02631 [astro-ph.SR]

Vaughan AH, Baliunas SL, Middelkoop F, et al (1981) Stellar rotation in lower main-sequence stars measured from time variations in H and K emission-line fluxes. I. Initial results. Astrophys. J.250:276–283. https://doi.org/10.1086/159372

Vida K, Oláh K, Szabó R (2014) Looking for activity cycles in late-type Kepler stars using time-frequency analysis. Mon. Not. Roy. Astron. Soc.441(3):2744–2753. https://doi.org/10.1093/mnras/stu76010.48550/arXiv.1404.4359, https://arxiv.org/abs/1404.4359 [astro-ph.SR]

Waite IA, Marsden SC, Carter BD, et al (2017) Magnetic fields on young, moderately rotating Sun-like stars - II. EK Draconis (HD 129333). Mon. Not. Roy. Astron. Soc.465(2):2076–2091. https://doi.org/10.1093/mnras/stw2731, https://arxiv.org/abs/1611.07751 [astro-ph.SR]

Waldmeier M (1935) Neue Eigenschaften der Sonnenfleckenkurve. Astronomische Mitteilungen der Eidgenössischen Sternwarte Zurich 14:105–136

Willamo T, Hackman T, Lehtinen JJ, et al (2020) Shapes of stellar activity cycles. Astron. Astrophys.638:A69. https://doi.org/10.1051/0004-6361/202037666, https://arxiv.org/abs/2002.04300 [astro-ph.SR]

Willamo T, Hackman T, Lehtinen JJ, et al (2022) V889 Her: abrupt changes in the magnetic field or differential rotation? arXiv e-prints arXiv:2203.13398. https://arxiv.org/abs/2203.13398 [astro-ph.SR]

Wilson OC (1968) Flux Measurements at the Centers of Stellar H- and K-Lines. Astrophys. J.153:221. https://doi.org/10.1086/149652

Wilson OC (1978) Chromospheric variations in main-sequence stars. Astrophys. J.226:379–396. https://doi.org/10.1086/156618

Woodard MF, Noyes RW (1985) Change of solar oscillation eigenfrequencies with the solar cycle. Nature318(6045):449–450. https://doi.org/10.1038/318449a0

Yeo KL, Krivova NA, Solanki SK, et al (2014) Reconstruction of total and spectral solar irradiance from 1974 to 2013 based on KPVT, SoHO/MDI, and SDO/HMI observations. Astron. Astrophys.570:A85. https://doi.org/10.1051/0004-6361/201423628, https://arxiv.org/abs/1408.1229 [astro-ph.SR]

Supplementary information.

Declarations

There are no conflicting interests to declare.