RECENT ADVANCES IN STELLAR CYCLE RESEARCH

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ABSTRACT We review recent work on stellar cycles, focusing on a preliminary analysis of the first 25 years of data from the Mount Wilson Ca II program. Cyclic variations are generally solar-like (rapid increase, slow decline), but some stars show multiple cycle periods. About 10–15% of the stars may be in the stellar equivalent of "Maunder minima": epochs when cycles, but not all magnetic activity, temporarily cease. Well-determined cycle periods show no clear dependence on single stellar parameters, but do show correlations with more complex formulations (e.g. $\alpha$-$\Omega$ dynamo number) when normalized to the magnetic diffusion timescale. The relation between this normalized cycle frequency ($\Omega_{cyc}$) and dynamo number appears to change with activity or age. Cycle amplitudes also correlate with $\Omega_{cyc}$, and tend to increase with convection zone depth and $P_{rot}$. Giants in young clusters also exhibit many of these phenomena, suggesting similar, dynamo-related origins. Stellar differential rotation can differ markedly from the Sun in both amplitude and form. Photometric variability increases rapidly with increasing Ca II emission, first reversing, and eventually eliminating the correlation between brightness and activity. Dynamos of active stars thus appear to produce a larger spot-to-plage ratio than inactive stars; more high-latitude spots are also seen. Surface convective properties may also change during the cycle.

1. INTRODUCTION AND OBSERVATIONS

The primary observational diagnostic of the solar dynamo is the 11 year activity cycle, as seen in, e.g. variations in sunspot number, magnetic flux, and activity indicators such as chromospheric Ca II emission. Study of the solar cycle began well over a century ago, and the data include more than three centuries of systematic sunspot observations, plus indirect measurements (e.g. radiocarbon records) spanning many millennia. In contrast, study of stellar magnetic cycles is of far more recent origin, and the data are still sparse. Some photographic records stretch back to early 1900's (e.g. Hartmann et al. 1981), but the most detailed investigation of stellar cycles began at the Mount Wilson Observatory in 1966, when Olin Wilson launched his landmark survey of Ca II

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emission in 91 lower main sequence stars (Wilson 1978). Here, we focus on the preliminary results from the first quarter century of this continuing program.

Most of the data we analyze here are from the extended Wilson survey (Noyes et al. 1984a), complete through early 1991, which includes 99 stars in all (36 F, 38 G, and 25 K stars). The present data have several advantages over previous studies (Baliunas and Vaughan 1985, Soderblom and Baliunas 1988). Most obviously, 6 – 7 years have passed since the last analysis, considerably lengthening the time series and allowing more accurate and longer cycle periods to be determined. Second, the data have been recalibrated in a consistent way. A longstanding problem – discontinuous changes in $S$ in a few stars at the transition between instrument setups (Wilson 1978, Vaughan et al. 1978) – is also being corrected. Finally, for some stars, long–term trends have been subtracted, permitting shorter timescale cyclic behavior to be extracted with greater precision. As we are still in the process of the last two tasks, the results presented here must be regarded as somewhat tentative. Nevertheless, our results should still represent a significant improvement over previous studies.

Measurements of the $S$ index, defined as the ratio of the flux in 1Å passbands centered on the Ca II H and K emission cores to the flux in the nearby continuum (see Vaughan et al. 1978, Baliunas et al. 1983), were typically made three times per night every 1–2 nights during an observing season (~200 days). In the cycle analyses, data taken after 1978 are averaged into monthly bins to prevent domination of the results by the much more frequent observations made after this date. Periodogram analysis for the unevenly sampled data was performed following Horne and Baliunas (1986), yielding cycle periods ($P_{cy}$), cycle amplitudes ($A_{cy}$), and a figure of merit, the “false alarm probability” (FAP). The FAP is the probability that a periodogram signal is false compared with the total variance of the data, assuming it was produced by Gaussian noise.

2. ANALYSIS AND DISCUSSION

2.1 $P_{cy}$: General Trends and Correlations with Simple Stellar Parameters We studied the derived $P_{cy}$ for trends. One immediate result is that a significant fraction (≈ 10–15%) of stars show no periodic variation. We return to these later (§2.4). Roughly 40% (16 F, 18 G, and 4 K stars) show either chaotic or high FAP cyclic variation, and another ≈ 15% (5 F, 6 G, and 5 K stars) exhibit long–term trends with $P_{cy} > 25$ years (if cyclic). The “chaotic” stars are typically active stars where the cycle is likely masked by active region growth and decay, sporadic short–term variability (flares?), or rotational modulation (see Dobson et al. 1991). A few of the data records are shown in Figure 1. Direct inspection of the $S$ variations in the sample reveals that most stars have “solar–like” cycles, i.e. they have short, rapid rises to maximum activity, followed by a slower decline.

To avoid uncertainties that poorly–determined (and possibly spurious) $P_{cy}$ values might introduce into the correlation studies, we restrict discussion to those stars which show FAP ≤ 10⁻⁶. We note that this is a considerably more restrictive criterion than has been used previously (e.g. Baliunas and Vaughan 1985), resulting in fewer (but more certain) measurements of cycle.
properties. Our FAP limit reduces the 99 star sample to 30 stars (5 F, 10 G, and 15 K stars). The limit biases the sample only slightly: if we measure activity using \( R'_{HK} \equiv F'_{HK}/a T_{eff}^4 \), where \( F'_{HK} \) is the Ca II HK surface flux with the photospheric contribution subtracted, Noyes et al. 1984a), the mean log \( R'_{HK} \) in the low FAP sample is (F: \(-4.76\), G: \(-4.74\), K: \(-4.76\)) compared with the whole survey averages of (F: \(-4.76\), G: \(-4.71\), K: \(-4.69\)). Some stars show two cycle periods with small FAP values (4 G and 5 K stars), generally showing a shorter \( P_{cy} \) for the larger FAP. These stars show no distinct activity differences with the full sample. We relaxed the FAP requirements on the secondary period to \( FAP_2 \leq 10^{-5} \); however, symbols are not plotted at the secondary \( P_{cy} \) if \( 10^{-6} \leq FAP_2 \leq 10^{-5} \). A number of the stars show \( P_{cy} \) close to the 25 year length of the record; their values should be treated with caution.

![Graphs showing Ca II S index behavior](image)

Fig. 1: Behavior of the Ca II S index with time for six inactive G8 – K2 dwarfs. Data after 1978 are monthly averages (from Baliunas 1992).

Following Baliunas and Vaughan (1985), we first searched for correlations between \( P_{cy} \) and individual stellar parameters related to the dynamo, such as convection zone depth (\( d \)), stellar radius (\( R \)), activity level (e.g. \( S, F'_{HK} \)), and rotation (e.g. \( P_{rot} \), Rossby number). No strong correlations are present (Figures 2 – 7). Here we have taken \( d \) from Copeland et al. (1970), \( R \) from Allen (1973), \( T_{eff} \) from Gray (1988), and \( P_{rot}, F'_{HK} \) and \( R'_{HK} \) from Noyes et al. (1984a). We also tested the use of residual Ca II flux, \( \Delta F_{HK} \), using the calibration of Rutten (1987) and the conversion factor of Schrijver et al. (1989). In practice, \( \Delta F_{HK} \) and \( F'_{HK} \) yielded similar results, so we focus on \( F'_{HK} \) hereafter.
Fig. 2: \( P_{\text{cyc}} \) vs. (B-V) color for stars with FAP \( \leq 10^{-6} \): F stars = triangles, G stars = diamonds, K stars = squares, unconnected open symbols have possible aliasing problems (\( P_{\text{cyc}} \) close to the 25 year length of the data record). Double period stars have their main and secondary \( P_{\text{cyc}} \) (open symbol) connected with dashed lines; no symbol is plotted \( 10^{-6} \leq \text{FAP}_2 \leq 10^{-5} \).

Fig. 3: \( P_{\text{cyc}} \) vs. \( d \); symbols as in Figure 2.

Fig. 4: \( P_{\text{cyc}} \) vs. \( S \) index; symbols as in Figure 2.

Fig. 5: \( P_{\text{cyc}} \) vs. \( F'_{HK} \) (in \( 10^6 \) ergs cm\(^{-2}\) s\(^{-1}\)); symbols as in Figure 2.
Figures 2 through 4 demonstrate no clear trends exist in \( P_{\text{cyc}} \) vs. (B-V), \( d \), or \( S \). Note that \( F \) stars no longer dominate low \( P_{\text{cyc}} \) (cf. Baliunas and Vaughan 1985); these stars generally have high FAP values and are not included here. If \( S \) is converted into a (background subtracted) surface flux, there is a decrease in the upper envelope of \( P_{\text{cyc}} \) with \( F_{\text{HK}} \) (Figure 5) if one ignores two possibly aliased \( P_{\text{cyc}} \) values. Normalized flux, \( R_{\text{HK}} \), does not show this trend as clearly. \( P_{\text{cyc}} \) appears to have a large range at short \( P_{\text{rot}} \) (Figure 6), the spread narrows for \( P_{\text{rot}} > 30 \) days. Noyes \textit{et al.} (1984b) found a relationship between \( P_{\text{cyc}} \) and Rossby number (\( R_o = P_{\text{rot}} / \tau_C \)), the ratio between rotational and convective turnover (\( \tau_C \)) timescales. However, their determination that \( P_{\text{cyc}} \propto R_o^{1.3} \), was made for a small subsample of 13 inactive stars with very clear periods spanning only 17 years of data. Most of their stars lie in the lower right corner of Figure 7, and still roughly describe a \( R_o^{1.3} \) relationship. The larger sample, however, belies this simple relation (Figure 7). Thus, clearly, no obvious trend appears to exist between \( P_{\text{cyc}} \) and any single stellar parameter. This result is generally consistent with previous analyses (Baliunas and Vaughan 1985, Soderblom and Baliunas 1988).

Fig. 6: \( P_{\text{cyc}} \) vs. \( P_{\text{rot}} \); symbols as in Figure 2.

Fig. 7: \( P_{\text{cyc}} \) vs. \( P_{\text{rot}} / \tau_C \); symbols as in Figure 2.

2.2 \( P_{\text{cyc}} \): Comparison with Simple Dynamo Theory
In the face of such weak correlations, it is reasonable to ask whether stellar cycles actually are magnetic in nature. Though much indirect evidence suggests that they are indeed magnetic, recently \textit{direct} evidence has been found (Saar and Baliunas 1992). Studies of the active G5 dwarf \( \kappa \) Ceti show a weak, positive correlation between measured magnetic flux (\( \Phi_M \)) and \( \Delta F_{\text{HK}} \) spanning four years (1984–1988) during a recent decline phase in the star’s cycle. A power law fit to the relation yielded \( \Delta F_{\text{HK}} \propto \Phi_M^{0.4} \), roughly consistent with correlations for active regions on the Sun (Schrijver \textit{et al.} 1989) and with correlations seen for individual “snapshot” measurements of stars (\( \Delta F_{\text{HK}} \propto \))
\(\Phi^9_M\), Saar 1991). Thus, for the Sun and \(\kappa\) Ceti, at least, the cycles in \(S\) do appear to be related to changes in magnetic fields.

As our searches for single-parameter correlations proved largely unsuccessful, we turned next to simple dynamo theory to investigate the possibility of more complex relationships between \(P_{cyg}\) and stellar properties. Mean field theories predict that two dimensionless numbers are important in governing the standard \(\alpha-\Omega\) dynamo: \(D_\alpha\), which characterizes the production of poloidal field through helicity generated by the interaction of rotation and convection (the \(\alpha\) effect); and \(D_\Omega\), which measures the generation of toroidal flux from the shearing of poloidal flux by differential rotation. These numbers are typically parameterized as \(D_\alpha = \alpha R/\eta_M\), and \(D_\Omega = \Omega' R^3/\eta_M\), where \(\alpha\) is related to the mean helicity, \(\eta_M\) is the magnetic diffusivity, and \(\Omega'\) is the differential rotation rate (e.g. Steenbeck and Krause 1969). If we take \(\alpha \sim dR\Omega_{rot} \), and \(\Omega' \sim \Omega_{rot} R\), we can construct an \(\alpha-\Omega\) dynamo number \(N_{\alpha\Omega} \equiv (D_\alpha D_\Omega)^{0.5} = d^{0.5}R^2\Omega_{rot}/\eta_M\) (Tuominen et al. 1988). When \(P_{cyg}\) is similarly normalized by the magnetic diffusion timescale, yielding \(\Omega^*_{cyg} \equiv R^2\Omega_{cyg}/\eta_M\), clear trends are seen with \(N_{\alpha\Omega}\) (Figure 8). Here, we have taken \(\eta_M\) from Belvedere et al. (1980), assuming it is equal to the turbulent diffusivity. A somewhat similar diagram can be obtained plotting \(\Omega^*_{cyg}\) vs. \(\tau_{C\Omega_{rot}}\) (Figure 9), although some stars are scattered off the tracks to high values of \(\tau_{C\Omega_{rot}}\) and the trends are less distinct. Unfortunately, too few stars in our low FAP sample have direct magnetic flux measurements (e.g. Saar 1990) to look for correlations between, for example, \(\Omega^*_{cyg}\) and \(\Phi^9_M\).

**Fig. 8:** \(\Omega^*_{cyg} \equiv R^2\Omega_{cyg}/\eta_M\) vs. \(\alpha-\Omega\) dynamo number \(N_{\alpha\Omega}\). Symbols are as in Figure 2, with “active” and “inactive” tracks indicated by long dashed lines. Note the apparent evolution from lower right (highly active) to upper left (inactive).

Two tracks can be seen in the \(\Omega^*_{cyg}\) vs. \(N_{\alpha\Omega}\) diagram. The upper track, given by \(\Omega^*_{cyg} \propto N_{\alpha\Omega}^{1.6}\), is composed of old, relatively inactive stars (5 G and 11 K dwarfs) such as the Sun, HD 81809, HD 4628 and HD 201091 (mean...
log $R'_{HK} = -4.95$ [G] and $-4.88$ [K]). Most of the Noyes et al. (1984b) sample belongs to this group. Stars in the lower track (3 F, 4 G, and 4 K stars, tracing $\Omega_{cyc} \propto N_\alpha \Omega^{1.3}$) are all more active, probably younger stars such as HD 154417, HD 152391, and HD 115404, with mean log $R'_{HK} = (F: -4.81; G: -4.63; K: -4.54)$. Three stars lie below the tracks: these are still more active (mean log $R'_{HK} = -4.61$) and one (HD 39587) is a member of the UMa stream (age $\approx 0.7$ Gyr). Thus the tracks seem to indicate a progression from young, active stars at high $N_\alpha \Omega$ and low $\Omega_{cyc}$ to old, inactive stars at low $N_\alpha \Omega$ and high $\Omega_{cyc}$. (In retrospect, these trends may be vaguely discerned in Figure 6 as an inactive locus with $P_{cyc} \approx 0.25 \times P_{rot}$, and an active locus with $P_{cyc} \approx P_{rot}$.) Active stars in the lower track with two cycle periods often show their second, shorter $P_{cyc}$ at or near the upper track. Perhaps these stars are transitional between the two branches. The tracks themselves may indicate different dynamo modes excited at certain $\Omega_{rot}$ rates (Robinson and Durney 1982), or transitions between different forms of convection (e.g. Knobloch et al. 1981). Thus, we see the first evidence for the evolution of stellar dynamos with rotation and time.

Dynamo theory, however, predicts a linear relation between $\Omega_{cyc}$ and $N_\alpha \Omega$. The non-linearity of the observed relations may indicate that the stellar dynamo in cool stars is more complex than the simple model we have tested here, or that the mechanism is actually different, e.g. an $\alpha^2 \Omega$ dynamo. A second clue that simple dynamo theory is not complete is seen in the correlation between $P_{cyc}/P_{rot}$ and $d$. The theory predicts $P_{cyc}/P_{rot} \propto d^{-0.5}$ (e.g. Tuominen et al. 1988); the observed relation is best fit by $P_{cyc}/P_{rot} \propto d^{-3.4}$ (Figure 10).

Fig. 9: $\Omega_{cyc}$ vs. $\tau_C \Omega_{rot}$; symbols as in Figure 2.

Fig. 10: $P_{cyc}/P_{rot}$ vs. $d$; symbols as in Figure 2.

We caution that there is considerable uncertainty about our estimates of $N_\alpha \Omega$. The approximation $\Omega' \sim \Omega_{rot}/R$ is only dimensionally correct; as yet, there is not enough reliable data on stellar $\Omega'$ values for single dwarfs.
to define the correct relationship. Data from RS CVn and BY Dra binaries actually indicate an inverse trend (i.e. $\Omega' \sim \Omega_{\text{rot}}^{-1}$; Hall 1991), but this is probably caused by the effects of tidal forcing. Some indications of differential rotation exist in the Mount Wilson data – primarily multiple rotation rates which evolve in time (Figure 11) – but these are as yet few in number and only set lower limits on $\Omega'$ (Baliunas et al. 1985, Donahue and Baliunas 1992b). Several of these $\Omega'$ detections exhibit trends quite unlike the Sun, with amplitudes $\Delta P_{\text{rot}}/P_{\text{rot}}$ of as much as 21% (Baliunas et al. 1985) and latitudinal dependences the reverse of the solar case (e.g. Figure 11). Values for the magnetic diffusivities are also quite uncertain. It is likely, for example, that $\eta_M$ is a function of magnetic filling factor or $\Phi_M$, and thus is a (probably non-linear) function of $\Omega_{\text{rot}}$ (e.g. Brandenburg et al. 1990). One must also keep in mind that with only 25 years of data, $P_{\text{cyc}}$ is not accurately determined for most of the stars; tests of $P_{\text{cyc}}$ accuracy by analyzing arbitrary 20 year time spans of solar data, for example, yielded periods between 9 and 13 years (Gilliland and Baliunas 1987, Donahue and Baliunas 1992a).

Fig. 11: Average yearly $P_{\text{rot}}$ seen in HD 114710 (G0V) as a function of $S$. Two loci of periods are seen: the upper locus appears to evolve in phase with the activity cycle – evidence for differential rotation – while the lower track at a constant $P_{\text{rot}}$ is perhaps caused by a long-lived equatorial activity band. Note that the Sun’s $\Omega'$ track is similar to the upper locus, but evolves with activity cycle phase in the opposite direction (i.e. left to right) – suggesting HD 114710 may have poleward $\Omega_{\text{rot}}$ acceleration, the reverse of the solar case (from Donahue and Baliunas 1992b).

2.3 $A_{\text{cyc}}$: General Trends and Correlations with Stellar Parameters
The amplitude of cycle variations is also an important dynamo parameter. One measure of this is the fractional cycle amplitude: $A_{\text{cyc}} \equiv \Delta F_{HK,cyc}/F_{HK}$. 

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where $\Delta F_{HK,cyc}$ is the amplitude, expressed as a surface flux, of a sinusoidal fit to the Ca II data (period $= P_{cyc}$). Taking the Sun as a guide, $A_{cyc,0}$ varies significantly from cycle to cycle and may even disappear in “Maunder minima”, which according to radiocarbon data, occur $\approx 1/3$ of the time (Damon 1977). Thus, considerable dispersion is expected in stellar $A_{cyc}$ relations. In practice, several interesting trends are seen, generally in upper limits to $A_{cyc}$ as a function of some stellar property. For example, the maximum $A_{cyc}$ appears to increase with (B-V) up to a plateau around (B-V) $\approx 0.9$ (K2V), thereafter $A_{cyc,max}$ may decline (Figure 12). $A_{cyc,max}$ varies similarly with $d$ (Figure 13), suggesting that stars with deeper convection zones can show larger scale inhomogeneities (e.g. Giampapa and Rosner 1984), stronger cycles, and more significantly non-axisymmetric dynamos (e.g. Moss et al. 1991), at least up to some critical $d$. $A_{cyc,max}$ also shows decreases with $S, F'_{HK}$, and $R'_{HK}$ (Figure 14), perhaps because the larger magnetic region coverage on active stars inhibits significant inhomogeneities (and hence large $A_{cyc}$). Alternatively, the more rapid rotation and larger $\Phi_M$ on active stars may actually suppress the dynamo through the $\Lambda$-effect (e.g. Kichatinov 1988). Consistent with these ideas, $A_{cyc,max}$ increases with $P_{rot}$ and $P_{rot}/\tau_C$ (i.e. decreasing activity; Figure 15).

Fig. 12: $A_{cyc}$ ($\equiv \Delta F_{HK,cyc}/\langle F_{HK} \rangle$) vs. (B-V) color; symbols as in Figure 2.

Fig. 13: $A_{cyc}$ vs. $d$; symbols as in Figure 2.

There is no clear relation between $A_{cyc}$ and $P_{cyc}$, however (Figure 16). Instead, we find that $A_{cyc}$ correlates with the normalized cycle frequency, $\Omega_{cyc}$, with the best fit given by $A_{cyc} \propto \Omega_{cyc}^{-2/3}$ (Figure 17). This may be the result of more non-linear behavior (and correspondingly larger $A_{cyc}$) being excited at high $\Omega_{cyc}$. The success of $\Omega_{cyc}$ in defining relationships with both $N_0\Omega$ (Figure 8) and $A_{cyc}$ (Figure 17) implies that it is an important parameter for understanding cool star dynamos.
Fig. 14: $A_{cyc}$ vs. $F_{HK}$ (in $10^6$ ergs cm$^{-2}$ s$^{-1}$); symbols as in Figure 2.

Fig. 15: $A_{cyc}$ vs. $P_{rot}$; symbols as in Figure 2.

Fig. 16: $A_{cyc}$ vs. $P_{cyc}$; symbols as in Figure 2.

Fig. 17: $A_{cyc}$ vs. $\Omega_{cyc}$; symbols as in Figure 2.

2.4 Evidence for "Maunder Minima" on Other Stars

The distribution of the variation of $S$ with time is also of interest in probing the nature of the underlying magnetic dynamo. Such distributions can be used to infer long-term (centuries to millenia) magnetic behavior. Baliunas and Jastrow (1990) gathered $S$ values for a group of 74 dwarfs, solar-like in both color ($0.60 \leq (B-V) \leq 0.76; \approx G1V - G8V$) and age, or equivalently, activity ($0.13 \leq \langle S \rangle \leq 0.20$), from the combined Wilson and solar neighborhood surveys (Vaughan and Preston 1980). When $S$ is binned in 0.1 year averages,
the resulting distribution shows an intriguing two-part structure: a broad
distribution for $S > 0.15$, separated by a sharp gap from a narrowly peaked
distribution for $S < 0.15$ (Figure 18). Stars in the higher-$S$ group have
generally solar-like cycles, and the broad distribution traces the stars’ cyclic
$S$ variations. Stars below the gap have no cycles, and lie at the minimum $S$
levels for their spectral types. Baliunas and Vaughan (1985) proposed that
one of these stars (HD 10700; Figure 1) may be in the stellar equivalent of a
“Maunder minimum” – a period when cyclic dynamo variation temporarily
ceases (or is considerably reduced). Baliunas and Jastrow (1990) find that
roughly 30% of solar-like dwarfs are in the analog of a “Maunder minimum”
state, in agreement with the solar behavior inferred from radiocarbon records
(Damon 1977). Further support for this idea comes from observations of HD
3651, a slowly rotating ($P_{\text{rot}} = 48$ days) K0 dwarf, which showed $P_{\text{cyc}} \approx 12.3$
years before 1979, after which time the star’s $S$ dropped to the lowest levels
seen to date, and the cycle amplitude practically vanished (Figure 1; $S$ should
have begun to rise again in $\approx 1988$ if the star had remained cyclic). This
behavior is suggestive of a star entering a “Maunder minimum”-like state
(Baliunas 1992). Overall, 10–15% of the entire Mount Wilson sample show
such diminished, non-varying Ca II levels, concentrated mostly in the old (i.e.
relatively low $S$, low $P_{\text{rot}}$) G and F stars.

![Frequency distribution of the $S$ index (0.1 year averages) for inactive ($0.13 \leq \langle S \rangle \leq 0.20$) solar-like ($0.60 \leq (B-V) \leq 0.76$) dwarfs (from Baliunas and Jastrow 1990).](image)

The “Maunder minimum” state does not, however, imply that all
magnetic activity has ceased. Just as a few spots were seen on the Sun during
this period, stars in “Maunder minima” do show some signs of residual
activity. While calibration of Ca II fluxes in terms of magnetic activity
is problematic, especially at low $S$, due to the need to subtract a (often
dominant) photospheric component, and possible contribution due to non-magnetic sources (Schrijver et al. 1990), ultraviolet emission from the transition region is less ambiguous. Recent IUE measurements of "Maunder minimum" stars (Baliunas et al. 1992) show weak C IV lines (Figure 19), indicating that some magnetic activity (e.g. active network or a few weak plages) may still remain.

![Graphs showing UV emission from stars.](image)

Fig. 19: Far UV emission from four inactive stars: one with cyclic behavior (HD 141004) and three stars in "Maunder minima". Two of the "Maunder minimum" stars show emission at C IV (1550 Å) like HD 141004, indicating the likely presence of residual magnetic activity (from Baliunas et al. 1992).

Another important clue about the nature of stellar dynamos comes from Ca II observations of giant stars in the Hyades and Praesepe clusters started in 1983 (Baliunas et al. 1991). The data show that Ca II cycles in these coeval giants have some interesting similarities with those in dwarfs. A group of four nearly identical giants in the Hyades (θ¹, γ, δ, and ε Tau), for example, show a large range of mean S and cycle behavior (Figure 20). One star, ε Tau, appears to be in a low S, non-cyclic state, again reminiscent of "Maunder minimum"-like behavior. This combined with the clear cycles seen in the other stars suggests that giants have dynamo cycles surprisingly like dwarf stars: a range in behavior at a given age; P_{cyc} and A_{cyc} similar to dwarf stars; and a similar fraction of stars in "Maunder minima" states, despite the lack of conventional magnetic activity in their main sequence progenitors (early A dwarfs).
Fig. 20: $S$ vs. time for four nearly identical Hyades giants (from Baliunas et al. 1991), showing rotation ($P_{\text{rot}} \approx 120$ days) and a wide range of cycle morphologies: from strongly cyclic ($\gamma$ Tau) to "Maunder minimum"-like states ($\epsilon$ Tau).

2.5 Other Characteristics of Stellar Cycles
The combination of photometry (sensitive to the disk intergrated sum of dark spot and bright plage/network areas) and Ca II emission (sensitive to magnetic activity from any source) offers another probe of cyclic behavior. As this topic is reviewed in much more detail elsewhere (Radick et al. 1989, Radick 1992), we only briefly summarize it here. Older, inactive stars like the Sun tend to show a positive correlation between changes in chromospheric emission (e.g. $\Delta S/(S)$) and photometric changes: i.e. as the star becomes more active, it becomes brighter. (For the Sun, this was actually confirmed recently using ACRIM data; Wolff and Hickey 1987, Willson and Hudson 1988.) This positive correlation arises because, although more dark spots are produced as the star progresses through its cycle, an even larger fraction of bright plage and active network is produced, leading to a net positive increase in the star's brightness (e.g. Foukal and Lean 1988). The opposite is true for an active star (Figure 21). Here, a larger ratio of spot to plage appears to be produced, and the net result is that as the star becomes more active, it grows fainter, yielding a negative correlation between $\Delta S/(S)$ and brightness. The very rapid "turn-on" of significant photometric variability as a function of rotation (e.g. Hall 1991) – much quicker than the smooth change in $F_{HK}$ with $\Omega_{\text{rot}}$ (e.g. Noyes et al. 1984a) – clearly mirrors this effect. In extreme cases (e.g. Saar et al. 1990), there is sometimes no significant change in activity with time, yet a clear photometric cycle can remain. Perhaps these stars have reached a
“saturated” magnetic state, wherein changes in the dynamo phase merely shift plage into spot and back again. Frequent flaring and multiple active region growth and decay may further confuse the $P_{cyc}$ signal in Ca II in very active stars (Baliunas 1991).

Another new development in cycle research is the observation of line asymmetry changes over a cycle in both the Sun (Livingston 1991) and stars (Gray 1992). Sharp drops in the magnitude of the asymmetries, and by inference, sharp changes in the surface convective properties, were noted at certain points in the stellar cycle. Presumably, the variations are due to the cyclic changes in the magnetic flux, which affects the convective patterns (and hence the line shapes) by suppressing convective flows. In the Sun, the largest line asymmetries are observed when the magnetic flux and luminosity are lowest. Similarly, maximum asymmetries in the inactive K0 dwarf $\sigma$ Dra also appear when $T_{eff}$ is lowest. In contrast, the active K2 dwarf $\epsilon$ Eri exhibits the largest asymmetries when its $T_{eff}$ is highest. We propose the following explanation: asymmetries are anti-correlated with $T_{eff}$ in the Sun and $\sigma$ Dra because magnetic flux is greatest (and convection suppressed) when the surface coverage of bright plage (and thus $T_{eff}$) is at a maximum. The more active $\epsilon$ Eri has a larger spot-to-plage ratio; asymmetries are therefore correlated with $T_{eff}$ because here, when $\Phi_{M}$ is highest, $T_{eff}$ is at a minimum due to the large spot filling factor. This explanation neatly ties the asymmetry work in with the photometry results (e.g. Radick et al. 1989), and suggests that stellar dynamos actually affect cyclic changes in the surface convective properties of stars. Further monitoring of line asymmetries would clearly be useful.

![Fig. 21: $S$ index vs. change in visible magnitude for two stars during the course of their activity cycles. The more active star (HD 152391; G8V) shows $S$ anticorrelated with brightness, while the inactive star (HD 76572; F3V) shows a positive correlation, like the Sun (from Radick et al. 1989).]
A final clue on the nature of stellar dynamos is the growing evidence that very active, rapidly rotating stars (including those not in tidally locked systems) show significant activity and spots even at high latitudes. The regions are also often long-lived, implying significantly non-axisymmetric magnetic flux generation. The evidence arises from analyses as diverse as photometry (e.g. Rodonò et al. 1986, Jetsu et al. 1990, Zeilik 1991), Doppler imaging studies (Vogt 1988, Piskunov et al. 1990), and analysis of the (anomalously strong) molecular bands of the pole-on BY Dra BD +26° 730 (Saar and Neff 1990). Magnetic surface imaging of the active, single K2 dwarf HD 82558 explicitly associates high latitude cool regions with areas of strong magnetic flux (Saar et al. 1992). While these results are not inconsistent with dynamo theory, as some models reproduce poleward spot migration (e.g. Gilman 1983) and non-axisymmetric field distributions (Moss et al. 1991), it certainly indicates the situations on rapidly rotating stars may differ considerably from our quieter Sun.

3. SUMMARY

We find that the majority of lower main sequence stars show roughly periodic activity cycles, with the exception of a few with non-varying records (perhaps analogous to the Sun’s behavior in the “Maunder minimum”), and a few stars which appear to vary on longer timescales with no obvious periodicity. Stars in “Maunder minima” appear to retain some residual magnetic activity. Many young, active stars have poorly defined cycles, as their cycle amplitudes are swamped by other sources of variability. Coeval giants in the Hyades and Praesepe clusters show cycle periods, amplitudes, and “Maunder minima” similar to old dwarf stars, suggesting that their dynamos may be similar in many respects. Although considerable differences in physical properties exist between dwarfs and giants, the observation of similar dynamo behavior may be an important clue to how the dynamo actually operates in these stars.

For a subset of stars with well-determined (FAP \( \leq 10^{-6} \)), periodic cycles, no single stellar parameter predicts \( P_{\text{cyc}} \). However, if the cycle frequency is normalized to the magnetic diffusion timescale (\( \Omega_{\text{cyc}} \)), and compared to \( N_{\alpha\Omega} \) (the \( \alpha-\Omega \) dynamo number), correlations do appear, though not those expected from simple dynamo theory. The relationship between \( \Omega_{\text{cyc}}^{*} \) and \( N_{\alpha\Omega} \) appears to depend on activity level (or equivalently, age), which may indicate an evolution from high \( N_{\alpha\Omega} \) and low \( \Omega_{\text{cyc}}^{*} \) to low \( N_{\alpha\Omega} \) and high \( \Omega_{\text{cyc}}^{*} \).

The fractional amplitude of the cycle, \( A_{\text{cyc}} \), appears to have an upper envelope which increases with \( d \) (at least to \( \sim K2V \)), which we interpret as the result of deeper convection zones permitting formation of larger scale inhomogeneities. \( A_{\text{cyc}} \) also increases with increasing \( P_{\text{rot}} \) and decreasing activity. It is possible that the increased plage coverage on active stars prevents significant inhomogeneities from developing, or perhaps, as some theories predict, rapid rotation suppresses the dynamo. \( A_{\text{cyc}} \) is also correlated with \( \Omega_{\text{cyc}}^{*} \), suggesting that non-linear effects at large \( \Omega_{\text{cyc}}^{*} \) may increase \( A_{\text{cyc}} \). The correlation of \( \Omega_{\text{cyc}}^{*} \) with both \( N_{\alpha\Omega} \) and \( \Omega_{\text{cyc}}^{*} \) implies that it may be an important parameter for understanding dynamo behavior.

Fragmentary evidence suggests that stellar differential rotation can differ significantly from the Sun in both form and amplitude. Dynamo production
of spots increases rapidly with activity level, eventually reversing the positive correlation of brightness and Ca II variations seen on the Sun once spots begin to dominate the light changes. Further increases in activity eventually erase the brightness–Ca II correlation altogether, as spot areas grow but the Ca II emission “saturates”. Very active stars also appear to form more spots at high latitude. Finally, even the surface convective properties appear to change during the dynamo cycle, though the sense of the change depends on the activity level of the star.

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REFERENCES

Giammappa and J. Bookbinder, in press.
Hartmann, L. W. Bopp, B. W., Dussault, M., Noah, P. V., and Klimke, A.
Hall, D. S. 1991, in *The Sun and Cool Stars: Activity, Magnetism, Dynamos*
IAU Colloquium 130, eds. I. Tuominen, D. Moss, G. Rüdiger, Springer,
p. 353.
Jetsu, L., Huovelin, J., Tuominen, I., Vilhu, O., Bopp, B. W., and Piirila, V.
IAU Colloquium 130, eds. I. Tuominen, D. Moss, G. Rüdiger, Springer,
p. 246.
Noyes, R. W., Hartmann, L., Baliunas, S. L., Duncan, D. K., and Vaughan,
Saar, S.H. and Baliunas, S. L. 1992, these Proceedings.

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