THE TIME EVOLUTION OF MAGNETIC FLUX, DYNAMOS, AND SURFACE STRUCTURES ON COOL DWARFS

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ABSTRACT I briefly summarize recent observations related to the time evolution of magnetic flux, associated surface features (spots and network/plage), and the dynamo mechanism which produces them.

INTRODUCTION

A diverse group of observations and analyses of CaII fluxes, photometry, Doppler images, and absorption line broadening are beginning to build up a picture of how the surfaces of solar-like stars evolve in time. In this review, I briefly describe some of these recent studies and their implications concerning the time history of magnetic flux, the dynamo which produces it, and the surface structures which are its visible manifestations. I will focus mostly on F to K dwarfs of Pleiades age \((t \approx 7 \times 10^7 \text{ years})\) and older. Further details can be found in other recent reviews by Baliunas (1991), Radick (1991), Saar & Baliunas (1992a), Radick (1992) and Saar (1994a).

TIME EVOLUTION OF MAGNETIC FLUX

The most straightforward way to study the time evolution of magnetic flux on cool stars is through direct measurements. This is unfortunately a difficult task (e.g., Saar 1990) fraught with insidious sources of systematic error (e.g., Marcy 1984; Gray 1988; Saar 1988; Basri et al. 1990, 1992; Saar & Solanki 1992; Saar, Bünte, & Solanki 1994 = SBS). In particular, the most recent measurements using improved models and better data indicate that previous measurements may have overestimated the magnetic flux density \(fB\), where \(B\) is the mean field strength in bright active regions (AR), and \(f\) is the area filling factor of these regions (see SBS, Linsky et al., Valenti et al., and Ruedi et al., all in this volume). There is likely a systematic trend in the errors if the magnetic regions are warm (plage/network-like), such that \(fB\) is underestimated for G dwarfs and overestimated for late K dwarfs (Solanki 1992). Because of these problems, and the basic difficulties in obtaining the high resolution, high S/N data required, relatively few high quality measurements of magnetic parameters are available. Multiline analyses and IR measurements will help in the future (see Valenti et al. and Ruedi et al., this volume), but the difficulty in correctly interpreting line modelling results for an unresolved, multicomponent, inhomogeneous, magnetic tube riddled atmosphere remains (true even for the Sun, see e.g., Solanki 1992).
FIGURE I  Magnetic flux density $fB$ versus age $t$ for dwarfs; G, K stars and the sun are denoted by $\Diamond$, $\Box$ and $\odot$, respectively, large symbols are cluster stars (best determined $t$), crossed symbols indicate better $fB$ data (1990 or later), dotted lines connect different measurements of the same star. The fit (solid) is $fB = 750 \times e^{-t}$ ($t$ in Gyr).

Despite these problems, it is still instructive to explore trends between $f$, $B$, and stellar parameters such as age, $t$. Here I update previous studies of these relations by including new measurements since mid-1991 (Saar et al. 1992; Saar 1994b; Saar, Piskunov, & Tuominen 1994 = SPT94; and Linsky et al., Valenti et al., and Ruedi et al., this volume) Magnetic measurements after about 1990 are likely more accurate, owing to the adoption of more realistic treatments of radiative transfer and/or disk integration around this date. Also, since only a few stars with $fB$ data have well determined ages (e.g., from cluster membership), I expand the sample by using ages estimated from the statistical $R'_{HK}-t$ relation of Donahue (1993), an improved version of the Soderblom et al. (1991) calibration ($R'_{HK} = F_{HK}/\sigma T_{\text{eff}}^4$, the normalized Ca II HK flux with photospheric background subtracted).

The results show a sharp decrease in $fB$ after about 1 Gyr (Fig. I). Scatter is large however, in part due to the different modeling techniques used, systematic errors, and intrinsic $fB$ variations. The general trend can be fit with an exponential relation $fB \approx 750 \times e^{-t}$ G, where $t$ is in Gyr. One star (GL 171.2A) deviates with unusually large $fB$ for its age, but since it is a tidally locked binary, its period ($\sim 1.8$ days) is much less than a typical single K5V Hyades member (and more like a much younger star). There is no clear spectral type dependence in the relation—somewhat surprising in view of the apparent spectral type dependence of the maximum observed $B$, $B_{\text{max}} \propto P_{\text{gas}}^{0.5}$, (where $P_{\text{gas}}$ is the photospheric gas pressure; e.g., Saar 1991).

Since $B$ is independent of $t$ for this sample, one can infer that it is primarily the AR area which changes in time. This is confirmed by comparing $f$ with $Ro^{-1} = \tau_C/P_{\text{rot}}$, where $\tau_C$ is the convective turnover time (Fig. II). A non-linear relationship is evident, with saturation for $Ro^{-1} \gtrsim 3$. The relationship can be fit by an exponential relation $f \approx 0.7 \times 10^{-Ro}$ (cf. Stepień 1988; Montesinos & Jordan 1993) or a power-law + saturation defined by $f \approx 0.06 Ro^{-2}$, for $Ro^{-1} \leq$
FIGURE II  Magnetic filling factor \( f \) versus inverse Rossby number \( \Ro^{-1} = \tau_c / \Pr \) for dwarfs; G, K, and M stars and the sun are denoted by \( \diamond \), \( \square \), \( \triangle \) and \( \bigcirc \), respectively; better \( fB \) data are thicker symbols, multiple measurements are connected. Fits for \( f \propto 10^{-\Ro} \) (solid) and \( f \propto \Ro^{-2} \) plus a saturated state (dashed) are shown.

3 and \( f = 0.65 \) for \( \Ro^{-1} > 3 \). Thus, magnetic flux decreases with time in cool stars due largely to a corresponding decrease in \( f \) with time.

It is important to note that these \( fB \) measurements refer primarily to active areas analogous to solar plage and network; spots are dark in the continuum and contribute little to the \( f \) inferred from optical spectra (see, however, Ruedi et al., this volume). Even magnetic Doppler images (e.g., Donati et al. 1990; Saar et al. 1992) are likely misleading when they ascribe minimal \( fB \) to cool areas because of systematic effects in the inversion, and some trade-offs between \( fB \) and local \( T_{\text{eff}} \) (SPT94). Thus, the while the magnetic data indicate that the coverage of plage saturates at around \( \Ro^{-1} \approx 3 \), it says little or nothing about spot area, \( f_s \). From photometric studies (see below), it appears that \( f_s \) continues to increase for larger \( \Ro^{-1} \) (Hall 1991). Dynamo production of magnetic flux therefore does not saturate at \( \Ro^{-1} \approx 3 \), rather, its surface manifestation changes (yielding more spots than plage). This is also seen in the long-term cyclic behavior of GL 171.2A (=BD +26°730; \( \Ro^{-1} \approx 10 \)), which shows little \( fB \) change in time (Saar et al. 1990, and more recent measurements) despite significant photometric variation (Hartmann et al. 1981). Since Figure I only describes the plage/network component of flux, it is possible that the total \( fB \) (including spot fields) continues to increase in young stars. Indeed, it is also possible that \( B > B_{\text{max}} \) for very active stars (Solanki, this volume), consistent with fields seen in some active RS CVn stars (e.g., Bopp et al. 1989). Since the chromosphere and corona over spots are relatively dark (Sams et al. 1992), however, this increase in total \( fB \) can still be consistent with the observed saturation in outer atmospheric heating (e.g., Vilhu 1984).
TIME EVOLUTION OF MAGNETIC DYNAMOS

Morphology of Dynamo Variations
One can also indirectly study the evolution of the dynamo mechanism itself. Cycles seen in Ca II are indeed related to magnetic fields, as demonstrated by the decrease in both mean Ca II flux and $fB$ during the declining phase of a cycle on κ Ceti (Saar & Baliunas 1992b). Due to the scarcity of $fB$ data, though, we must turn to proxies for magnetic field generation such as chromospheric emission (a measure of plage/active network area) or photometry (primarily a measure of spot area). Probably the most significant dataset for this purpose comes from the Mount Wilson Ca II monitoring program, which has followed the chromospheric Ca II H+K flux variations of $\approx 100$ F, G, and K dwarfs since 1966. In the first analysis of the results Wilson (1978) already noted that the stars could be broadly grouped into stars with irregular Ca II variations, stars with cyclic variations, and stars with constant $F_{HK}^\prime$. More active, presumably younger stars fell primarily into the first group, while older stars tended to be cyclic or non-variable. A few of the cyclic variables show evidence for a second, lower amplitude cycle in addition to the primary cycle; these stars appear to be the most active, and hence presumably youngest of the cyclic stars (e.g., Baliunas & Vaughan 1985). The non-variable stars tend to have the lowest $F_{HK}^\prime$ at a given spectral type. This, plus the similarity of the abundance of such stars ($\approx 30\%$ of G stars in the solar neighborhood sample) with the fraction of time which the Sun is in a Maunder minimum-like state (MM-like) led Baliunas & Jastrow (1990) to postulate that many of the stars with steady $F_{HK}^\prime$ are in similar, temporarily quiescent dynamo states. Indeed, one star (HD 3651) appears to have been currently entering a MM-like condition.

Using the same statistical Ca II flux - age relation employed in section 2, Saar et al. (1994, this volume) assigned approximate ages to the Mount Wilson stars and investigated the evolution of dynamo morphology with mass and $t$. They confirm that the youngest stars are nearly all irregular variables, and find that cyclic variability begins earlier with decreasing mass, starting at log(t) $\approx 8.8$ in G and K stars, but log(t) $\approx 9.3$ in F stars. Stars with two cycle periods occupy the border region (at $t \approx 1$ Gyr) between irregular and cyclic variables. Assuming the constant stars are in MM-like states, these inactive periods begin to appear at roughly constant age ($\approx 3$ Gyr), independent of mass. The sharp decrease in the number of MM-like stars as $T_{eff}$ decreases suggests that the frequency and/or duration of Maunder-like minima decreases as a function of convection zone depth, $d$. In contrast, cycles are much more frequent in K stars than in F stars (though the small cycle amplitudes $A_{cyc}$ in the latter may affect their detectability somewhat). There also appears to be an age range around log(t) $\approx 9 - 9.5$ when G and K stars can show irregular, multicyclic, or cyclic behavior, but not Maunder minima. In general, the RMS amplitude of the variability (irregular or cyclic) increases with increasing $d$ (Saar & Baliunas 1992a = SB92a).

Fewer late-type dwarfs have published long-term photometric records: the Hyades K5 dwarf binary BD +26° 730 shows a 60 year photometric cycle (Hartmann et al. 1981), and BY Dra shows a 50 year period (Phillips & Hartmann 1978) with a possible weak 8 year secondary cycle (Cutispoto & Rodonó 1992). Both of these stars, however, are close binaries, and thus have important tidal
forces which may make their dynamo properties not directly comparable to the main sample. In particular, their differential rotation rates may be close to zero, making their cycles difficult to even explain for many simple dynamo models. As a cautionary note, though, the detection of a photometric cycle on BD +26° 730 demonstrates that the morphology of dynamo variations can look quite different depending on the dynamo proxy used. BD +26° 730, despite its clear spot cycle, shows only chaotic variability in Hα and UV emission (Saar et al. 1990). In the younger stars, photometry (sensitive to starspots) may be the only proxy to “see” a cycle, since emission in the outer atmosphere is saturated and/or confused by frequent flares and AR growth and decay.

Period and Amplitude of Cyclic Dynamos
One of the major tests of a dynamo theory is its ability to correctly predict the cycle period \( P_{\text{cyc}} \) and amplitude (as measured, for example, by \( A_{\text{cyc}} = \Delta F_{\text{HK}}/F'_{\text{HK}} \)) for a range of stars. Noyes et al. (1984) found a relationship between \( P_{\text{cyc}} \) and \( P_{\text{rot}} \) for slowly rotating, older stars for the limited \( P_{\text{cyc}} \) data then available. With the more recent analysis of the first 25 years of Mount Wilson data (Baliunas et al. 1994), better \( P_{\text{cyc}} \) and \( A_{\text{cyc}} \) values can be used to search for correlations with stellar parameters. Simple plots of \( P_{\text{cyc}} \) versus \( P_{\text{rot}} \) show considerable scatter; if one requires that the probability is small \( (\lt 10^{-5}) \) that a given \( P_{\text{cyc}} \) is a false detection, a weak trend of increasing \( P_{\text{cyc}} \) with \( P_{\text{rot}} \) can be seen for older stars (SB92a; their Fig. 6). Much tighter relations can be seen if \( P_{\text{cyc}} \) and \( P_{\text{rot}} \) are also normalized to a theoretical magnetic diffusion timescale (SB92a; their Fig. 8) or \( \tau_{C} \) (Saar 1994a; his Fig. 8). In both cases, inactive/old and active/young stars resolve to two nearly parallel tracks. When the theoretical \( \tau_{C} \) is used, both tracks can be fit with \( \tau_{C}/P_{\text{cyc}} \propto \text{Ro}^{-1.3} \). Interestingly, this is nearly the same power law as is found between differential rotation and \( P_{\text{rot}} \) (see below), suggesting a possible connection \( P_{\text{cyc}} \propto \Delta P \), where \( \Delta P \) is the range of rotation rates on a given star (Saar 1994a). The separation into two branches immediately implies a transition takes place in the dynamo mechanism at some point. Several of the multi-cyclic stars display a point on each branch; they may represent stars in a transitional phase. Furthermore, since \( \text{Ro}^{-1} \) can be approximately related to \( t \), the \( P_{\text{cyc}} - \text{Ro}^{-1} \) relation implies evolution along the branches as well. Soon et al. (1993) take a slightly different approach and study the quantity \( (P_{\text{cyc}}/P_{\text{rot}})^2 \), which is proportional to the dynamo number. They find that \( (P_{\text{cyc}}/P_{\text{rot}})^2 \) increases with decreasing \( T_{\text{eff}} \) (increasing \( d \)), and exhibits a definite age dependence in older stars. They also note a separation between old and young stars, and estimate that the transition between the branches occurs between 1 and 3 Gyr.

The maximum cycle amplitude observed increases with decreasing \( d \), at least until mid-K stars (SB92a; their Figs. 12 and 13). This is consistent with stars with deeper convection zones exhibiting larger spatial inhomogeneities on their surfaces (Giampapa & Rosner 1984). \( A_{\text{cyc}} \) also increases with \( P_{\text{rot}} \) (SB92a; their Fig. 15), though with considerable scatter. The upper envelope of the \( A_{\text{cyc}} \) versus \( F'_{\text{HK}} \) shows a sharp peak at low \( F'_{\text{HK}} \) with a long tail, perhaps because cycles in the more active, younger stars with larger \( f \) cannot achieve the degree of spatial inhomogeneity needed for large \( A_{\text{cyc}} \) that less active stars can muster (SB92a; their Fig. 14).
TIME EVOLUTION OF MAGNETIC SURFACE STRUCTURES

Spots and Plages
Lowell observatory has undertaken photometric coverage of 33 field dwarfs and 13 Hyades dwarfs in tandem with Mount Wilson Ca II measurements (Radick et al. 1987, 1989; Radick 1992). When these data are combined with the Ca II timeseries, an interesting pattern of correlations results (Radick et al. 1989; Radick 1992): stars with log \( R'_{\text{HK}} \gtrsim -4.6 \) grow darker with increasing cycle activity, while less active stars, like the sun, grow brighter with increasing cycle activity (see Radick 1992; his Fig. 3). This can be understood in the context of the non-linear increase of photometric amplitude with \( R'_{\text{HK}} \) (Radick et al. 1989) — spot area increases faster than the plage area as a function of activity. Thus, while cycle-related brightness changes are dominated by bright plage in the sun and inactive stars, spots dominate photometric variations in cool stars and thus the sign of the brightness - activity relation is reversed. The change appears to take place at roughly Hyades age in early G stars and somewhat later (\( \sim 2 \) Gyr) in K stars. The photometric amplitude increases sharply for \( R_{\text{HK}}^{-1} \geq 3 \) (Hall 1991; after rescaling his \( R_{\text{HK}}^{-1} \) values to ours), which coincides with the saturation point for the plage \( f \) (Fig. II).

One can also explore the spatial distribution of activity. Both photometric (e.g., Rodonò et al. 1986) and Doppler imaging studies (e.g., Vogt & Hatzes 1991) of cool stars give strong evidence for high latitude spots on rapid rotators. While most of this data involves low gravity RS CVn stars and their cousins, the available data on dwarfs are consistent with the idea of near-polar spots on young, rapid rotators (e.g., Saar & Neff 1990; Strassmeier et al. 1993; SPT94). Theoretically, polar spots may result from the dominance of the Corolis force over magnetic bouyancy in short \( P_{\text{rot}} \) stars (Schüssler & Solanki 1992). Larger Ca II HK and photometric amplitudes seen in cooler stars suggest another effect as well - deeper convective zones allowing larger surface inhomogeneities to form (Giampapa & Rosner 1984).

Differential Rotation
Until recently, there is relatively little direct information on the surface differential rotation (SDR) rates on cool stars. In a few cases, some limits on the SDR rate can be derived by comparing Doppler images (Vogt & Hatzes 1991; SPT94). Most of the data, though, comes from variations in seasonal \( P_{\text{rot}} \) (from photometry or Ca II), which are interpreted as changes in the mean active region latitude during the course of a magnetic cycle on a differentially rotating star. Only a handful of dwarfs have photometric SDR estimates, but the results appear to follow the general trend seen in active giants and subgiants, namely that the spread in rotation rates for a given star, \( \Delta P \), increases with increasing \( P_{\text{rot}} \) (Hall 1991). Analysis of \( \Delta P \) from a larger sample of stars has recently been made using Mount Wilson Ca II data (Donahue et al. 1994), with the result of \( \Delta P \propto P_{\text{rot}}^{-1.35} \) independent of mass. This implies that at fixed age, K stars have larger SDR than G stars. Note that both data sets suggest SDR increases with \( P_{\text{rot}} \), quite the reverse of most expectations.

In cases where several seasons of Ca II data yield \( P_{\text{rot}} \) measurements, the relationship between \( P_{\text{rot}} \) and seasonal mean \( F'_{\text{HK}} \) can be determined, thus constructing a simplified stellar equivalent of the "butterfly" diagram. In one well
studied case (β Comae; Donahue & Baliunas 1992), two active bands were detected: one at constant period and another where activity decreased with increasing $P_{\text{rot}}$, similar to the solar case. Unlike the solar case, however, the evolution went from high activity - low $P_{\text{rot}}$ to low activity - high $P_{\text{rot}}$, suggesting possible poleward migration of active regions during the cycle. Other kinds of activity - $P_{\text{rot}}$ patterns are seen as well (see Donahue 1993), including multiple bands with fixed $P_{\text{rot}}$ (in younger stars) and solar-like (in older stars).

**Convection and Granulation**

Gray (1984), in his studies of macroturbulent velocity dispersion ($\zeta$) in cool dwarfs, noted that $\zeta$ generally declined with decreasing $T_{\text{eff}}$, but was significantly larger in the active G8V star ξ Boo A than in inactive G8 dwarfs (see also Toner & Gray 1988). Since $\zeta$ is a measure of the average granular flow velocities in the photosphere, Gray suggested that magnetic activity might affect convection in active stars. Observations of the sun (Livingston 1991; 1994) appear to support this – there is evidence for a cyclic modulation of the amplitude of line bisector curvature during the solar cycle, and clear indication of bisector suppression in AR. The differing dependences of convective strength with photometry between an active and inactive K dwarf (Gray 1992) is then less mysterious: both stars have suppressed convection when they are more active, but ε Eri (the active star) grows fainter with increased activity, while inactive σ Dra does the reverse.

Recent measurements of $\zeta$ for more than 40 southern hemisphere dwarfs (Saar & Osten 1994, in prep.; see also Saar 1994a) appear to confirm Gray’s hypothesis. Although there is considerable scatter (due in part, perhaps, to cyclic $\zeta$ variations), stars showing strong activity generally show $\approx 1$ km s$^{-1}$ larger $\zeta$ than for inactive stars of the same $T_{\text{eff}}$. Since convective flux is suppressed in magnetic regions, it seems possible that the significant AR coverage on active stars forces the net convective flux (and $\zeta$) in quiet areas to be enhanced to compensate.

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**REFERENCES**


Donahue, R.A. 1993, PhD thesis, New Mexico St. U.
Saar, S.H., & Baliunas, S.L. 1992b, ibid, 197
Saar, S.H., Bünte, M., & Solanki, S.K. 1994, this volume (SBS)
Saar, S.H., Piskunov, N.E., & Tuominen, I. 1994, this volume (SPT94)
Saar, S.H., & Solanki, S.K. 1992, ibid, 259