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TIME EVOLUTION OF THE MAGNETIC ACTIVITY CYCLE PERIOD

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ABSTRACT

We propose a new interpretation of the relationships between the dynamo cycle period ($P_{\rm cyc}$) as observed in Ca II H and K, the rotational period ($P_{\rm rot}$), the activity level, and other stellar properties. Viewed within this framework, the data suggest that the dynamo α-parameter increases with magnetic field strength, contrary to the conventional idea of α-quenching. The data also suggest a possibly discontinuous dependence of the ratio of cycle to rotation frequency, $\omega_{\rm cyc}/\Omega$, as a function of Rossby number, Ro (or equivalently, activity or age). Stars evolve with $\omega_{\rm cyc}/\Omega \propto t^{-0.35}$ (or $\mathrm{Ro}^{-0.7}$), until age $t \approx$ 2–3 Gyr (roughly at the Vaughan-Preston gap), where a sharp transition occurs, in which $\omega_{\rm cyc}/\Omega$ increases by a factor of ≈6. Thereafter, evolution with $\omega_{\rm cyc}/\Omega \propto t^{-0.35}$ continues. The age at which transition occurs may be mass dependent, with K stars making the transition first.

Subject headings: stars: activity — stars: evolution — stars: late-type — stars: magnetic fields

1. INTRODUCTION

Nearly all stars with outer convection zones show chromospheric activity (e.g., Linsky 1980). In many cases, the level of activity varies cyclically, akin to the solar sunspot cycle (Wilson 1978; Baliunas et al. 1995, hereafter Bea95), implying a magnetic origin for the bulk of the emission. If the magnetic fields are generated by some kind of a hydromagnetic dynamo, theory predicts that the cycle period ($P_{\rm cyc}$) should depend on rotation, spectral type (e.g., through the convection zone depth), and possibly other parameters. Early work by Noyes, Weiss, & Vaughan (1984a) suggested that $P_{\rm cyc}$, in old stars at least, might be a function of the Rossby number, Ro, alone ($\mathrm{Ro} \propto P_{\rm rot}/\tau_c$, where $P_{\rm rot}$ is the rotation period and τ_c is the convective correlation or turnover time). However, later work using more data showed much more scatter. Baliunas & Vaughan (1985, p. 405) concluded in their review: "In the sample whose periods could be measured objectively, there is no obvious correlation between cycle period, cycle amplitude, rotation period, fractional chromospheric radiative loss $R'_{\rm HK}$, $B-V$ color index, or Rossby number."

If this were the final word on the matter, the situation would be somewhat frustrating, since the lack of a correlation then suggests that stellar activity cycles may be the result of a random (or chaotic) process and perhaps beyond the reach of theoretical prediction. On the other hand, since most stellar activity appears to be ultimately caused by a dynamo process, there should be *some* systematic behavior in the cycle data, since the various activity fluxes show correlations with rotation, spectral type, and each other. So now that a much longer time series (∼25 yr) of Ca II data is available, and with it many new and improved $P_{\rm cyc}$ measurements (Bea95), it is worthwhile to revisit the question of correlations between $P_{\rm cyc}$ and other stellar properties.

Already, several promising directions have been explored. Instead of using the cycle period (e.g., Noyes et al. 1984a), one can study the ratio $P_{\rm cyc}/P_{\rm rot}$. This was first done by Tuominen, Rüdiger, & Brandenburg (1988), who found a negative correlation between this ratio and the fractional convection zone depth. Soon, Baliunas, & Zhang (1993) found a negative correlation between $P_{\rm cyc}/P_{\rm rot}$ and $B-V$, suggesting a similar mass dependence. They also found a positive correlation of this ratio with age, as estimated by $\langle R'_{\rm HK}\rangle$. Baliunas et al. (1996a) found that the ratio increased with $P_{\rm rot}^{-1}$. Saar & Baliunas (1992) and Ossendrijver (1997) compared selected samples of well-determined $P_{\rm cyc}$ values with simple dynamo theory, with some success.

In this Letter, we similarly use a small sample of stars with the most reliable cycle measurements. For these stars, we consider correlations between (1) the ratio of cycle and rotation frequencies, $\omega_{\rm cyc}/\Omega$; (2) the inverse Rossby number, Ro^{-1}; and (3) the mean fractional Ca II H and K flux, $\langle R'_{\rm HK}\rangle$ ($=F'_{\rm HK}/F_{\rm bol}$). The ratio $\omega_{\rm cyc}/\Omega \equiv P_{\rm rot}/P_{\rm cyc}$ is particularly interesting, because in mean field dynamo theory, this ratio is proportional to the square root of the α-effect (see § 3). Simple formulations of the mean field dynamo number (e.g., Parker 1979) are proportional to Ro^{-2}, and Ro^{-1} is also well correlated with activity (e.g., $\langle R'_{\rm HK}\rangle$; Noyes et al. 1984b); $\langle R'_{\rm HK}\rangle$, a proxy for the total chromospheric losses and activity in general, is an indirect measure of the mean magnetic field strength, $\langle B\rangle$ (e.g., Schrijver et al. 1989). A correlation between $\omega_{\rm cyc}/\Omega$ and $\langle R'_{\rm HK}\rangle$ could thus be used to determine the dependence of α on $\langle B\rangle$. The standard assumption is that α decreases with increasing $\langle B\rangle$ (α-quenching), but we shall see that this may be incorrect.

2. OBSERVED CORRELATIONS

Before presenting the correlations between the three parameters, we consider the cycle data in detail. We include only cases where the "false alarm probability" (FAP) of the $P_{\rm cyc}$ detection is low (numerically, $\mathrm{FAP} \le 10^{-5}$, equivalent to FAP "grades" of good or excellent). We consider only the primary $P_{\rm cyc}$ (as defined by Bea95), since this period has the most Fourier power and FAP values for the secondary $P_{\rm cyc}$ are less well determined (Bea95). The values of $P_{\rm cyc}$ and $B-V$ are taken from Bea95 with updates from Donahue (1996), the values of $\langle R'_{\rm HK}\rangle$ come from Baliunas, Sokoloff, & Soon (1996b), and $P_{\rm rot}$ values came from Donahue and coworkers (Donahue, Saar, & Baliunas 1996; Donahue, Dobson, & Baliunas 1997), or Baliunas et al. (1996b), in order of preference (except HD 3651, which is taken from Baliunas et al.). We define $\mathrm{Ro}^{-1} = 2\Omega\tau_c$, where τ_c is the empirical value taken from Noyes et al. (1984b).

Several modifications should be noted. HD 219834A was excluded from the fits (although still plotted) because visual

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TABLE 1

ACTIVE (A) AND INACTIVE (I) STELLAR PROPERTIES

Symbol, Type[a]	HD	$B-V$	$P_{\rm rot}$ (days)	$P_{\rm cyc}$ (yr)	τ_c (days)	$\log \langle R'_{\rm HK}\rangle$
0, A	114710	0.57	12.35	16.6	7.4	−4.745
1, A	78366	0.60	9.67	12.2	9.1	−4.608
2, A	152391	0.76	11.43	10.9	17.8	−4.448
3, A	149661	0.82	21.07	16.2	20.0	−4.583
4, A	115404	0.93	18.47	12.4	22.3	−4.480
5, A	156026	1.16	21	21.0	24.2	−4.662
a, I	Sun	0.66	26.09	10.0	12.6	−4.901
b, I	103095	0.75	31	7.3	17.3	−4.896
c, I	219834A	0.80	42	21.0	19.4	−5.066
d, I	81809	0.80	40.2	8.2	19.4	−4.921
e, I	26965	0.82	43	10.1	20.0	−4.872
f, I	10476	0.84	35.2	9.6	20.6	−4.912
g, I	3651	0.85	44	14.6	20.9	−4.991
h, I	166620	0.87	42.4	15.8	21.3	−4.955
i, I	4628	0.88	38.5	8.6	21.5	−4.852
j, I	219834B	0.91	43	10.0	22.0	−4.944
k, I	160346	0.96	36.4	7.0	22.6	−4.795
l, I	16160	0.98	48.0	13.2	22.8	−4.958
m, I	32147	1.06	48.0	11.1	23.5	−4.948
n, I	201091	1.18	35.37	7.3	24.4	−4.764
o, I	201092	1.37	37.84	11.7	25.9	−4.891

[a] Plot symbol, activity type.

inspection of its $\langle S\rangle$ time series (see Bea95, their Fig. 1*f*) left the authors unconvinced of the existence of a well-determined cycle with $P_{\rm cyc} \approx 21$ yr. Although a few other cases also appeared somewhat dubious (e.g., HD 201092 shows a cycle during only the first *part* of its 25 yr time series), we refrained from making any other "corrections" to the cycle data. For HD 81809, we use the value $B-V = 0.80$, the approximate value for the K dwarf secondary, which likely dominates the cyclic activity observed in that system (see Bea95). A summary of the data is given in Table 1, and the results are shown in Figure 1. Note that our results, using updated stellar parameters, differ slightly from and supersede those of Brandenburg (1998).

Except for the relation between Ro^{-1} and $\langle R'_{\rm HK}\rangle$, there is a sharp segregation into two distinct groups separated by $\log(\omega_{\rm cyc}/\Omega) \approx -2.3$. This type of segregation, which essentially divides stars into a "young/active branch" and an "old/inactive branch," was found earlier by Saar & Baliunas (1992), who plotted a normalized cycle frequency versus dynamo number (see also Soon et al. 1993). Without exception, $\log\langle R'_{\rm HK}\rangle \approx -4.75$ separates the inactive and active stars. Interestingly, this is very close to the $\langle R'_{\rm HK}\rangle$ level defining the Vaughan-Preston (1980) gap, the locus of an apparent lack of stars with intermediate activity.

From Figure 1, we obtain approximate power-law fits $\omega_{\rm cyc}/\Omega = c_1\mathrm{Ro}^{-\sigma}$ (Fig. 1*a*), $\omega_{\rm cyc}/\Omega = c_2\langle R'_{\rm HK}\rangle^{\nu}$ (Fig. 1*b*), and $\langle R'_{\rm HK}\rangle = c_3\mathrm{Ro}^{-\mu}$ (Fig. 1*c*). The $\omega_{\rm cyc}/\Omega$-Ro relation can also be derived from the other two, with $c_1 = c_2 c_3^{\nu}$ and $\sigma = \mu\nu$. The fit results and standard deviations ($\sigma_{\rm fit}$) are given in Figure 1. Since the scatter in Figure 1*a* is larger than in Figures 1*b* and 1*c*, we have used the derived c_1 and σ-values to determine the "best" fit given in Figure 1*a* (*dashed lines*).

3. COMPARISON WITH DYNAMO THEORY

We now turn to the relationship between $\omega_{\rm cyc}/\Omega$, the α-effect in mean field dynamo theory, and $\langle B\rangle$. We first consider a simple dynamo model with fixed wavenumber, k. This type of model has been employed earlier (Robinson & Durney 1982; Noyes et al. 1984a) and has been investigated for the case where α increases with B (Brandenburg 1998). However, as recently pointed out by Tobias (1997), the periods obtained for models with fixed k may be spurious. We discuss this problem, first giving the main results for fixed k models and then comparing them with models in one and two dimensions without prescribed wavenumber.

Using the standard ($\alpha\Omega$) dynamo equations (Parker 1979), one can show that there is a wavelike solution. In a local approximation with fixed k, the dynamo wave is governed by the equations $\dot{A} = \alpha B - \tau^{-1}A$ and $\dot{B} = ikL\Omega' A - \tau^{-1}B$, where A and B are, respectively, the toroidal components of the vector potential and the mean magnetic field, $\tau^{-1} = \eta_t k^2$ is the magnetic diffusion time, η_t is the turbulent magnetic diffusivity, Ω' is the radial gradient of the angular velocity, α describes the α-effect, and L is a typical length scale of the dynamo. In the linear case, when α and τ are independent of the magnetic field, the solution is of the form $B \sim \exp(\lambda t - i\omega_{\rm cyc}t)$, where $\lambda = \pm|\alpha\Omega' kL/2|^{1/2} - \tau^{-1}$ and $\omega_{\rm cyc} = \pm|\alpha\Omega' kL/2|^{1/2}$. Even in the nonlinear case, when α and τ^{-1} depend on B, these expressions are useful. By solving the nonlinear problem numerically, one finds that $\alpha(B)$ and $\tau^{-1}(B)$ take values such that $\lambda \rightarrow 0$ and that $\omega_{\rm cyc}$ is still given as before. We now assume that in the asymptotic regime, where the magnetically controlled α-effect exceeds the classical one, α and τ^{-1} are given by power laws

$$\alpha \sim \alpha_0|B/B_{\rm eq}|^n, \quad \tau^{-1} \sim \tau_0^{-1}|B/B_{\rm eq}|^m. \tag{1}$$

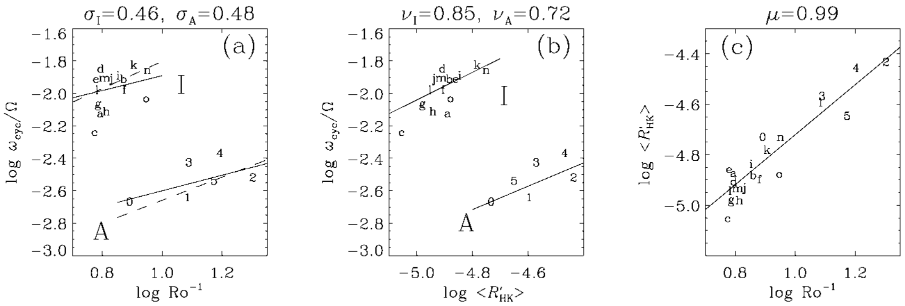

FIG. 1.—Plots showing the correlations (*solid lines*) between the three parameters $\omega_{\rm cyc}/\Omega$, Ro^{-1}, and $\langle R'_{\rm HK}\rangle$; the symbols are discussed in Table 1. The active and inactive branches are denoted by A and I, respectively; the power-law slopes are given at top. The standard deviations for the fits (in units of dex) are (*a*) I: $\sigma_{\rm fit} = 0.10$, A: $\sigma_{\rm fit} = 0.11$; (*b*) I: $\sigma_{\rm fit} = 0.08$, A: $\sigma_{\rm fit} = 0.10$; and (*c*) $\sigma_{\rm fit} = 0.06$. The dashed lines in (*a*) give the dependence derived (see text) from the fits in (*b*) and (*c*): here $\sigma_I = 0.84$ and $\sigma_A = 0.71$, with $\sigma_{\rm fit} = 0.10$ and 0.12, respectively. Note that HD 219834A (symbol c) is excluded from the fits (see text).

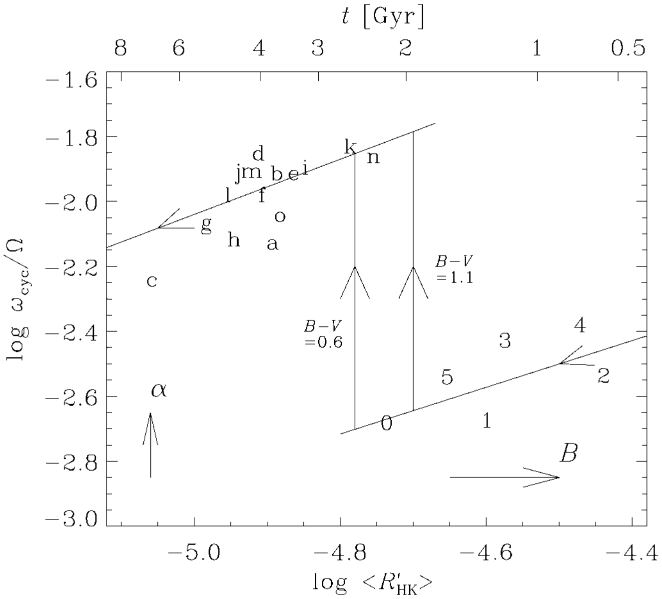

FIG. 2.—Sketch of evolutionary tracks in a $\omega_{\rm cyc}/\Omega$ vs. $\langle R'_{\rm HK}\rangle$ diagram; the approximate stellar age t (Donahue 1993) is given at top. As stars age, their value of $\omega_{\rm cyc}/\Omega$ eventually jumps up onto the upper branch. The location of this jump may depend on $B-V$, as indicated; the position of the jump corresponds to the approximate location of the Vaughan-Preston gap. The arrows indicate the directions in which B and α increase.

Negative values of n correspond to "α-quenching," a mechanism that leads to saturation of the dynamo even for constant τ. However, for positive values of n (which, we shall see, the data tend to favor), we need positive values of m ($m > n/2$) for saturation.

The solution is governed by a balance between generating terms, $(\alpha_0\Omega' kL/2)^{1/2}|B/B_{\rm eq}|^{n/2}$, and dissipating terms, $\tau_0^{-1}|B/B_{\rm eq}|^m$. We now take $\tau_0 \approx \tau_c$, so the balance between generation and dissipation (i.e., $\lambda = 0$) can be written as $S^{1/2}|B/B_{\rm eq}|^{n/2} = 2{\rm Ro}|B/B_{\rm eq}|^m$, or $\frac{1}{2}{\rm Ro}^{-1}S^{1/2} = |B/B_{\rm eq}|^{m-n/2}$, where $S = (\alpha_0\Omega'/\Omega^2)(kL/2)$ is a dimensionless quantity that may be dependent on ${\rm Ro}^{-1}$; we assume $S = S_0{\rm Ro}^{-q}$. Note that $\omega_{\rm cyc} \propto \alpha^{1/2} \propto B^{n/2}$ for a fixed ${\rm Ro}^{-1}$.

To compare the predictions of this model with the data, we need estimates of $\langle B\rangle$. Schrijver et al. (1989) showed that the residual Ca II H and K flux $\Delta F_{\rm HK} \propto (fB_{\rm loc})^{1/2} = \langle B\rangle^{1/2}$ for stars with nonsaturated chromospheres, where f is the magnetic area filling factor and $B_{\rm loc}$ is the local field strength. We have taken the best currently available magnetic data for G and K dwarfs (compiled in Saar 1996), combined them with $\langle R'_{\rm HK}\rangle$ (from Bea95 and Rutten 1987) and gas pressure equipartition field strengths $B_{\rm eq} \propto P_{\rm gas}^{1/2}$ (e.g., Bünte & Saar 1993), and find

$$\langle R'_{\rm HK}\rangle \propto (\langle B\rangle / B_{\rm eq})^{\kappa}, \quad \text{with } \kappa = 0.47 \qquad (2)$$

for 13 stars (fit rms = 0.10 dex). We now identify the mean toroidal field B in equation (1) with $\langle B\rangle$. Equation (2) allows us then to connect $\langle R'_{\rm HK}\rangle$ with $B/B_{\rm eq}$ and to relate the observational parameters μ, ν, and $\sigma = \mu\nu$ to n and m. The calculation is straightforward (see Brandenburg 1998), and the final result is $m = \kappa(\nu + 1/\mu)$ and $n = \kappa(2\nu - q/\mu)$. The value of q can be anywhere between -0.3 (if $\alpha_0 \propto \Omega$ and $\Omega' \propto \Omega^{0.7}$; see Donahue et al. 1996) and -2 (if α_0 and Ω' are independent of Ω; see Donati & Cameron 1997). Thus, n_I is between 0.9 and 1.7, and n_A is between 0.8 and 1.6. The value of m is, however, independent of q, and the model predicts the empirical values $m_I = 0.9$ and $m_A = 0.8$.

We now turn to the discussion of results in one and two dimensions. We found saturation only for $m > n$, so in the one-dimensional case, we chose (arbitrarily) $m = n + 2$ and varied the value of n. In all cases we found only *negative* values of σ ($\sigma = -0.62$, -0.48, and -0.38 for $n = 2$, 4, and 6). Results in the two-dimensional case were similar. Here we solved the axisymmetric dynamo equations in a meridional plane using realistic boundary conditions in radius and latitude. We used uniform profiles for Ω' and α_0 (allowing, however, for a $\cos\theta$ dependence with colatitude θ). For details of this type of model, see Brandenburg et al. (1989). Again, we always found *negative* values of σ (we used $m = 4$ in all cases and found $\sigma = -0.49$, -0.39, and -0.31 for $n = 1$, 2, and 3, respectively). Of course, we cannot exclude that more complicated profiles of Ω' and α_0, or possibly more complex nonlinearities (cf. Rüdiger & Arlt 1996), could lead to remarkable changes and produce $\sigma > 0$. Thus, the conclusion that α increases with $\langle B\rangle$ is supported by models with fixed k, but not by the (small) sample of one- and two-dimensional models we have studied. A fixed k model, possible if α and η_t depend on k such that αk and $\eta_t k^2$ are constant, might be justifiable: Brandenburg & Sokoloff (1998) found some evidence that in shear flow turbulence, the magnitudes of α and η_t decrease with k in approximately such a way.

4. EVOLUTION OF THE DYNAMO

As stars evolve, ${\rm Ro}^{-1}$ and $\langle R'_{\rm HK}\rangle$ decrease owing to magnetic braking of rotation; a parallel reduction occurs in $\langle B\rangle$ and hence also in magnetic heating. Applying this to Figures 1*a* and 1*b* then implies that $\omega_{\rm cyc}/\Omega$ also evolves in time t, but in a more complex way (Fig. 2). At first, $\omega_{\rm cyc}/\Omega$ decreases along the active branch as the star ages, roughly proportional to ${\rm Ro}^{-0.7}$ (adopting an average power law for the two branches). Once its activity is in the range $-4.8 \le \log\langle R'_{\rm HK}\rangle \le -4.7$, however, (or equivalently, $0.9 \le \log {\rm Ro}^{-1} \le 1.0$), the star makes a rapid, perhaps discontinuous transition to the inactive branch, reflecting a sudden increase in $\omega_{\rm cyc}$ by a factor of ~6. The evolution of $P_{\rm cyc}$ with similar breaks has been previously suggested by Saar & Baliunas (1992) and Soon et al. (1993), among others. The $\langle R'_{\rm HK}\rangle$ range where the break occurs brackets the position of the Vaughan-Preston gap. Using the age calibration of Donahue (1993) (based on Soderblom et al. 1991), the $\omega_{\rm cyc}$ transition seems to occur between $t \sim 2$ and 3 Gyr (cf. Soon et al. 1993). After the jump to the inactive branch, $\omega_{\rm cyc}/\Omega$ resumes its decrease as the star ages, again roughly proportional to ${\rm Ro}^{-0.7}$. Since $\Omega \propto t^{-1/2}$ (Skumanich 1972), the age dependence on both branches is approximately $\omega_{\rm cyc}/\Omega \propto t^{-0.35}$.

The range in $\langle R'_{\rm HK}\rangle$ and ${\rm Ro}^{-1}$ over which the transition occurs *may* be mass dependent. K stars do not appear on the active branch for $\log\langle R'_{\rm HK}\rangle < -4.7$ (Fig. 2). The active branch star with the lowest $\langle R'_{\rm HK}\rangle$ (star 0) is also the hottest ($B-V = 0.57$). Two inactive stars (k and n) have similar $\langle R'_{\rm HK}\rangle$ to star 0, but they are cooler ($B-V = 0.91$ and 1.18, respectively). At slightly lower $\log\langle R'_{\rm HK}\rangle \approx -4.9$, G stars appear on the inactive branch. These are all consistent with a transition at $\log\langle R'_{\rm HK}\rangle \approx -4.7$ for $B-V \approx 1.1$ and one around $\log\langle R'_{\rm HK}\rangle \approx -4.8$ for $B-V \approx 0.6$.

The positive correlations between $\omega_{\rm cyc}/\Omega$ and $\langle R'_{\rm HK}\rangle$ may imply that α increases with $\langle B\rangle$ and also evolves in time. The exact relationship between α and $\langle B\rangle$ depends on the radial differential rotation, Ω'; our results suggest $\alpha \propto B^n$, where $0.8 \lesssim n \lesssim 1.7$ (depending on q). This is quite different from conventional α-quenching, for which $n = -2$ is typical. Such models with $n > 0$ resemble those of Leighton (1969), Schmitt, Schüssler, & Ferriz-Mas (1996), and Thelen (1997).

We note that Baliunas et al. (1996a) found that $P_{\rm cyc}/P_{\rm rot} \propto \Omega^{0.74}$. This would imply $\sigma < 0$, in contrast to the positive values found here. However, they considered only a single fit to active and inactive stars combined. We argue that the new relations between $\omega_{\rm cyc}/\Omega$ and Ro^{-1} are more appropriate since they correlate two dimensionless quantities and lead to fits with less scatter: a least-squares fit to the data from all the stars in Table 1 (except c) yields $P_{\rm cyc}/P_{\rm rot} \propto \Omega^{1.20}$ with $\sigma_{\rm fit} = 0.13$ dex, compared with $\sigma_{\rm fit} = 0.10$ dex for the combined $\omega_{\rm cyc}/\Omega$-Ro^{-1} fits (both branches, 4 degrees of freedom).

The underlying reason for the segregation of young and old stars into two different branches is unclear. It may be associated with a change in the convection pattern (Knobloch et al. 1983) or the excitation of higher dynamo modes (Durney, Mihalas, & Robinson 1981). However, if the α-effect is driven by magnetic instabilities, as our results may suggest, the segregation could be connected with a change in the dominant instability (buoyancy or magnetic shear instabilities, for example). A change in the differential rotation pattern, from generally solar-like to more complex, combined forms and dual activity bands (e.g., star 0; Donahue & Baliunas 1992) for stars above the Vaughan-Preston gap (see Donahue 1993), may also be important. We will explore this and some other remaining questions (e.g., the significance of double $P_{\rm cyc}$ stars and long-term H and K trends) in a forthcoming paper.

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