

THE RELATION BETWEEN STELLAR ROTATION RATE AND ACTIVITY CYCLE PERIODS

ROBERT W. NOYES AND NIGEL O. WEISS

Harvard-Smithsonian Center for Astrophysics

AND

ARTHUR H. VAUGHAN

Mount Wilson and Las Campanas Observatories of the Carnegie Institution of Washington; and the Perkin-Elmer Corporation

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ABSTRACT

The empirical relation between rotation period, spectral type, and activity cycle period is investigated for a sample of 13 slowly rotating lower main-sequence stars, including the Sun, all of which show long-term chromospheric variability like that of the solar cycle. It is found that for slowly rotating stars of similar spectral type, the cycle period P_{cyc} and rotation period P_{rot} are related by $P_{\text{cyc}} \propto P_{\text{rot}}^n$, where $n \approx 1.25$. When the stars, whose individual spectral types range from G2 to K7, are considered as a group, their cycle periods are found to be consistent with the relation $P_{\text{cyc}} \approx (P_{\text{rot}}/\tau_c)^n$, where τ_c is the convective turnover time near the bottom of the convection zone appropriate to each spectral type, and n is the same as before. These relations are interpreted in terms of simple nonlinear dynamo models. The increase of P_{cyc} with increasing P_{rot} disagrees with models in which the magnetic field is limited by quenching of the α effect or of differential rotation; however, it is consistent with models in which dynamo action is limited by losses due to magnetic buoyancy.

Subject headings: Ca II emission — hydromagnetics — stars: late-type — stars: rotation

I. INTRODUCTION

In a landmark paper, Wilson (1978) showed that many lower main-sequence stars exhibit quasi-cyclical variations in their mean level of Ca II H and K emission which are strikingly similar to the 11 year variation of that emission seen in the Sun as a star. By analogy with the Sun, such variations may be interpreted as due to magnetic cycles; this suggestion is strongly supported by the large body of evidence linking Ca II emission in lower main-sequence stars to their surface magnetic activity. The cycle period implied by the data varies from about 7 to more than 12 years.

It is natural to expect that the stellar activity cycle period should be dependent on the rotation rate of the star, for the standard mean field (α - ω) model of the dynamo ascribes the cyclical amplification of magnetic fields in the Sun and similar stars to helicity produced by the action of rotation on convection (the α effect) and shear produced by differential rotation (the ω effect) (Moffatt 1978; Parker 1979; Krause and Rädler 1980). In such models the dynamo behavior is often characterized by a rotation-dependent dynamo number D which is essentially proportional to the square of the inverse Rossby number $\sigma = \tau_c/P_{\text{rot}}$, where P_{rot} is the stellar rotation period and τ_c the convective overturn time near the base of the stellar convection zone (Parker 1979). The behavior of nonlinear dynamos as D is varied has been investigated by Gilman (1983a, b) using numerical simulations; it has also been studied using a simple analytic model of dynamo waves, which yields both periodic and aperiodic solutions (Cattaneo, Jones, and Weiss 1983; Weiss, Cattaneo, and Jones 1984).

Recently, Noyes *et al.* (1984) have presented empirical evidence that overall chromospheric activity levels in lower main-sequence stars (and hence surface magnetic activity) depends mainly on the inverse Rossby number σ . The implied relationship between magnetic activity and the dynamo number D is in good accord with the concepts of mean field dynamo theory. This, plus the tightness of the empirical relation between

chromospheric emission and inverse Rossby number, suggest that we investigate the dependence of the period of activity cycles on the same parameter. In § II we discuss the observations bearing on this dependence. In § III we compare the results with general expectations from dynamo theory, and § IV contains our conclusions.

II. THE OBSERVED RELATION BETWEEN CYCLE PERIOD, ROTATION PERIOD, AND SPECTRAL TYPE

Vaughan (1980) noted that the stars in Wilson's sample with well-defined apparent activity cycles like that of the Sun invariably fell within the group of old stars with low chromospheric emission. Subsequently it was noted that these stars also have rotation periods exceeding about 20 days (Vaughan *et al.* 1981). Here we deal with the same stars, neglecting the more active and more rapidly rotating stars labeled "young" by Vaughan (1980), which generally show more irregular long-term activity variations. We note at the outset that cyclical activity could well be present in the young rapidly rotating stars, but be simply masked by the presence of large shorter term and less-ordered fluctuations. Indeed, a few of the more rapidly rotating and chromospherically active stars do show variations containing apparent periodicities (e.g., HD 152391, period ≈ 12 years, or HD 190406, period ≈ 2.5 years). We have restricted our attention to the older, slowly rotating stars in order to obtain a reasonably homogeneous sample. The justification of this procedure requires the assumption that the more rapidly rotating stars belong to a physically distinct population, as far as their activity mechanisms go. While some suggestions along this line have been advanced (e.g., Durney, Mihalas, and Robinson 1981; Knobloch, Rosner, and Weiss 1981) the assumption must be considered to be untested at this point.

Table 1 lists those stars whose long-term chromospheric variations strongly suggest Sun-like magnetic activity cycles, together with our best estimates of the cycle period. The stars

TABLE 1
DATA FOR STARS WITH SUN-LIKE MAGNETIC ACTIVITY CYCLES

Star (HD)	$B-V$	$P_{\text{cyc}}(\text{yr})$	$P_{\text{rot}}(\text{d})^a$	$\tau_c(\text{d})^b$	$\sigma = \tau_c/P_{\text{rot}}$
Sun	0.66	11	25.4	12.6	0.49
81809	0.64	9	(21.7)	11.4	0.52
161239	0.65	12.5	(28.5)	11.9	0.42
103095	0.75	7.5	(34.0)	17.3	0.51
3651	0.85	10	48	20.9	0.44
4628	0.88	8.5	38	21.5	0.57
10476	0.84	9.5	(38.0)	20.6	0.54
26965	0.82	9	(37.0)	20.0	0.54
16160	0.97	11.5	45	22.7	0.50
160346	0.96	7	33.5	22.6	0.67
32147	1.07	9.8	(46.8)	23.5	0.50
201091	1.18	7	37.9	24.4	0.64
201092	1.38	11	48	26.0	0.54

^a From Table 1 of Noyes *et al.* 1984. Figures in parentheses are predicted from Ca II flux.

^b From eq. (4) of Noyes *et al.* 1984.

are placed in groupings of similar $B-V$. In selecting the stars to be included, as well as in estimating the periods, we have made use of updated but presently unpublished survey data extending the data of Wilson (1978) through 1982. (The publication of this extended data set is in preparation.) Thus a total span of time of 16 years is covered, beginning in 1966. For each star selected on the basis of an apparent smoothly varying activity cycle, two of us (R. W. N. and A. H. V.) independently estimated the cycle period, by simple measurement of times of maximum and minimum. Stars were included in the table only if both estimators obtained essentially the same cycle period and independently assigned high weight to the estimation. A similar list, published by Vaughan (1983), included these stars plus a number of others whose cycle period estimates were assigned a lower weight, as well as a few more rapidly rotating "young" stars whose activity appeared cyclic.

We believe that the principal uncertainty in the cycle periods given in Table 1 is produced, not by the estimation method or the quality of the data, but rather by the relatively short time span of the data, which extends over only one or at most two cycles for the stars included here. In fact, as more data accumulate, the individual estimates may be expected to change somewhat. It should be remembered that in the case of the Sun, the intervals between cycle maxima measured between 1710 and 1980 have varied from 8 to 14 years. From the historical record, we calculate that a probable error of about 1.6 years, or 15%, would have been made in estimating the solar cycle period, if one were simply to equate a single measured interval between consecutive maxima or minima of the solar cycle with the long-term average cycle period. This error may be taken as a rough estimate of the probable percentage error in the assignment of the measurements in the third column of Table 1 to mean cycle periods.

Rotation periods are given for the stars under consideration in the fourth column of Table 1. The stars are placed in groups of comparable $B-V$. Numbers not surrounded by parentheses were measured from rotational modulation observations (Baliunas *et al.* 1983), while those surrounded by parentheses were predicted from the mean chromospheric emission level

and the star's spectral type, using the method described by Noyes *et al.* (1984). According to Noyes *et al.*, such predictions should typically be accurate to about $\pm 20\%$.

The fifth column of Table 1 contains the convective overturn time τ_c , near the bottom of the convection zone, from equation (4) of Noyes *et al.* (1984), which in turn is derived from calculations reported by Gilman (1981). This estimate of τ_c assumes a ratio of mixing length to scale height $\alpha \approx 2$ (Noyes *et al.* 1984). The sixth column contains the inverse Rossby number $\sigma = \tau_c/P_{\text{rot}}$.

In Figure 1a we plot the cycle frequency P_{cyc}^{-1} versus $B-V$ for the 13 stars in Table 1. A similar plot was given by Vaughan (1983), where it was noted that there is no clear correlation between cycle period and $B-V$, when stars are considered independently of their rotation rate. However, it may be seen in the figure that there is some tendency for the more rapidly

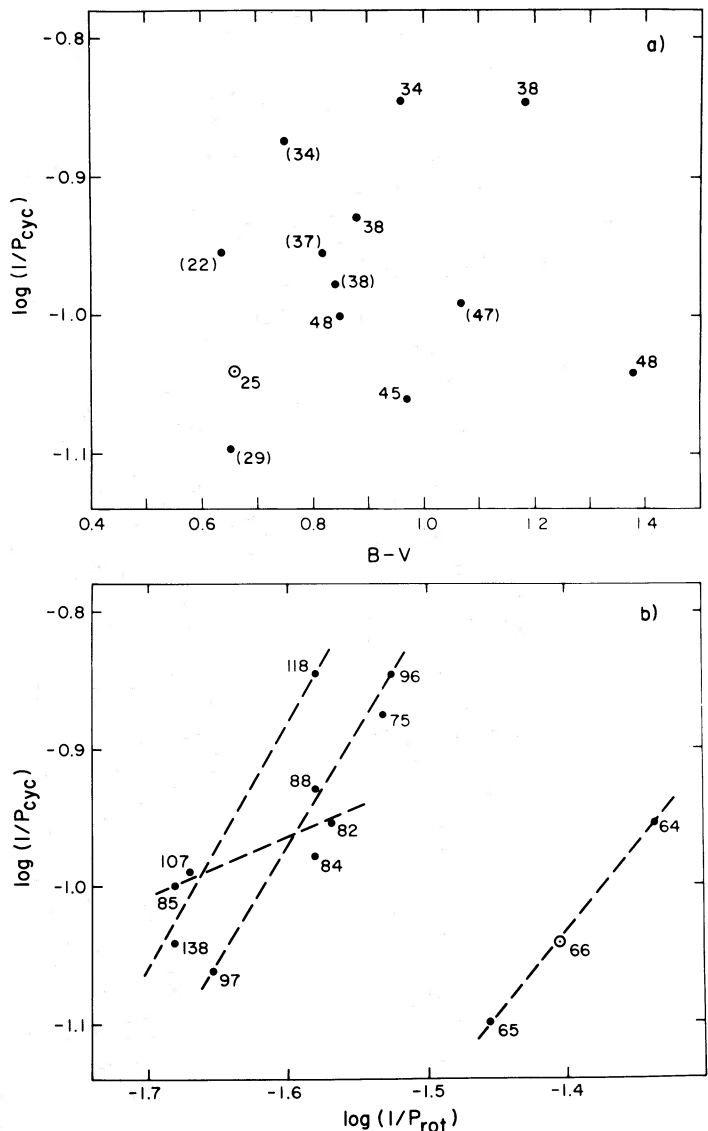


FIG. 1.—(a) $\log(1/P_{\text{cyc}})$ vs. $B-V$ for the stars in Table 1. Labels give P_{rot} in days; those in parentheses are predicted, and the others are observed. The Sun is indicated by $\odot$. (b) $\log(1/P_{\text{cyc}})$ vs. $\log(1/P_{\text{rot}})$ for the stars in Table 1. Labels give $100(B-V)$. The Sun is indicated by $\odot$. The dashed lines are linear least square fits to the four groups of stars with multiple members in Table 1.

rotating stars of a given $B-V$ to have shorter cycle periods. In Figure 1b we plot cycle frequency P_{cyc}^{-1} versus rotation frequency P_{rot}^{-1} . There is no apparent correlation between cycle frequency and rotation frequency, when stars are considered independently of their spectral type. However, when stars are considered only within a narrow range of spectral type (such as those connected by dashed lines in the figure), there is a tendency for stars with shorter rotation periods to have shorter cycle periods. This is true for all four groups of stars shown. Furthermore, the slope $n = d \log P_{\text{cyc}} / d \log P_{\text{rot}}$ is similar for the three groups of stars with $B-V \approx 0.65, 0.95$, and 1.2 . The group with $B-V \approx 0.85$ has a lower slope, determined principally by the position of a single star, HD 3651.

The segregation of the data in Figure 1b according to spectral type suggests that cycle periods are determined by stellar structure as well as by rotation rate. As already mentioned, it is reasonable to expect the structure effect to involve the convective time scale τ_c , as embodied in the inverse Rossby number $\sigma = \tau_c / P_{\text{rot}}$. In Figure 2 we plot P_{cyc}^{-1} versus σ ; compared to Figure 1b, data points are simply translated to the right by $\log [\tau_c(B-V)]$. It is seen that the points are now consistent with a single relationship. The unweighted correlation coefficient between $\log (P_{\text{cyc}}^{-1})$ and $\log \sigma$ for the points in Figure 2 is 0.55, leading to 95% confidence in the reality of the correlation. Giving tenfold weight to the more accurate solar data increases the confidence of a positive correlation to greater than 99%.

The rms deviation in $\log (P_{\text{cyc}})$ of the points in Figure 2 from the fit corresponds to $\pm 12\%$ in P_{cyc} . This is comparable to the above-mentioned spread of $\pm 15\%$ for historically observed solar cycle periods and therefore is consistent with the hypothesis that activity cycles of slowly rotating stars in general undergo comparable changes in length from cycle to cycle.

We derived a linear least squares fit to the slope $n = \partial \log (P_{\text{cyc}}^{-1}) / \partial \log (P_{\text{rot}}^{-1})$ of the points in Figure 1a, by finding the slope separately for the four subgroups indicated by the dashed lines, and then averaging the slopes with appropriate weighting. In this procedure we assumed that each point

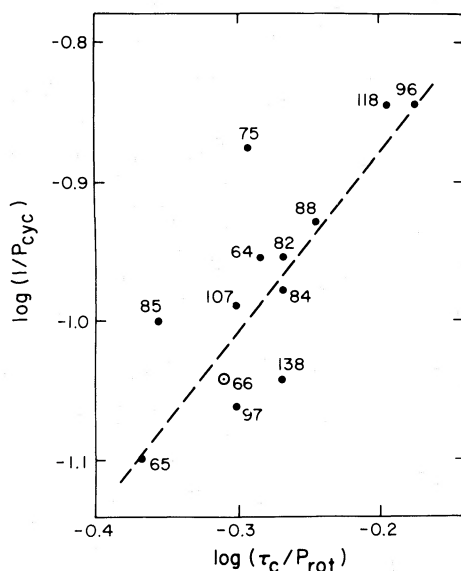


FIG. 2.— $\log (1/P_{\text{cyc}})$ vs. $\log (\tau_c/P_{\text{rot}})$ for the stars of Table 1. The dashed line is a linear least squares fit to the data.

had a standard error in $\log P_{\text{cyc}}$ of 0.1 (i.e., 25% uncertainty), except the point for the Sun, to which we assigned a standard error of 0.03. These uncertainties are larger than the expected uncertainty of 15% in P_{cyc} alone, to allow for additional uncertainties in the assignment of P_{rot} . The result of this process is $n = 1.25 \pm 0.54$ where the quoted error is the formal standard deviation. We also derived a linear fit to the data set of Figure 2, using the same weights for individual stars as before. The result is essentially the same: $n = d \log (P_{\text{cyc}}^{-1}) / d \log \sigma = 1.28 \pm 0.48$. We believe the quoted uncertainties are conservative, based on the tightness of the relation shown in Figure 2.

The power law given above can be rewritten in dimensionless form by introducing a characteristic global diffusion time $\tau_\eta = \tau_c(R/d)^2$, where R and d are the stellar radius and convection zone depth respectively (cf. eq. [2] below). It happens that $\tau_c \propto (d/R)^{3.7}$ over the spectral range considered here (cf. Gilman 1981); hence we find that $\tau_\eta/P_{\text{cyc}} \propto \sigma^{1.28}(d/R)^{1.7}$.

In summary, we have found the following for the stars in Table 1:

1. For stars of a given spectral type, activity cycle period depends on rotation period, as

$$P_{\text{cyc}} \propto P_{\text{rot}}^n, \quad \text{where } n = 1.25 \pm 0.5 \quad (1)$$

2. There is an additional dependence of cycle frequency on stellar structure, such that for all stars considered, regardless of spectral type, cycle frequency depends on the single parameter $\sigma = \tau_c/P_{\text{rot}}$.

III. DYNAMO MODELS

For slowly rotating stars, the cycle period P_{cyc} appears to depend both on the angular velocity $\omega = 2\pi/P_{\text{rot}}$ and on stellar structure, as parameterized by spectral type. For fixed rotation frequency, P_{cyc} decreases with increasing $B-V$, in agreement with the predictions of Robinson and Durney (1982) but contrary to those of Belvedere, Paterno, and Stix (1980).

Equation (1) above describes the dependence of cycle period upon rotation period for stars of fixed internal structure (that is, stars of similar mass and age) within the range $0.64 < B-V < 1.4$, and with rotation periods in excess of about 20 days. Here we seek theoretical models that are compatible with this relation.

In mean field dynamos the regeneration of the poloidal magnetic field depends on the parameter $\alpha \propto -\tau_c \langle \mathbf{u} \cdot (\nabla \times \mathbf{u}) \rangle$, where $\mathbf{u}$ is the convective velocity (with typical magnitude U and length scale L) and $\tau_c = L/U$ is the convective turnover time. The mean helicity $\langle \mathbf{u} \cdot (\nabla \times \mathbf{u}) \rangle$ depends on the effect of Coriolis forces on convection in a stratified layer and scales as ωU , so that $\alpha \propto \omega L$. The α -effect is measured by a magnetic Reynolds number $N_\alpha = \alpha R/\eta$, where the turbulent magnetic diffusivity $\eta \approx L^2/\tau_c$. Similarly, the production of toroidal magnetic flux through the ω -effect is measured by $N_\omega = \omega' R^3/\eta$, where the angular velocity gradient $\omega' \propto (\omega/L)$. The overall behavior of the dynamo depends on a single dimensionless parameter, the dynamo number

$$D = N_\alpha N_\omega = \alpha \omega' \tau_\eta^2 \propto (\omega \tau_c)^2 (R/L)^4, \quad (2)$$

where the magnetic diffusion time $\tau_\eta = R^2/\eta$. Thus for stars with the same internal structure, $D \approx \omega^2$. The main features of the solar cycle are successfully reproduced by $\alpha\omega$ -dynamos, and the justification for applying this parameterization to stars has been discussed by Cowling (1981), Stix (1981), and Weiss (1983).

Kinematic dynamo theory, which is purely linear, shows that oscillatory magnetic fields can develop as an instability of the field-free state if the dynamo number, D , exceeds a critical value, D_c , of order unity. In the unstable regime, the dimensionless frequency $p = (\tau_\eta/P_{\text{cyc}}) \propto D^{1/2}$ so that for stars with the same structure, the cycle period $P_{\text{cyc}} \propto D^{-1/2} \propto \omega^{-1}$. While this is in agreement with observations (eq. [1]), the agreement is fortuitous, for linear theory cannot be applied in the nonlinear domain, where $D > D_c$.

In a nonlinear dynamo, the magnetic field, B , grows until the Lorentz force alters the velocity field so as to permit some equilibrium. The simplest models assume that the α -effect or the velocity shear is reduced as the field strength increases (e.g., Jepps 1975; Ivanova and Ruzmaikin 1977; Yoshimura 1978). Then the effective value of N_α or N_ω is a monotonically decreasing function of $|B|$: as the magnetic field increases, the effective value of the dynamo number, D_{eff} , is reduced until a steady state is attained with $D_{\text{eff}} \approx D_c$. Therefore the cycle period has approximately the same value as it had for $D = D_c$: quenching of dynamo action yields a cycle period that is more or less independent of ω . This, however, is not compatible with the observations.

Other models assume that dynamo action is limited by losses owing to magnetic buoyancy (Leighton 1969; Yoshimura 1975). The resulting breakup of the submerged field, which emerges in active regions, can be represented by an enhanced diffusivity $\tilde{\eta}$, so that $D_{\text{eff}} \approx (\eta/\tilde{\eta})^2 D$. In a steady state, $D_{\text{eff}} \approx D_c$ and $P_{\text{cyc}} \propto \tau_\eta = (\eta/\tilde{\eta})\tau_\eta \propto D^{-1/2} \propto \omega^{-1}$. This is compatible with observations.

To illustrate these general arguments we consider plane dynamo waves, propagating in the x -direction (Parker 1979). Let $B = \{0, B(t)e^{ikx}, \partial/\partial x[A(t)e^{ikx}]\}$; then the dimensionless equations can be written as

$$\frac{dA}{dt} = \frac{2DB}{1 + \kappa_1(|B|^2)} - [1 + \lambda_1(|B|^2)]A \quad (3a)$$

$$\frac{dB}{dt} = \frac{iA}{1 + \kappa_2(|B|^2)} - [1 + \lambda_2(|B|^2)]B, \quad (3b)$$

where A, B are complex and $\kappa_1, \kappa_2, \lambda_1$, and λ_2 are monotonically increasing functions of $|B|^2$ that are zero when $B = 0$ (Robinson and Durney 1982; Weiss, Cattaneo, and Jones 1984). Then κ_1 and κ_2 represent nonlinear quenching of the α -effect and of differential rotation respectively, while λ_1 and λ_2 represent enhanced losses owing to magnetic buoyancy. These equations possess nonlinear solutions with A, B varying as $\exp(ipt)$ provided that the dynamo number $D > D_c = 1$ (cf. Weiss, Cattaneo, and Jones 1984).

Suppose that $\lambda_1 = \lambda_2 = 0$, so that saturation occurs only through quenching of dynamo action. It can readily be shown that this leads to finite-amplitude dynamo waves with a fixed frequency, $p = 1$, which is independent of D . In order to compare this simple model with the observations, we show the exponent $n \equiv 2d \log P/d \log D$ as a function of D in Figure 3. The line (a), with $n = 0$, lies well outside the observational range, indicated by dashed lines in Figure 3, and in fact may be rejected at the 99% confidence level. If, on the other hand, we suppose that $\kappa_1 = \kappa_2 = 0$ and that $\lambda_1 = \lambda_2$, so that saturation occurs through buoyant loss of magnetic flux, then the frequency $p = D^{1/2}$ and $n = 1$ (curve [b] in Fig. 3). It is more usual to set $\lambda_1 = 0$, so that buoyancy affects only the toroidal field (Leighton 1969; Yoshimura 1975; Robinson and Durney

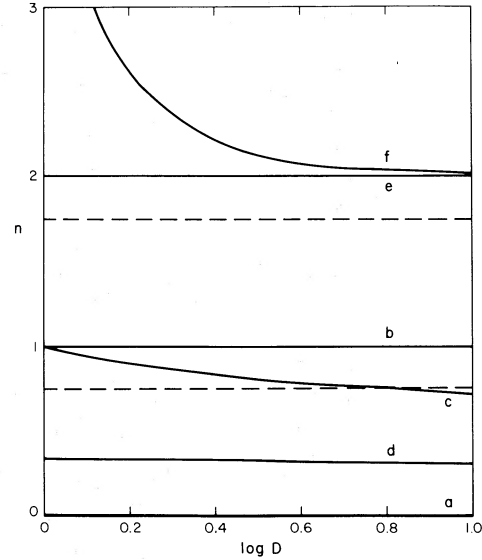


FIG. 3.—The theoretical slope $n = 2d(\log p)/d(\log D)$ plotted as a function of dynamo number D , where p is the dimensionless cycle frequency τ_η/P_{cyc} . The labeled solid lines correspond to different models discussed in the text. The dashed lines are empirical limits to the slope, as given by eq. (1).

1982). In that case, n decreases from unity to $\frac{2}{3}$ as D increases from 1 to infinity (curve [c] in Fig. 3). Both curves (b) and (c) appear to be compatible with the observations. Note, however, that an equal combination of quenching of dynamo action with losses through magnetic buoyancy leads to values of n that are too low, as shown by curve (d), for $\kappa_1 = \kappa_2 = \lambda_2$, $\lambda_1 = 0$.

The Lorentz force also generates fluctuations in differential rotation with twice the frequency of the basic cycle, which resemble the torsional waves that have been observed on the Sun (Howard and LaBonte 1980). These fluctuations can be modeled by adding an equation that describes the generation of a fluctuating contribution $w(t) \exp(2ikx)$ to the velocity shear, with w complex. The sixth-order system

$$\frac{dA}{dt} = 2DB - A, \quad (4a)$$

$$\frac{dB}{dt} = iA - \frac{iA * w}{2} - B, \quad (4b)$$

$$\frac{dw}{dt} = -iAB - vw, \quad (4c)$$

where ηv is the (turbulent) viscous diffusivity, has periodic solutions for $D > 1$ with $w \propto \exp(2ipt)$. If $v < 1$ these solutions become unstable, leading to aperiodic (chaotic) behavior that mimics the modulation of the solar cycle (Cattaneo, Jones, and Weiss 1983; Weiss, Cattaneo, and Jones 1984). For $v = 2$, $p = D$ and so $n = 2$ (curve [e]), but for $v = \frac{1}{2}$ we find that $5 \geq n > 2$ (curve [f]). In comparing these curves with observations we should only consider their slopes over a range of values of D (say $2 < D < 8$) that seems appropriate for stars like the Sun. Then both curves lie at or above the limit of compatibility with the observations. However, we note that adding in quenching of the dynamo action could bring the slope down within the observed range, just as its inclusion brought the slope of curve (c) down to that of curve (d).

IV. CONCLUSIONS

Our limited set of observational results implies that there is a definite dependence of the cycle period on the rotation rate for slowly rotating stars of fixed internal structure. Provided that both ω and $B-V$ lie within a restricted range we find that $P_{\text{cyc}} \propto \omega^{-n}$, $n = 1.25 \pm 0.5 > 0$ (eq. [1]). The exponent n can be used to place constraints on theoretical models. Thus we can rule out quenching of the α -effect or of differential rotation (curve [a] in Fig. 3) as the dominant mechanism limiting the dynamo. Limitation by losses through magnetic buoyancy (curves (b) and (c)), is quite compatible with the observations. On the other hand, limitation owing to fluctuations in differential rotation gives a value of n significantly larger than observed (curves [e] and [f]), although it cannot be ruled out, especially if quenching occurs as well. To proceed further requires more elaborate calculations for α - ω dynamos in spherical geometry, with nonlinear processes that vary with position and with time, (e.g. Yoshimura 1978) or for three-dimensional magnetohydrodynamic models (Gilman 1983a, b).

Given the relation $P_{\text{cyc}} \approx (\omega\tau_c)^{-1.25}$, we may explore how solar rotation and activity varied in the geological past. It has been suggested (Williams 1981) that the varved sediments laid down in Australia 7×10^8 years ago with an apparent near-periodicity of 11 years reflect an 11.2 year cycle of solar magnetic activity at that time. Recent solar wind measurements (Pizzo *et al.* 1983) imply that ω has decreased by about 2% over the last 7×10^8 years; this corresponds to one-quarter of the deceleration derived from Skumanich's (1972) relation. In the same interval, τ_c has decreased by about 0.5% (D. O. Gough 1984, private communication). Hence we expect the cycle period to have increased by about 3%. This seems still to be consistent with Williams's measurements. On the other hand, if the solar spindown over the same interval followed Skumanich's (1977) relation, we would expect the cycle period

to have increased by about 11% over that interval. Such a conclusion would conflict with Williams's results.

If relation (1) held throughout the Sun's evolution on the main sequence we would predict a cycle period of about 1 year at an age of 7×10^7 yr (corresponding to G stars in the Pleiades). However, it is by no means obvious that such a simple power law holds for rapidly rotating stars; indeed, the active BY Dra and RS CVn stars seem to have much longer cycle periods than the Sun (Hartmann 1981; Vogt 1983). Even within Wilson's (1978) sample, those few rapidly rotating active chromosphere stars which show indications of periodicity do not conform to the relation derived here. Thus this relation should not be taken as applicable to stars other than slowly rotating stars with dynamo number not much greater than unity.

Our procedure exemplifies the importance of the solar-stellar connection: by measuring magnetic activity in stars we can gain a better understanding of dynamo action in the Sun. Our exploratory study shows the need for an extended series of observations on a larger group of stars, in order to determine the dependence of P_{cyc} on σ more exactly for slowly rotating stars, and to discover what relationships hold for more rapidly rotating stars. By comparing these results with more elaborate theoretical models, it may then be possible to isolate the physical processes that dominate nonlinear dynamos.

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ROBERT W. NOYES: Solar and Stellar Physics Division, Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

ARTHUR H. VAUGHAN: Applied Optical Division, Perkin-Elmer Corporation, 7421 Orangewood Avenue, P.O. Box 3115, Garden Grove, CA 92642

NIGEL O. WEISS: Department of Applied Mathematics and Theoretical Physics, Silver Street, Cambridge, CB3 9EW, England