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STELLAR ROTATION IN LOWER MAIN-SEQUENCE STARS MEASURED FROM TIME VARIATIONS IN H AND K EMISSION-LINE FLUXES. I. INITIAL RESULTS

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ABSTRACT

Fluxes at 1 Å bands at the centers of the H and K lines in 46 lower main sequence field stars, and in eight selected subgiants and giant stars, have been measured at nightly intervals in the course of a nearly continuous 14-week observing run. In 19 stars we have found clear evidence of rotational modulation, from which values of the rotational periods can be assigned by inspection. In nine others, periods have been found by an autocorrelation analysis of the flux records. The periods obtained imply rotation velocities that are in good accord with spectroscopically determined values of $V \sin i$ in the literature for 13 of the stars we have observed.

Much of the short term scatter in H-K flux observed by Wilson appears to be caused by rotational modulation, although variations on other time scales are also present.

As many as 80% of the chromospherically active (i.e., young) stars display prominent rotational modulation, and in some cases the phase of the modulation remained unchanged for the entire observing period, suggesting that markedly asymmetric and long-lived distributions of active regions are common in such stars.

At a given $(B - V) < 1.0$, the strength of H-K emission is shown to vary as a function of rate of rotation, suggesting that rotation, rather than initial conditions or age *per se*, is the chief parameter influencing chromospheric output.

From data on stellar activity cycles available at present, it is suggested that periodic cycles resembling the Sun's are almost exclusively found in stars with rotation periods in excess of about 20 days; and, except for this threshold effect, the cycle periods are uncorrelated with rotation rate.

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

I. INTRODUCTION

In his study of chromospheric variations in main sequence stars, Wilson (1978) called attention to the fact that in the observed chromospheric H and K flux variations a periodic component might be present as the result of rotational modulation, if active regions giving rise to the emission are nonuniformly distributed in longitude, as is often the case in the Sun. He suggested that frequent observations over several weeks might yield rotational periods for such stars. Knowledge of rotational periods found in this way would allow many questions to be explored anew concerning the evolution of stellar angular momentum, and the connection between chromospheric activity and rotation. We were thus motivated to look for rotational modulation in the H-K fluxes of 46 late-type main sequence stars and eight subgiants and giants, in an observing run that extended almost continuously from 1980 July 1 through October 15, on the 1.5 m telescope of the Mount Wilson Observatory.

The present article is a brief account of the initial results of our survey, and of the most evident conclusions that we believe can be drawn from it. A more detailed analysis of the data is in preparation.

II. OBSERVATIONS AND ANALYSIS

Our observations were obtained with the four-channel chopping spectrometer (HKP2) at the Mount Wilson 1.5 m telescope. The instrument and its operation have been described by Vaughan, Preston, and Wilson (1978). An LSI-11/2 computer-controlled flexible disk data-logging system and a television slit viewer were implemented for this project.

Each integration with the HKP2 yields the value of a flux index, S (defined in Vaughan *et al.* 1978), proportional to the total equivalent width of the Ca II H and K emission reversals and residual photospheric light in 1 Å bands centered at H and K. Doppler wavelength shifts corresponding to each star's geocentric velocity were computed for each night, and compensating offsets were introduced manually with a nominal precision of about 1 km s^{-1} (i.e., 0.01 Å). Temperature drifts in the calibration

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of the zero-point wavelength degraded the final precision to only 3–5 km s^{-1}. Such drifts were unimportant on some nights when the temperature changed little; on other nights, as necessary, the drift was compensated by frequent recalibration. In our standard procedure three integrations were made for each star, each to a preset count of 2000 in the K-channel, so that the formal statistical accuracy of the derived mean flux index was near 1%. The count was increased for the brightest stars to ensure integrating times in excess of 30 s in order to hold chopper noise below 1%. The count was sometimes decreased for the faintest stars, or when extinction by clouds required, to keep net integrating times below an upper limit of about 600 s. The instrumental and sky background was measured between every few stars or with each star as conditions required; the flux indices presented here have been corrected accordingly.

Five of the stars routinely followed in our program were "standard stars" found by Wilson (1978) to exhibit low and nearly constant values of H-K flux. As an additional check on the stability of the equipment, we made daily measurements of an artificial continuum light source mounted so as to simulate the f/16 beam of the telescope.

These measurements of artificial and standard star sources should ultimately permit any systematic instrumental effects to be estimated and corrected in the data. Such corrections have not been applied to the data we present here; instead, a constant scale factor derived from the mean measures of standard stars has been applied, merely to bring the flux index scale into registration with previously published work (cf. Vaughan and Preston 1980). Our inspection of the data indicates that any systematic instrumental effects were actually quite small, probably not exceeding the 1 or 2% level.

Table 1 lists in order of color index the identifications and spectral types of the stars selected for observation (cols. [1] and [2]), the $(B - V)$ color index (col. [3]), the span of time, ΔT, over which our observations extended for each star (col. [4]), the mean value $\langle S \rangle$ of the H-K flux during this time and the observed range, ΔS, relative to $\langle S \rangle$, expressed as percentage (cols. [5] and [6]). Where rotation periods could be deduced from the observations, these are listed and compared with published $V \sin i$ values (cols. [7]–[9]), as discussed below.

The first 46 entries in Table 1 are main sequence stars, comprising nearly all of Wilson's (1978) list within the right ascension limits set by the observing season. An active M1 dwarf (Gliese 685) from the survey by Vaughan and Preston (1980) was included although the long-term behavior of chromospheric activity is unknown for this star. The final eight entries in Table 1 are of luminosity classes III and IV; a more extensive discussion of these than can be given here is in preparation.

In most cases each star was observed once per night. This frequency of observation was deemed sufficient on the basis of earlier studies, including a preliminary two-week test run at Mount Wilson in 1979 November by Middelkoop, Vaughan, and Preston (1981). The frequency of observation allowed periods of only a few days to be determined, while the overall length of the program made possible detection of periods as long as 50 days. These choices also provided sufficient sampling to distinguish "random" chromospheric fluctuations from periodic rotational modulation for a large fraction of the stars.

Examination of the records of the H-K fluxes of the observed main sequence stars reveals that about 40% show clear periodic variations; these are sufficiently unambiguous that approximate periods can be determined simply by inspection of the data. Examples of several such records are illustrated in Figure 1. An additional 20% of the stars show fluctuations suggestive of periodic behavior, but insufficiently clear to allow a period to be assigned with confidence by inspection.

We have computed autocorrelation functions for the 54 stars in our survey (see Fig. 2). Of these, 28 show clear evidence of periodic variations through their autocorrelation functions, including those already mentioned whose periods are directly measurable. The rotation periods for these 28 stars, measured from autocorrelation functions, are listed in column (7) of Table 1.

For the remaining 26 stars, rotational periods have not been determined, for one or more of the following reasons: (*a*) fluctuations are present at a significant level in the data, but do not show significant periodicity, (*b*) the amplitude of stellar fluctuations, whether produced by rotation or not, is undetectably small compared to the fluctuation level of the data (as evidenced by variations among the normally three observations during each night), or (*c*) detectable fluctuations exist, but the total length of the observing program for the star in question (col. [4] of Table 1) is too short to allow unambiguous determination of rotation periods. For many of these stars rotational periods may be derived in the future from analysis of the present data or from further data currently being acquired.

If the periodicities in the observed records are caused by rotation, there should be agreement between the period P and the spectroscopically determined projected velocity of rotation, $V \sin i$, in the sense that for a star with radius R and inclination i of its rotation axis, $2\pi R/P \geq V \sin i$.

Nominal values of $2\pi R/P = V$, estimated from an adopted mass-radius relation (Harris, Strand, and Worley 1963) are given in column (8) of Table 1, along with values or upper limits of $V \sin i$ in column (9), found in the literature for 34 of the observed stars. In 13 of these we have determined rotation periods, and for these stars, as may be judged from the data in Table 1, agreement with the observed $V \sin i$ appears to be virtually universal. In HD 201091 (61 Cyg A) our determination of the period of rotation does not agree with the line broadening reported by Vogt and Fekel (1979), although both methods indicate slow rotation. The equatorial velocity of this star according to our result (1.0 km s^{-1}) would lie below the expected spectroscopic detection limit (Smith 1978) of about 2 km s^{-1}.

In an independent autocorrelation analysis, Stimets and Giles (1980) reported rotational modulations for 10

TABLE 1

STARS OBSERVED FOR ROTATIONAL MODULATION IN Ca II H AND K EMISSION

(1) Star		(2) Sp	(3) B−V	(4) ΔT (Days)	(5) ⟨S⟩	(6) ΔS/⟨S⟩ (Percent)	(7) P† (Days)	(8) V (Km/s)	(9) V Sin i	(10) Reference
207978	*	F0	0.42	95	0.150	8	–	–	≤6	K67
2454		F2	.43	86	.160	7	–	–	8	K67
3229		F2	.44	86	.216	6	–	–	≤10	W66
182101		F6	.45	95	.210	8	–	–	13	K67
187013	*	F5	.46	95	.148	6	–	–	9	K67
194012		F5	.51	95	.194	7	–	–	6	K67
16673	**	F6	.52	91	.210	10	(6.2)	10	≤ 6	K67
212754	*	F5	.52	85	.139	7	(13)	5	7	K67
25998	**	F7	.54	72	.282	9	2.5	23	22	K67
13421	*	F8	.56	95	.125	5	–	–	≤10	W66
187691	*	F8	.56	95	.146	6	(15)	4	≤ 6	K67
26923	**	G0	.57	72	.281	9	–	–	≤ 6	K67
154417		F8	.57	95	.259	9	7.6	7	≤ 6	K67
206860		G0	.58	95	.319	9	4.7	11	11	K67
6920		F8	.60	86	.199	7	(13)	4	–	–
30495		G1	.61	36	.290	8	–	–	–	–
190406		G1	.61	86	.190	13	14.0	4	3-5	K67
12235		G1	.62	86	.160	7	–	–	≤10	W66
161239		G6	.65	86	.134	8	–	–	≤10	W66
1835	**	G2	.66	95	.336	11	7.9	6	7.0+0.7	SO81
224930		G2	.66	86	.175	7	–	–	< 6	K67
217014		G5	.68	85	.148	6	–	–	1.7+0.8	SO81
20630	**	G5	.68	92	.348	12	8.5	6	<15	HS55
26913	**	G3	.70	71	.380	11	7.2	7	< 6	K67
10700		G8	.72	95	.168	4	–	–	2.4+0.7	SO81
152391		G8	.76	95	.412	17	11.0	4	–	–
219834A		G8	.79	86	.155	9	–	–	≤15	HS55
149661		K0	.81	53	.331	21	21.0	2	–	–
26965		K1	.82	27	.191	5	–	–	–	–
10476		K1	.84	95	.172	8	–	–	<20	HS55
3651		K0	.85	86	.171	8	–	–	–	–
155885		K1	.86	95	.399	13	23	1.8	–	–
155886		K1	.86	95	.337	11	21	2.0	–	–
17925	**	K0	.87	88	.606	8	6.9	6	–	–
166620		K2	.87	95	.210	8	(43)	1	–	–
22049	**	K2	.88	71	.533	10	11.8	4	<15	HS55
4628		K4	.89	86	.194	8	(20)	2	–	–
219834B		K2	.91	85	.201	29	–	–	–	–
160346		K3	.96	95	.314	13	34	1	–	–
16160		K4	0.97	85	.231	6	(45)	0.8	–	–
32147		K5	1.07	36	.302	9	–	–	–	–
190007		K4	1.12	95	.767	25	29	1.3	–	–
156026		K5	1.16	95	.893	22	17	2.2	–	–
201091		K5	1.18	95	0.694	16	37	1.0	2 (4)	VF79 (SM79)
201092		K7	1.38	95	1.088	18	48	0.7	<25	SL63
GL-685		M0	1.45	90	2.213	40	(9)	3.5	–	–
6903		F5III	0.69	95	0.294	18	–	–	100	FD70
218658		G2III	.76	95	.220	19	–	–	≤15	HS55
27022		G5III	.81	49	.181	6	–	–	<20	HS55
148387		G8III	.91	95	.110	6	–	–	<15	HS55
23249		K0IV	.92	70	.133	3	–	–	2.2+0.9	SD79
24555		G8III	0.94	58	.166	19	–	–	<15	HS55
29317		K0III	1.07	29	.218	18	–	–	<15	HS55
222107		G8IV-III	1.07	91	0.931	28	54	7	<20	HS55

* Wilson Standard

** Also observed in November 1979 test run (Middelkoop, et.al. 1981)

† Likely periods deduced from autocorrelation analysis alone are given in parentheses.

References to spectroscopic determinations of V sin i:

FD70	Faber and Danziger (1970) 13.6 A/mm	SD79	Smith and Dominy (1979)
HS55	Herbig and Spalding (1955) 11.0 A/mm	SO81	Soderblom (1981)
K67	Kraft (1967) 5.0, 4.5 and 2.4 A/mm	VF79	Vogt and Fekel (1979)
SL63	Slettebak (1963) 20 A/mm	W66	Wilson (1966)
SM79	Smith (1979)		

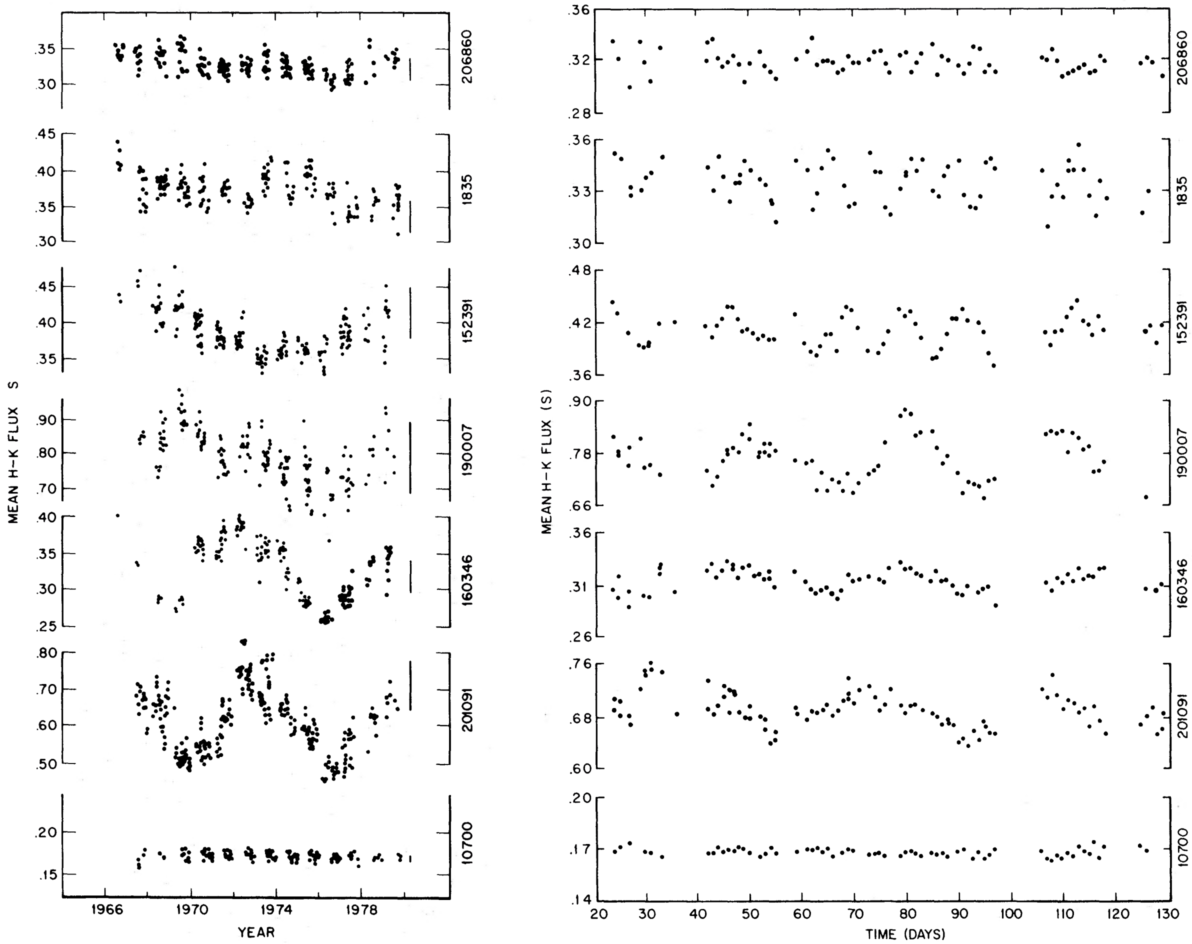

FIG. 1.—Mean H-K fluxes v. time for selected main sequence stars (*right*) as observed at daily intervals in present study; values along horizontal axis are JD −2,444,400 (*left*) previous long-term flux variations, from Wilson (1978) and subsequent unpublished measurements by Preston and Vaughan. Bars indicate the range of variation observed in 1980.

stars, based on Wilson's (1978) much more sparsely spaced data. Of the three stars overlapping our program stars, there is excellent agreement for two (HD 206860 and HD 201091; see Table 1). For the third, HD 155886, Stimets's period is a factor of 3 smaller than ours. Because HD 155886 is one of the stars whose rotational modulation is visible by inspection, as well as through study of its autocorrelation, we believe that our quoted period is in fact the correct one, and that Stimets and Giles's analysis may have suffered from aliasing, produced by an undersampling of the period.

III. DISCUSSION AND CONCLUSIONS

a) The Incidence of Rotational Modulation

The observations reported here demonstrate that, as foreseen by Wilson (1978), rotational modulation occurs in stars at a discernible level. This modulation provides a powerful new way to measure stellar rotation even when the rate of rotation is far too small to be detected by classical spectroscopic means. Periods determined from rotational modulation do not depend upon the (usually unknown) orientation of the rotation axis. Thus, by amassing sufficient data, it should be possible to investigate directly the distribution function of angular momentum among chromospherically active stars.

Our observations show that the "short-term" fluctuations in H-K flux observed by Wilson (1978) are produced largely by rotation (see Fig. 1*b*). Variations on other time scales are also present, however. Virtually all stars display measurable night-to-night fluctuations at levels well above the limits of observational error. In some stars, fluctuations are measureable in time scales of a few minutes (Baliunas *et al.* 1981). In some instances, we have also observed the rotational modulation to wax and wane, or to drift in phase, as would be expected (and is observed in the Sun) when individual active regions grow and decay.

Among 25 stars in our survey that could be classified according to their H-K fluxes as "young" (cf. Vaughan 1980), clearly defined rotational modulation was easily seen in about 20 of them. This suggests that such stars

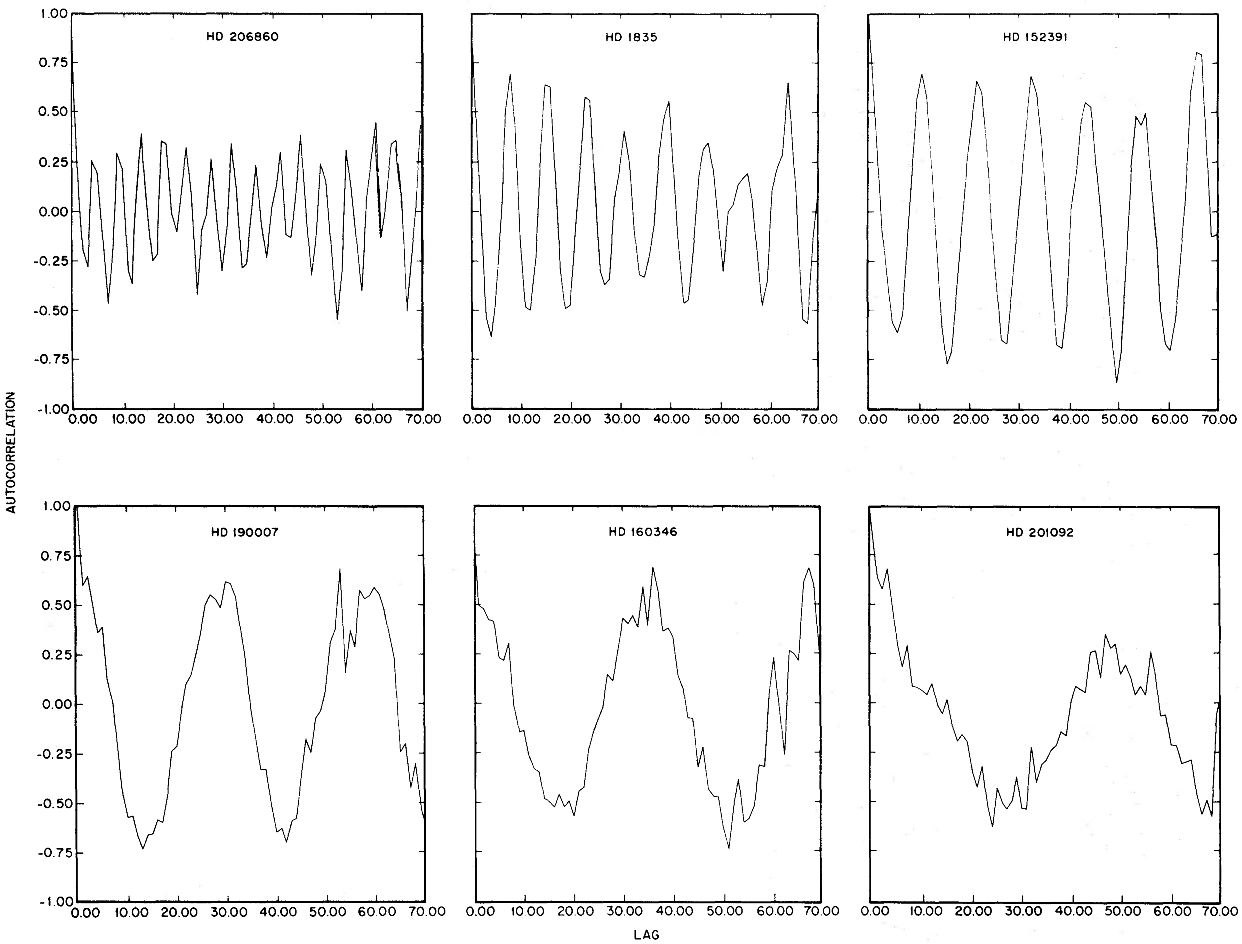

FIG. 2.—Fractional autocorrelation functions of H-K flux variations in selected main sequence stars observed at daily intervals

spend a large fraction (perhaps 80%) of their time with markedly asymmetric distributions of active regions on their surfaces. In several cases the modulation shows remarkable persistance in amplitude and phase. The modulation has been observed through as many as a dozen or more rotations in the case of rapidly rotating stars such as HD 25998 and 206860. Recent observations by J. Frazer at Mount Wilson (private communication) show that the rotational modulation we found in HD 20630, 190007, and 201092 has persisted essentially unchanged in phase over a duration of almost 5 months.

By analogy with the Sun, the active regions responsible for the observed modulation are likely to be associated with, and dominated by, strong photospheric magnetic fields. Evidence of a similar, although perhaps less pronounced, long persistance of activity complexes in the Sun has been reported (Bumba and Howard 1965; Wilcox *et al.* 1970), and has also been noted by LaBonte (1980, private communication).

Wilson (1978) showed that among stars of all spectral types the short-term fluctuation (expressed as a percentage of the mean H-K flux) varies more or less in proportion to the mean flux. Our observations are in accord with this result. Thus in "old" stars, rotational modulation is relatively hard to detect; we have detected it in only 6 out of 20 such chromospherically less active stars in our survey. Evidently the area occupied by active regions, their surface brightness relative to "quiet" regions, or both, decrease as the stars age.

Among the six stars of luminosity class III in our survey, we found the amplitude of scatter (i.e., signal contrast, in col. [6] of Table 1) to be small—about 6%—in two of them (HD 27022, G5 III; and 148387, G8 III), and significantly larger—15–20%—in the other three (HD 6903, F5 III; 218658, G2 III; and 24555, G8 III). In a conservative assessment of our measurements we do not find clear evidence of periodic modulation in these giants, although more detailed analysis may reveal significant periodicities. In HD 222107 (λ And, G8 III–IV) the scatter is large—25%—and in this one case a component of variation is clearly present with $P \sim 54^{d}$. This period matches the period found in broad-band measurements in the continuum (Landis *et al.* 1978); furthermore, the maximum of H-K emission in our data for this star occurs at the time of minimum photometric brightness, as would be expected if the "dark spots" postulated by Landis *et al.*

are associated with enhanced chromospheric activity (Baliunas and Dupree 1980).

In the dwarfs and subgiants that showed a large amplitude of scatter in S, significant variations occurred on a shorter time scale than we could resolve with only one observation per night. For some of these, a more frequent sampling schedule was followed during a few nights by one of us (S. L. B.); the results will be published separately.

b) The Dependence of H-K Emission upon Rotation

Figure 3 is the (log S, $B - V$)-diagram from the data listed in Table 1 for stars whose periods of rotation have been determined in the present work. The number printed beside each point is the rotational period in days. The diagram indicates the observed upper and lower limits of H-K flux among main sequence stars and the region occupied by the Hyades lower main sequence, from Figure 1 of Vaughan and Preston (1980). Inspection of Figure 3 reveals that at a given $B - V$, the strength of H-K emission increases with increasing stellar rotation rate. This result dramatically confirms the proposals of Wilson (1963), Wilson and Skumanich (1972), and Kraft (1967) that H-K emission and rotation in main sequence stars both decline with advancing stellar age. In addition, periods of rotation can be seen to increase toward the right in Figure 3. This result confirms and extends to later types the well known trend of decreasing $V \sin i$ with advancing spectral type (see Slettebak 1970).

Among stars of a given (young) age, namely those lying along the band defined by the (log S, $B - V$)-relation for the Hyades cluster (see Fig. 3), it appears that periods of rotation are essentially independent of spectral type for stars later than F8. The dispersion in the rotation periods of these youngest stars ($\bar{P} = 7.3 \pm 1.8$ s.d. days) is remarkably small in comparison with the overall range of the periods we have observed among stars of all ages. These periods are essentially in agreement with observed values of $V \sin i$ in the same spectral type range among Hyades cluster members (Kraft 1965).

Indications as to the possible form of a relationship connecting H-K emission, spectral type, and rotation can be extracted from the results now in hand, although much more data will be required for a definitive treatment. As a tentative suggestion of the form such a relationship might take, we have plotted, in Figure 4, the observed mean values of log S against P (from Table 1) for selected stars whose colors are confined to a few narrow intervals. For stars in the range $0.86 \leq B - V \leq 0.89$, it is particularly

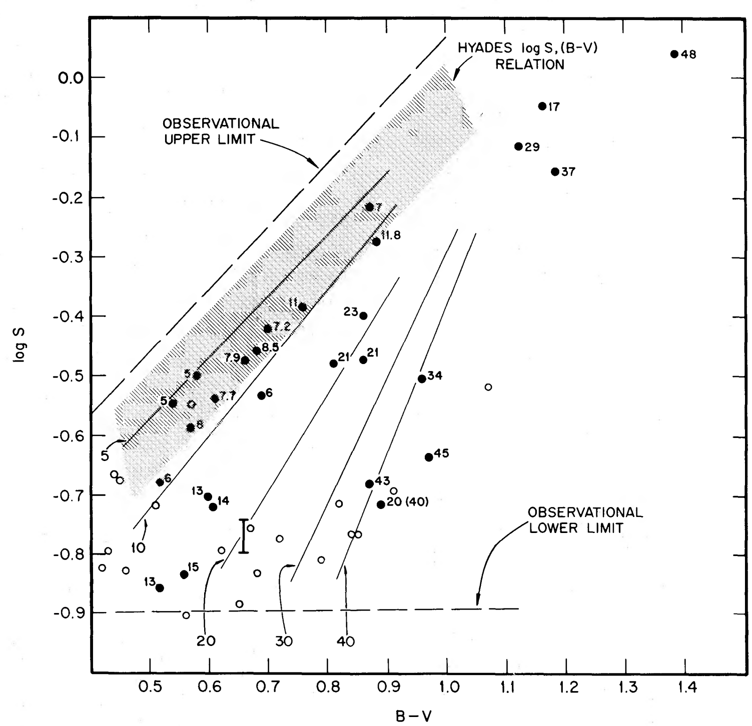

FIG. 3.—[Log S, ($B - V$)]-diagram for main sequence stars listed in Table 1. Filled circles represent stars whose period (printed beside each point, in days) was determined in the present work. Open circles are stars for which periods could not be ascertained in the data. Vertical bar represents the Sun's H-K flux and its variation, after Wilson (1978). Dashed lines indicate upper and lower boundaries of the distribution of H-K fluxes observed among main sequence field stars by Vaughan and Preston (1980). Shaded area depicts [log S, ($B - V$)]-relation observed by Wilson (1973) for Hyades cluster. Solid lines tentatively represent transformed loci of vertical cuts in Fig. 4, in which log S is plotted against period of rotation.

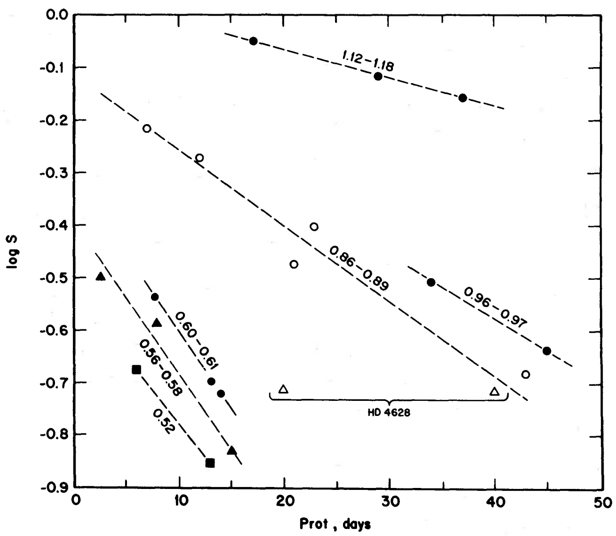

FIG. 4.—Log S vs. period of rotation for stars in selected narrow intervals of $B - V$. For a given color, the points appear to lie along well-defined sequences, which have been arbitrarily fitted here by straight lines in the diagram. Such trends indicate that chromospheric activity is driven by rotation.

apparent that a linear relation between log S and P represents the observations fairly well; thus, for these stars $S \approx 0.78e^{-P/30}$, provided S is large enough that a correction for the photospheric component of emission is unimportant. At other colors (and hence masses) the slope of the relation between log S and P appears to be different, being somewhat steeper for earlier types and less steep for later types. The exponential relation suggested here seems to fit the observations about as well as the linear relation $S \propto P^{-1}$ implied in Skumanich's (1972) discussion of the age-dependance of H-K flux and rotation. Our presentation in terms of an exponential relation does not mean that we believe such a law is necessarily correct.

If the linear relations noted in Figure 4 are taken at face value and a smooth interpolation is made, a grid of lines of constant P can be constructed. These lines, drawn in Figure 3, are tentative, and are intended only to be suggestive of the form of the actual relationship that may be revealed by sufficient additional data. In particular, we note that stars redder than $B - V = 1.0$ do not fit a straight line extrapolation of the grid from earlier types. Also, in the case of HD 4628, at $B - V = 0.89$, the rotation period we find (20^d) is about half that required to be consistent with its position in the (log S, $B - V$)-diagram according to our supposed relations among these parameters. Although a 20^d periodicity is seen clearly in the flux record of this star, it is possible that this period is a harmonic of the true period of rotation, caused by multiple active regions on the stellar surface.

Despite such uncertainties, the trends seen in Figures 3 and 4 are clear enough to suggest that conditions prior to a star's arrival on the zero-age main sequence are either universal or, more likely, are completely erased at an early stage and play little or no role in controlling the excitation of stellar chromospheres. *The mechanisms that give rise to the chromospheric activity seem to depend primarily or solely upon the rate of stellar rotation,* which in turn (in view of independent evidence of the age dependence of chromospheric activity) declines continuously with advancing age. This observational inference supports the validity of notions previously advanced implicitly or explicitly by others (cf. Kraft 1967; Skumanich 1972; Zwaan 1977, 1981, and 1979, private communication; see also Skumanich 1981).

c) *Rotation and the Incidence of Activity Cycles*

Wilson (1978) concluded that about a dozen of the stars in his survey had essentially completed a cycle of H-K flux variation in the interval 1966–1977. In an as yet unpublished continuation of his survey since 1977 by Vaughan and Preston, another four or five have completed an apparent cycle. For six of these cyclic stars the rotation periods are now also known. Of these, HD 4628, 16160, 16620, and probably 201092 have cycles lasting 10–12 years and rotation periods ranging from 20 to over 40 days. Among these the cycle duration shows no relation to either spectral type or rotation, except insofar as these stars, like the Sun, are slow rotators. In HD 160346 and 201091 these cycles clearly have durations of only about 7 years; these are also very slowly rotating stars. In the case of HD 155885/6, both of which rotate in about 20 days, it is difficult to assign cycle periods, although variations on a 5–10 year time scale are present. HD 17925 has declined in activity since 1970 ar earlier, with a possible recovery beginning in 1980 and thus a possible cycle in excess of 10–12 years; the rotation period we find for this star (6.9 days) is the shortest of any star showing a cycle, in this case not a particularly clear one.

If any generalization can be made from the meager data available at this point, it is that *obvious, 10–12 year activity cycles are found almost exclusively among stars with rotation periods longer than about 20 days, and the periods of these cycles are uncorrelated with the rotational velocities.*

This dichotomy, if supported by further observations, may imply that at least two modes of magnetic-field generation occur in late-type stars: globally organized cyclic activity in slow rotators ($P > 20^d$), and incoherent (i.e., noncyclic) eruptions in faster rotators ($P < 20^d$). Such behavior may be related to the existence of the gap in the (S, $B - V$)-diagram (see Vaughan and Preston 1980; Vaughan 1980); and, further, may place important constraints on theories of stellar magnetic field generation and dynamos.

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