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STELLAR ROTATION IN LOWER MAIN-SEQUENCE STARS MEASURED FROM TIME VARIATIONS IN H AND K EMISSION-LINE FLUXES. II. DETAILED ANALYSIS OF THE 1980 OBSERVING SEASON DATA

SALLIE L. BALIUNAS,[1] ARTHUR H. VAUGHAN,[2] LEE HARTMANN,[1] FRANS MIDDELKOOP,[3]
DIMITRI MIHALAS,[4] ROBERT W. NOYES,[1] GEORGE W. PRESTON,[2]
JAMES FRAZER,[2] AND HOWARD LANNING[2]
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ABSTRACT

For a sample of 47 lower main-sequence stars, including the Sun, and eight evolved stars, the relative strength of the Ca II H and K emission cores has been measured daily over a nearly continuous interval during 1980 July through October at Mount Wilson. From these time series measurements of chromospheric emission, rotation rates have been inferred with quantitative estimates of both the reality and precision of the rotation periods. We find rotation rates easily for the main-sequence stars with strong emission or those later than about spectral type K0. With this technique, rotation rates can be measured precisely for the first time for equatorial velocities as slow as 1 km s^{-1}, and independently of the aspect of the rotation axis. In a limited range of spectral type, a small sample of stars indicates that chromospheric emission decreases smoothly as a function of rotation period. No conclusion can be drawn on the question of the reality of a discontinuity in chromospheric emission as a function of time (the "Vaughan-Preston" gap for stars in the solar neighborhood).

In our sample of giant stars, the G2 III star HD 218658 shows a persistent fluctuation of 4.6 days, a period that is inconsistent with stellar rotation. The G0 III star HD 6903 is a previously unreported FK Comae–type star.

For a few main-sequence stars, measurements continued beyond 1980 October suggest the presence of active longitudes (if not individual active regions) persisting through the observing season 1981.

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

I. INTRODUCTION

That rotation is an important indicator of chromospheric emission strength measured at Ca II H and K in late-type stars was discovered empirically nearly two decades ago (Wilson 1963; Kraft 1967, 1970). Further, it is independently observed that chromospheric activity declines as a function of age in main-sequence stars (Wilson 1963; Wilson and Skumanich 1964; Wilson and Woolley 1970; Skumanich 1972). Our initial results confirmed that the strength of chromospheric activity is dependent upon the rate of stellar rotation (Vaughan *et al.* 1981, hereafter Paper I), an idea previously advanced by others (Kraft 1967; Skumanich 1972; Skumanich and Eddy 1981; Zwaan 1981).

Wilson (1978) monitored Ca II H and K chromospheric emission on a variety of cool dwarf stars exhibiting ranges of emission strength. In that landmark work, a wide range of chromospheric variations was revealed, including changes over time scales reminiscent of that of the solar 11 yr activity cycle. Vaughan (1980) suggested that young stars with strong chromospheric emission exhibit erratic long-term variations with no clearly defined period, while the old, weak-emission stars show variations comparable to the solar activity cycle. Since chromospheric emission is thought to be related to magnetic activity, the dichotomy in appearance of activity cycles between the weak and strong emission-line stars may be the result of the evolution of magnetic dynamo action. Notions proposing such a distinction from dynamo theory include, for example, changes in subsurface convection (Knobloch, Rosner, and Weiss 1981) or in the interference of dynamo modes (Durney, Mihalas, and Robinson 1981) as rotation rates evolve. While convectively driven dynamos are likely responsible for stellar magnetic fields, dynamo theory lacks quantitative

[1]Harvard-Smithsonian Center for Astrophysics.
[2]Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington.
[3]Sonnenborgh Observatory, University of Utrecht.
[4]Sacramento Peak Observatory, operated by Associated Universities for Research in Astronomy under contract AST 78-17292 with the National Science Foundation.

details linking chromospheric emission and rotation rate in cool stars (Gilman 1976; Weiss 1981). The expectation is, however, that measurements of rotation and stellar chromospheric activity will provide a basis for theoretical progress.

In Paper I we showed that rotation periods could be precisely determined in many late-type dwarf stars. The technique finds periods by monitoring surface inhomogeneities whose contrast is bright in Ca II H and K emission relative to a steady background level of emission and which persist longer than a stellar rotation. Most of the stars are a subset of Wilson's (1978) sample of cool dwarfs monitored for activity cycles. As suggested by Wilson, the modulation of chromospheric emission by rotation of surface features accounts for much of the seasonal scatter in Wilson's data. That rotation periods can be clearly defined is an important result, deriving its importance from an ability to detect rotation for equatorial velocities too small to be detected spectroscopically, as well as to determine rotational velocities independent of the ambiguity of the inclination of the rotation axis.

In this paper we quantify the periods reported in Paper I. We also extend analysis of the chromospheric emission fluctuations with time over a slightly longer time scale in a few stars observed beyond 1980 October, the end of the concentrated observing program in Paper I. From these data, we also examine the lifetimes of the sites of chromospheric emission and the morphology of the light curves in order to investigate the nature and distribution of chromospherically active areas on some of these stars.

II. OBSERVATIONS

a) *Procedures*

The sample of 46 lower main-sequence and eight subgiant and giant field stars remains the same as in Paper I. Of the main-sequence stars, all except Gliese 685 (dM0) were observed by Wilson (1978) for evidence of activity cycles analogous to the solar sunspot cycle.

Observations were made with the Mount Wilson 60 inch (1.52 m) reflector and four-channel chopping spectrophotometer as described by Vaughan, Preston, and Wilson (1978) and Paper I. Data presented here are a series of Ca II H and K flux measurements, S, as a function of time for our program stars. The quantity S, defined by Vaughan, Preston, and Wilson (1978), is proportional to the equivalent width of emission in the Ca II H and K cores contained within 1 Å passbands centered on the cores. Nightly measurements of S were obtained for each star during a nearly continuous interval between 1980 July 1 and October 1. For several stars, observations were occasionally extended through late 1980 or begun again early in 1981.

All of our instrumental flux values have been multiplied by a constant factor of 2.4 to create the final observational quantity, S. This scale factor, determined by Vaughan, Preston, and Wilson (1978) and Vaughan and Preston (1980), brings the measurements obtained with the spectrophotometer on the 60 inch telescope into registration with Wilson's original data obtained on the Mount Wilson 100 inch (2.54 m) telescope. Lacking evidence to readjust it, we have continued to use this constant factor. Measurements for the Sun and our program stars from the 1980 summer program are shown in Figures 1 and 2 and summarized in Tables 1–3. These data exist on magnetic tape and can be made available to interested scientists.

b) *Standard Stars*

Measurements of standard stars are our guideposts to the long-term precision and stability of the photometric system. Wilson (1978) chose a preliminary set of standard stars which showed the smallest contrast of emission relative to the nearby continuum. As might be expected, such stars show the least measured variation. Five of Wilson's standards plus HD 10700, which Wilson did not initially consider as a standard star, constitute our set of standards which are monitored as frequently as other program stars.

The precision of the spectrophotometric system is at least as good as the smallest measured variation in the standard stars in the sense that even our adopted standards may, in fact, exhibit intrinsic variations. The results for our six standards are listed in Table 1. Listed are the star name (col. [1]), and the total number of observations (col. [2]). Usually, two to three measurements of each star were made per night, and the individual measurements are used to calculate $\langle S \rangle$ (col. [3]), the average value of the series, and the standard deviation of an individual measurement from the mean of S (s.d.; col. [4]). Additionally, the ratio of the standard deviation to the mean of S, expressed as a percentage, is listed for our measurements (col. [5]) and for those of Wilson (1978), (col. [6]). Good agreement exists between Wilson's and our data for the standard stars, both for the values of $\langle S \rangle$ and their standard deviations.

Considered together, all the standards reflect a long-term instrumental precision of about 2% in S. Some of the standards, however, consistently exhibit larger variation than others, implying that for these stars at least some of the variation is real (cf. Wilson 1978; Vaughan, Preston, and Wilson 1978; and Baliunas *et al.* 1981). For example, the Sun may be classified as a relatively weak H and K emission star (cf. Vaughan and Preston 1980), yet it exhibits detectable flux variations (see below). Evidence for variation in the standard stars, however, is not conclusive in these data. We emphasize that the precision calculated above is a conservative estimate.

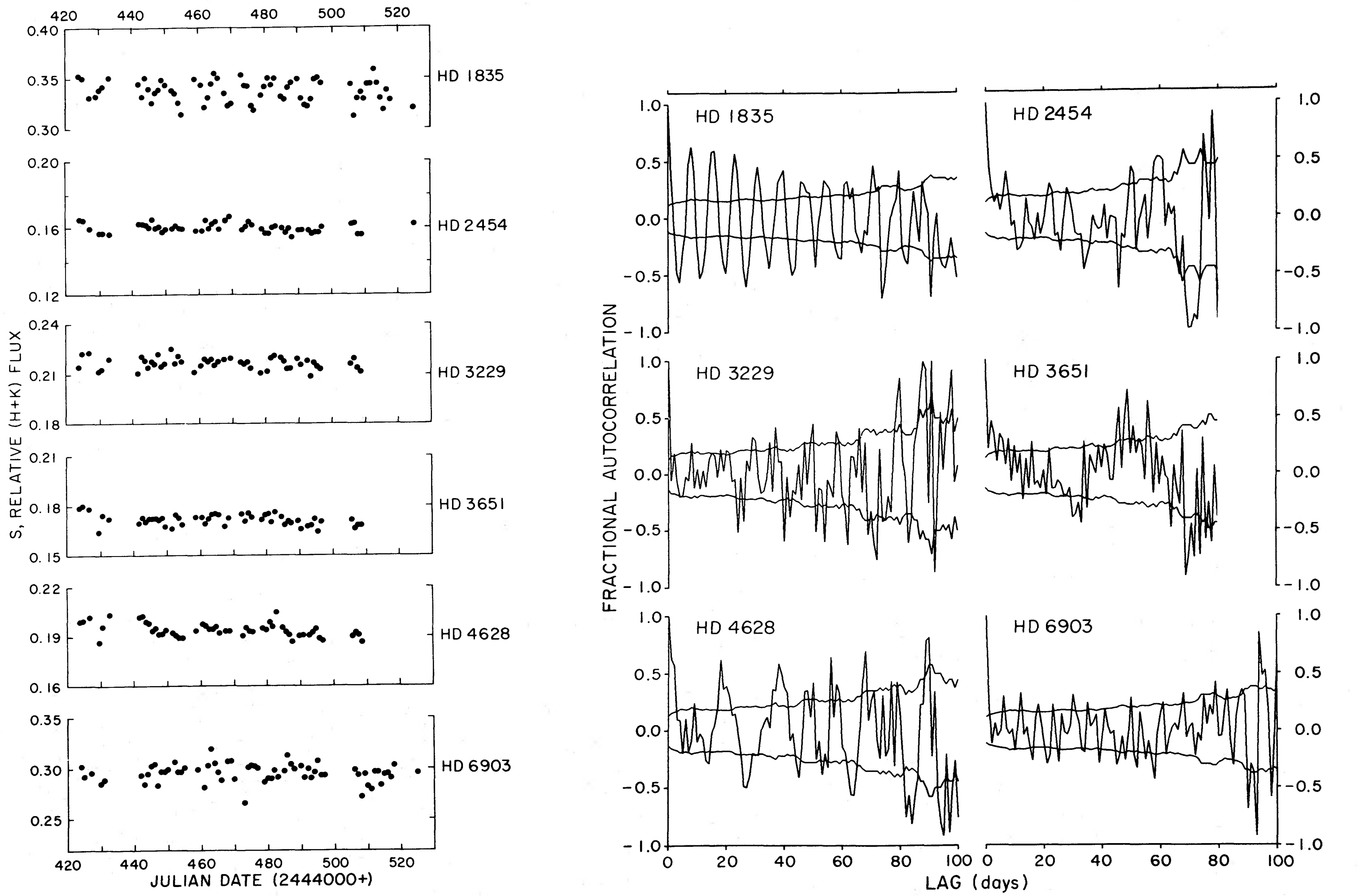

FIG. 1.—For all program stars, S is plotted as a function of time. The quantity S is the total chromospheric emission in Ca II H and K relative to the nearby stellar continuum. The fractional autocorrelation coefficients are plotted as a function of days in the lag of the autocorrelation.

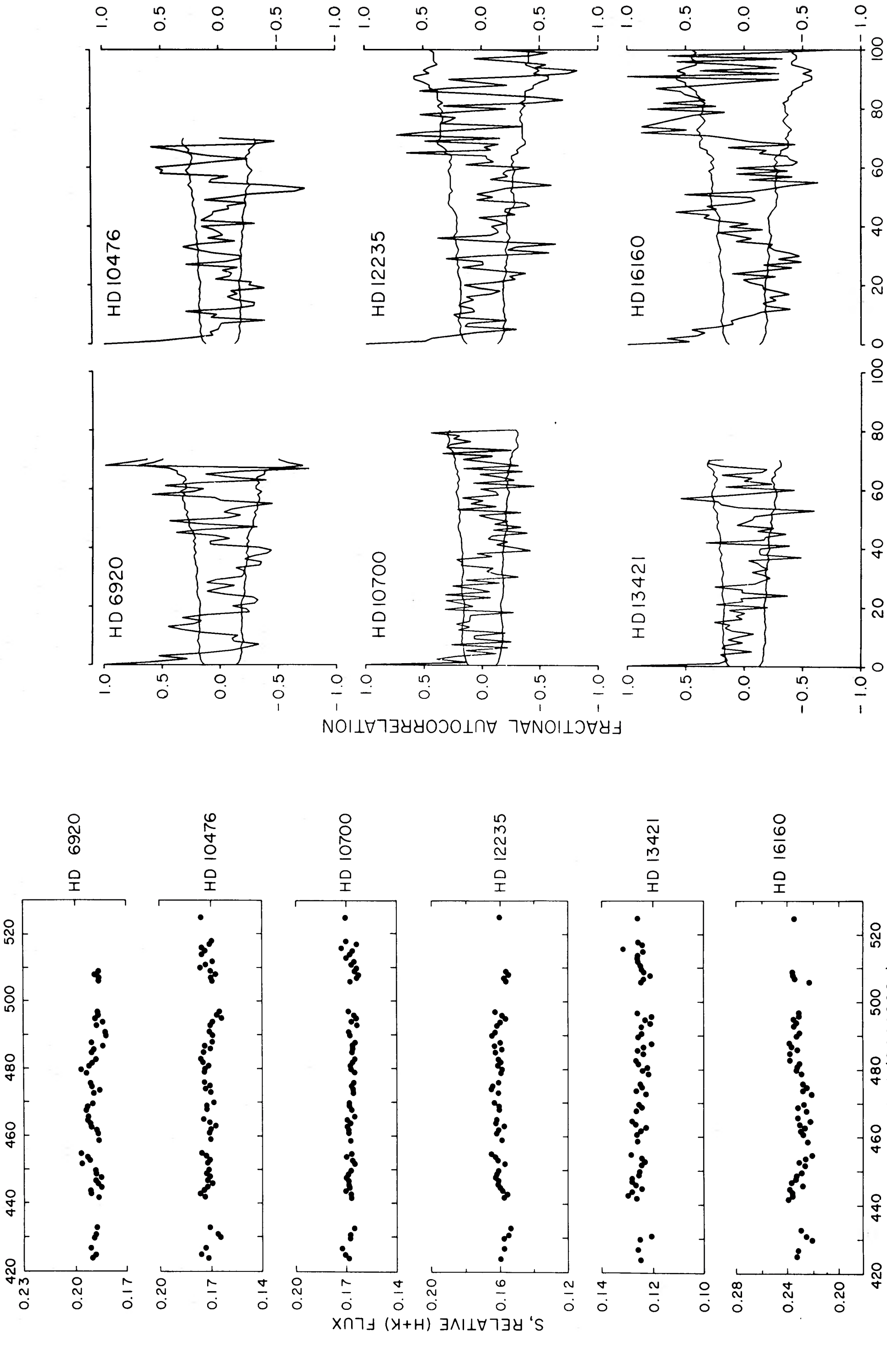

FIG. 1—*Continued*

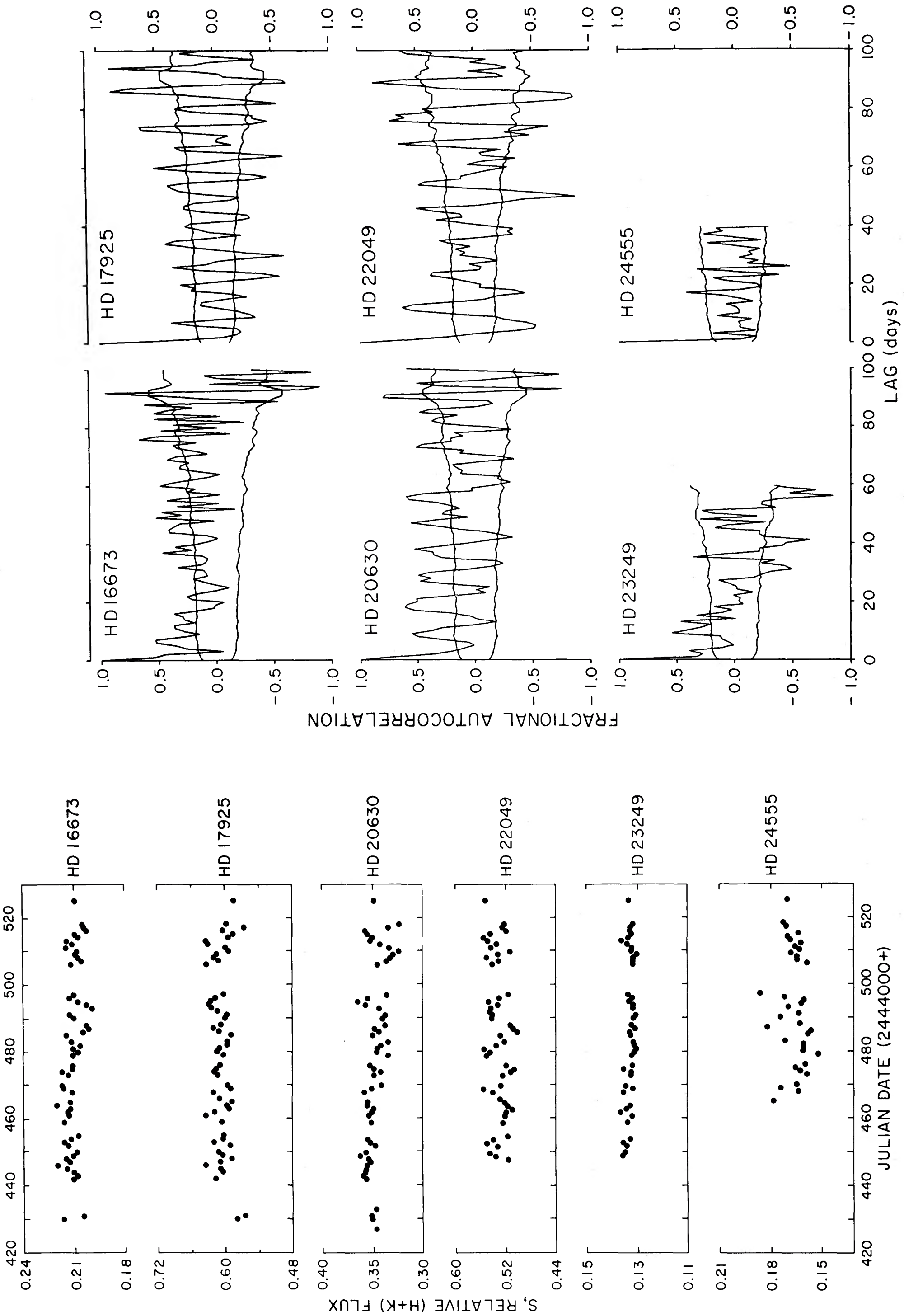

FIG. 1—*Continued*

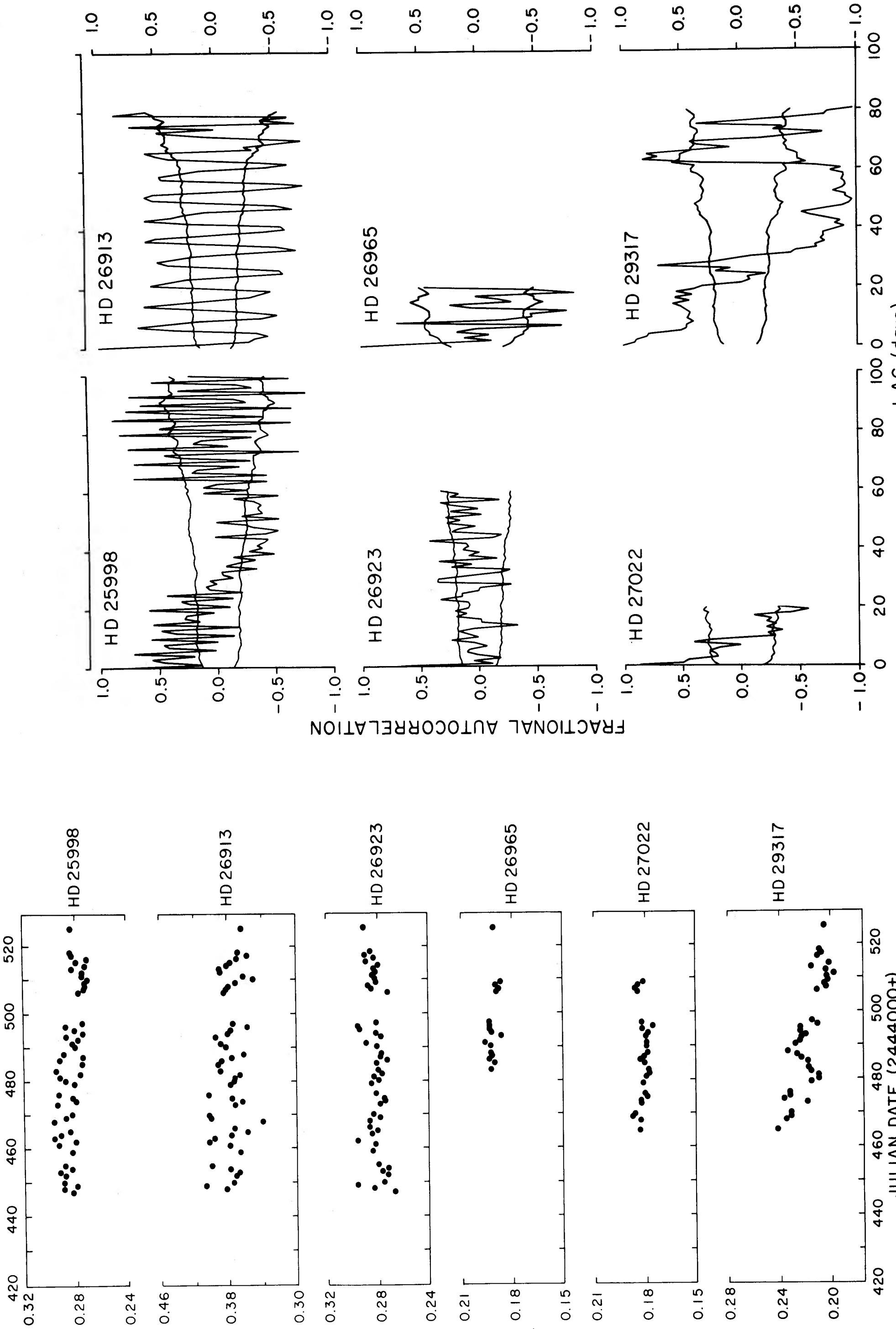

FIG. 1—*Continued*

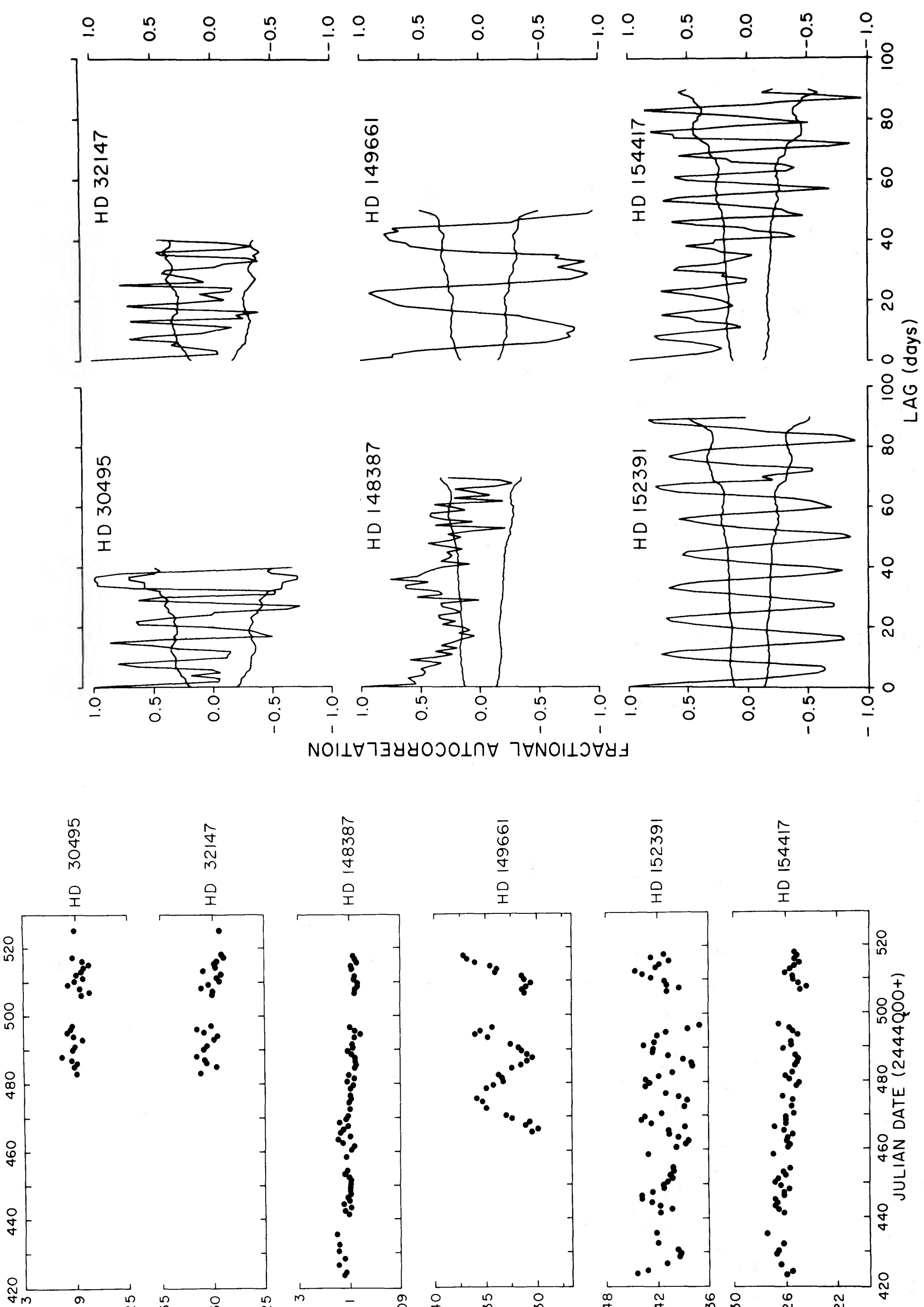

FIG. 1—*Continued*

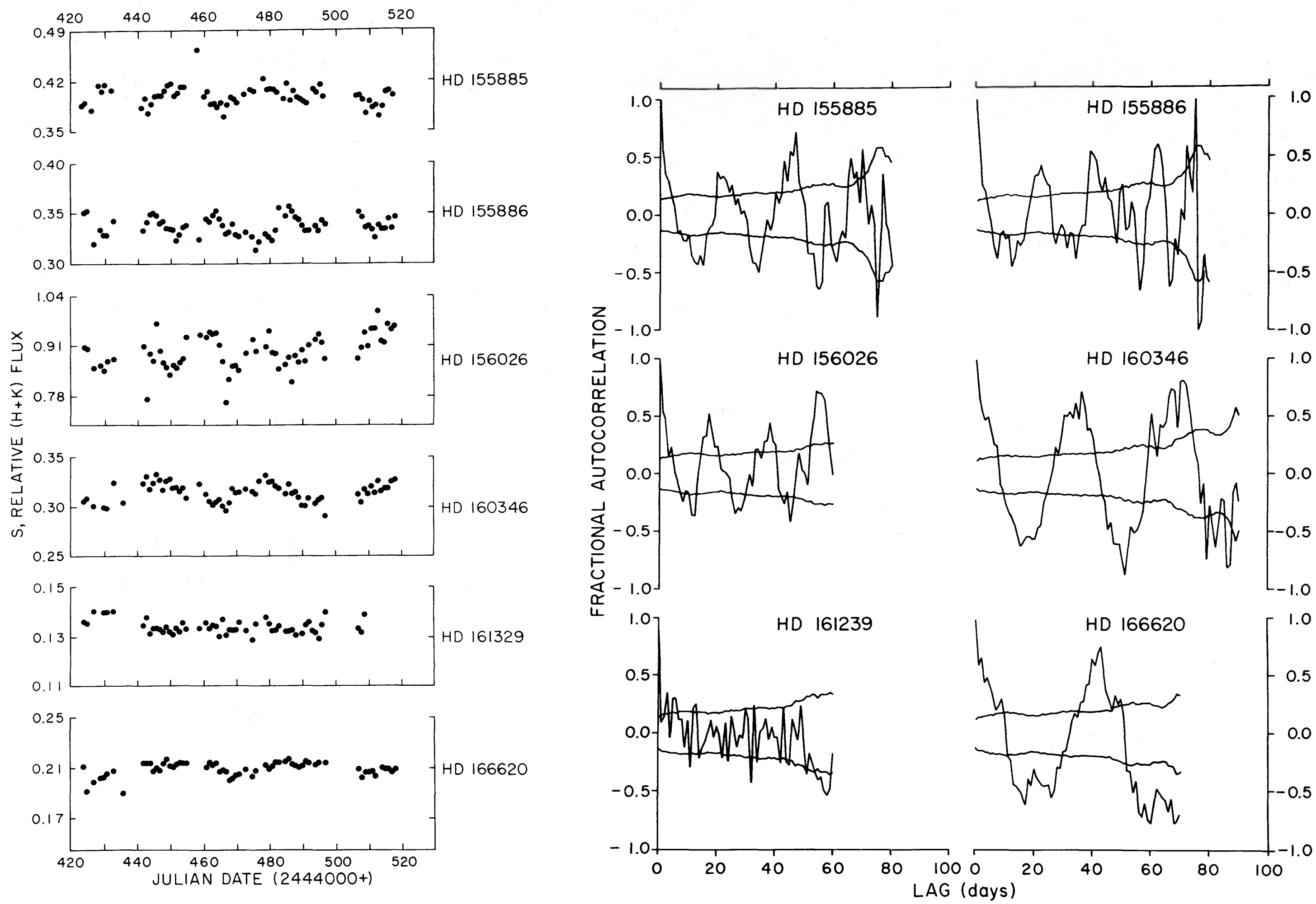

FIG. 1—*Continued*

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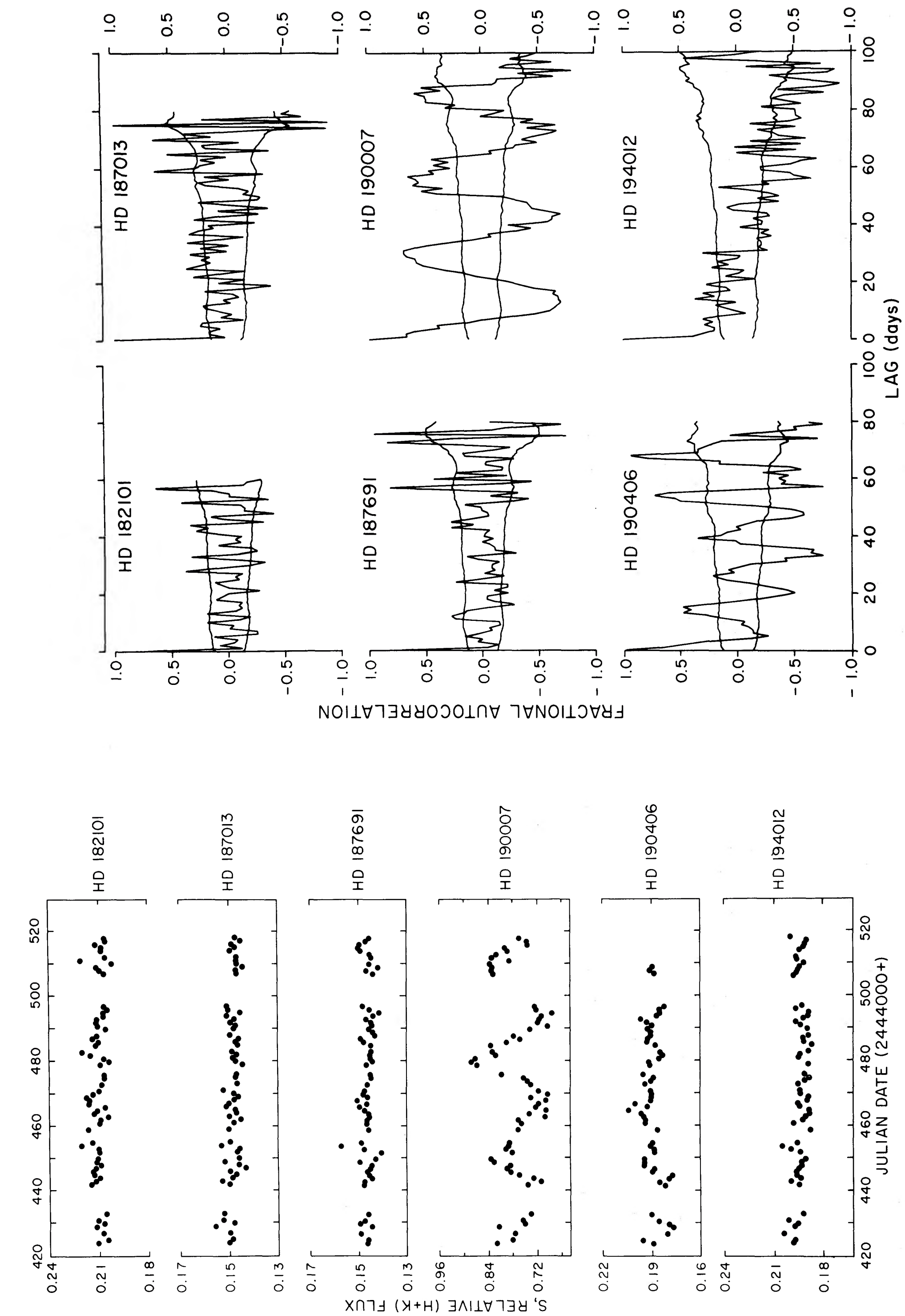

FIG. 1—*Continued*

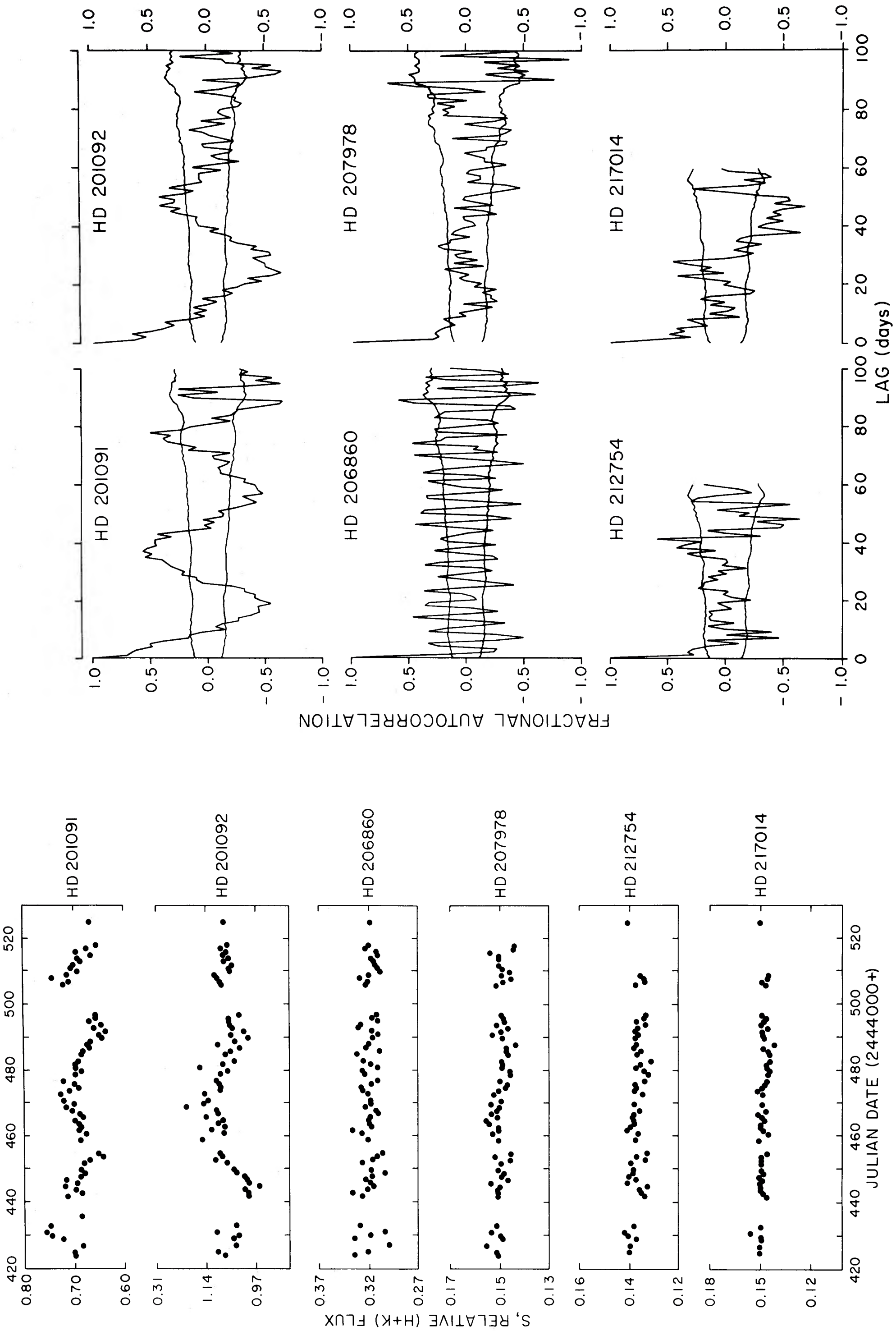

FIG. 1—*Continued*

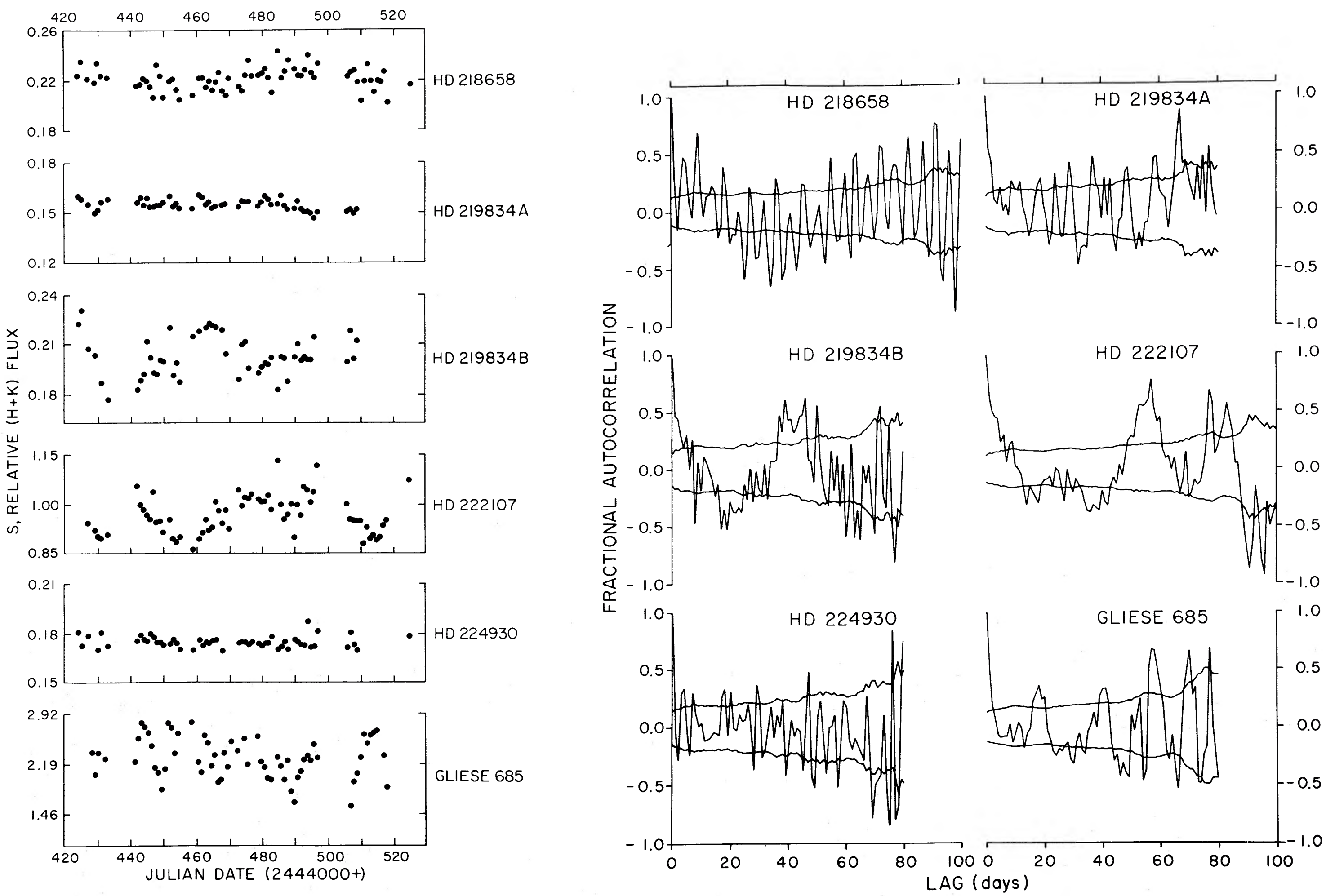

FIG. 1—*Continued*

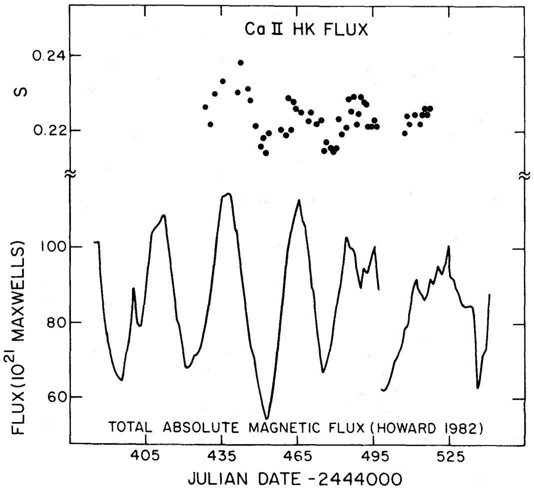

FIG. 2.—For the Sun, our measurements of the relative Ca II H and K emission strength as seen in the afternoon sky and the total absolute magnetic flux (Howard 1982) are plotted as a function of time. As discussed in the text, the point-to-point cross-correlation is significant between the two sets of data.

Thus, a best indication of the precision of the measurements is inferred from the smallest observed deviation, 1.7% for HD 10700.

We attempted to acquire a series of three measurements on each star for which the counts in the weakest channel ensured photon statistics theoretically near the 1%–1.5% level, or better. In the interest of efficient observing, however, clouds or exceptionally poor seeing meant sacrificing photon statistics for completion of the nightly list of program stars. With long enough data trains, these fluctuations would have little effect in the subsequent autocorrelation analysis. Usually, standard stars are also observed on these nights, and the effect of occasional low-quality measurements is included in the derivation of the precision quoted above.

III. TIME SERIES ANALYSIS

For each star, we have derived a string of nightly values S_i of the H–K flux. Each value of S_i is the mean

TABLE 1

SUMMARY OF STANDARD STARS' MEASUREMENTS

HD (1)	N (2)	$\langle S\rangle$ (3)	$\sigma(\langle S\rangle)$ (4)	$\sigma/\langle S\rangle$ (5) (%)	$\sigma_W/\langle S\rangle$ (6) (%)
10700[a]	201	0.1676	0.0029	1.7	2.5
13421......	191	0.1440	0.0030	2.1	2.4
187013......	198	0.1478	0.0033	2.2	2.0
187691......	205	0.1461	0.0031	2.1	2.1
207978......	230	0.1497	0.0034	2.3	1.7
212754......	174	0.1367	0.0032	2.3	1.7

[a]Wilson 1978 did not monitor this star as a standard.

of several measurements, usually three, on a given night. Each mean S_i is placed in a daily bin, with no provisions for a finer time mesh. This is suitable for all stars which rotate more slowly than the Nyquist sampling limit of approximately 2 days.

The autocorrelation coefficient r_k at lag period k (measured in units of days) is defined as the autocovariance at time i with respect to lagged time $i+k$ divided by the joint variation σ at time (i) and $(i+k)$ (cf. Makradakis and Wheelwright 1978):

$$r_k = \frac{\text{autocov}_{i,i+k}}{\sigma_i \sigma_{i+k}}.$$

In this equation, the autocovariance is defined as the average, over all times i, of the product of the difference of S_i from the mean value of the series S and the difference of S_{i+k} from the mean of S:

$$\text{autocov}_{i,i+k} = \langle (S_i - \bar{S})(S_{i+k} - \bar{S}) \rangle,$$

where $\bar{S}$ is the mean value of the series of S and the average is denoted by $\langle\ \rangle$. The joint variation is the product of the variances:

$$\sigma_i \sigma_{i+k} = \left[\langle (S_i - \bar{S})^2 \rangle \langle (S_{i+k} - \bar{S})^2 \rangle\right]^{1/2}.$$

In practice we calculate an estimate of the autocorrelation from the realization of the series of the limited number of observations of S. The sample autocorrelation function is (Jenkins and Watts 1968)

$$r_k = \frac{N(k)\Sigma S_i S_{i+k} - \Sigma S_i \Sigma S_{i+k}}{\left[N(k)\Sigma S_i^2 - (\Sigma S_i)^2\right]^{1/2}\left[N(k)\Sigma S_{i+k}^2 - (\Sigma S_{i+k})^2\right]^{1/2}},$$

where $N(k)$ is the total number of points i at lag k for which data were acquired on both day i and day $i+k$. $N(k)$ is generally less than its maximum possible value $i_{\max} - k$ for an observing sequence of duration $i_{\max}$ days, because of data interruptions (mainly caused by bad weather). When $N(k)$ is zero, r_k is not calculated. The sums include only the $N(k)$ values of the index i for which data were gathered on both day i and $i+k$. The data gaps do not change the overall value of the autocorrelation coefficient r_k, but do degrade its precision, because the precision depends on the number $N(k)$ of lagged products.

We have calculated autocorrelation coefficients for all stars observed for days ranging from zero days' lag up to about 70% of the total length $i_{\max}$ days of the observing interval. These autocorrelation coefficients are plotted in Figure 1, facing each record of nightly mean flux S_i.

Superposed on the autocorrelation coefficients plotted in Figure 1 standard error curves defined by values of the function $\varepsilon_k = \pm[N(k)]^{-1/2}$. Autocorrelation coefficients calculated from purely random data would have a distribution that is nearly a normal curve with mean equal to zero and a standard error of $[N(k)]^{-1/2}$, where $N(k)$ is the number of pairs of points with lag of k days (Makridakis and Wheelwright 1978, and references therein). Thus, for random data, about 67% of the autocorrelation peaks should lie within the band $\pm \varepsilon_k$ plotted in Figure 1. With increasing lag k, the number $N(k)$ of overlapping pairs of observations decreases, so ε_k tends to increase. However, because the observations are not always available nightly, the standard error curve is not smooth.

Our autocorrelation analysis of necessity assumes that the data set is stationary; that is, it assumes that our sampled realizations of S are good representations of the long-term behavior of S. At best this assumption can only be roughly correct. It is clear that nonstationary effects are present in the data. For example, a star which shows an activity cycle may show a continued, secular decrease in S superposed on rotational modulation. Long-term trends in the data will skew the weights of the autocorrelation coefficients and affect the determination of the rotational period. Nonstationarity is assumed to be present in the autocorrelations which do not fluctuate about zero, but rather are offset from zero. However, it is reasonably straightforward to remove such trends, as described below.

More troublesome in the determination of a rotation period is the phase stability of the chromospheric emission modulation. Solar active regions are known to form and decay over timescales of several weeks, so that an accurate measurement of the solar rotational period can be difficult to obtain from observations over only a few

TABLE 2

PERIOD ANALYSIS FOR STARS OBSERVED FOR ROTATIONAL MODULATION OF Ca II H AND K EMISSION

Star Name	HD Number[a] (2)	Paper I P (days) (3)	This work $P \pm d_p$ (days)[b] (4)	Σ' peak (5)	Max. Lag (days) (6)	Number of Peaks (7)	Comments[c] (8)
Sun	...	...	28[d]	2.3	70	1	
9 Cet	1835	7.9	7.7±0.1	7.8	100	5	
	2454	...	...	...	70	...	noise
14 Cet	3229	...	...	...	80	...	noise
54 Psc	3651	...	(48)	2	80	1	
	4628	(20)	38	2.6	50	1	see text
ψ^3(81) Psc	6903	...	6.2±0.1	4.1	80	5	see text
44 And	6920	(13)	13.1±0.0	4.0	70	2	
107 Psc	10476	...	...	...	70	...	noise
τ(52) Cet	10700*	...	...	...	100	...	noise
112 Psc	12235	...	...	...	100	...	noise
64 Cet	13421*	...	...	...	80	...	noise
	16160	(45)	45	2.2	70	1	
	16673	(6.2)	...	...	90	...	nonstationary
	17925	6.9	6.6±0.1	4.5	100	6	
κ(96) Cet	20630	8.5	9.4±0.1	5.5	100	6	nonstationary
ε(18) Eri	22049	11.8	11.3±0.2	3.4	80	2	
δ(23) Eri	23249	...	...	...	60	...	nonstationary
32 Eri	24555	...	...	...	60	...	insufficient
50 Per	25998	2.6	(2.6±0.1)	...	80	5	nonstationary
	26913	7.2	7.17±0.06	7.8	80	9	
	26923	...	...	...	80	...	noise
o^2(40) Eri	26965	...	...	...	30	...	insufficient
	27022	...	...	...	30	...	insufficient
3 Cam	29317	...	...	...	80	...	nonstationary, SB, see text
58 Eri	30495	...	7.6±0.2	3.0	30	...	
	32147	...	...	...	60	...	insufficient
η(14) Dra	148387	...	...	...	70	...	nonstationary, insufficient
12 Oph	149661	21.0	21.3±0.7	5.4	280	2	1980 and 1981
	152391	11.0	11.05±0.10	9.6	280	7	1980 and 1981
	154417	7.6	7.58±0.02	8.2	280	11	nonstationary, 1980 and 1981
36 Oph	155885	23	22.9±0.5	4.8	280	3	1980 and 1981
36 Oph	155886	21	20.3±0.4	5.5	280	3	1980 and 1981
	156026	17	18.0±0.5	4.8	70	3	
	160346	34	33.53±0.03	5.1	80	2	

TABLE 2—*Continued*

Star Name (1)	HD Number[a] (2)	Paper I P (days) (3)	This work $P \pm d_p$ (days)[b] (4)	Σ' peak (5)	Max. Lag (days) (6)	Number of Peaks (7)	Comments[c] (8)
84 Her	161239	...	...	...	70	...	noise
	166620	(43)	42	3.7	80	1	
	182101	...	...	...	70	...	noise
17 Cyg	187013*	...	...	...	70	...	noise
o(54) Aql	187691*	(15)	...	...	70	...	noise
	190007	29	29.3±0.7	5.6	100	3	
15 Sge	190406	14.0	13.5±0.2	4.8	80	4	
	194012	...	...		100	...	nonstationary, noise
61 Cyg	201091	37	37.9±1.0	4.4	100	2	
61 Cyg	201092	48	48	2.4	100	1	
	206860	4.7	4.63±0.02	8.4	100	16	
15 Peg	207978*	...	...	...	100	...	noise
34 Peg	212754*	(13)	...	...	60	...	noise
51 Peg	217014	...	...	...	60	...	nonstationary, noise
π(33) Cep	218658	...	(4.6±0.1)	9.5	100	14	nonstationary, SB, see text
94 Aqr	219834A	...	...	...	90	...	nonstationary, noise
94 Aqr	219834B	...	42	2.7	90	1	
λ(16) And	222107	54	56.4±0.8	4.3	120	2	see text, SB
85 Peg	224930	...	...	...	90	...	noise
Gliese 685	...	(9)	19.2±0.7	3.6	80	3	

[a]An asterisk indicates that the star is standard.
[b]Listed here are the measured mean period and standard deviation from the mean, as described in the text. Note that the standard deviation describes the precision of measuring the period according to our adopted technique and does not necessarily imply the accuracy of the period.
[c]The remark "SB" indicates a spectroscopic binary. The orbital periods are HD 29317, $P = 121$ days; HD 218658, $P = 556$ days; HD 222107, $P = 20.5$ days (Batten 1968). Correction of the wavelength of the passband for the stellar orbital radial velocity was made only for HD 222107. HD 218658 is also a visual binary with an F3 V component (2.2 mag fainter than the primary star) and a separation of about 1″ (Edwards 1976).
[d]Synodic period.

periods (cf. LaBonte 1982). Our observations also show evidence for such evolution of activity. It is impossible to make an accurate error estimate that includes this possibility. This problem is less significant for the stars for which many rotational periods have been observed. We caution, however, that periods based on one or two autocorrelation peaks may be uncertain by amounts substantially larger than the estimate of random errors.

The existence of a periodic component in the data (which is interpreted as stellar rotation), is established by recognizing time lags for which autocorrelation coefficients are significantly different from zero. For a possibly significant peak in the data, we calculate the statistical significance S'_p, the ratio of the height r_k of the suspect peak above zero to the value of ε_k plotted in Figure 1. S'_p is the peak height in units of the standard deviation for random data and has the usual interpretation in terms of significance of departure from a random data string: about 67% of the autocorrelation coefficients should be within this 1ε band. For the typical periods found by this analysis, the lag of a significant peak is likely to be the rotation period, as was shown in Paper I by comparison with rotation periods derived from spectrum line broadening, as well as by the lack of other plausible mechanisms operating on this time scale.

The confidence of an observed period is buttressed when several peaks appear at multiples of the period and each peak has a significant height. In cases of two or more peaks, we calculate the period by the following method. The lag of each significant peak (P_k) in the autocorrelation function is divided by k, the number of multiples of the period represented by that peak, then the mean ($\bar{P}$) and standard deviation (d_P) of these separate estimates of the period are determined, giving equal weight to each estimate. That is,

$$\bar{P} = \frac{1}{N} \Sigma \frac{P_k}{k}$$

$$d_P = \left[\frac{1}{N(N-1)} \Sigma \left(\frac{P_k}{k} - \bar{P} \right)^2 \right]^{1/2},$$

TABLE 3

ROTATIONAL VELOCITIES FOR OBSERVED STARS

Star[a]	Spectral Type (2)	$(B-V)$ (3)	$\langle S \rangle$ (4)	P (days) (5)	v (km s^{-1}) (6)	$v \sin i$ (km s^{-1}) (7)	Reference[b] (8)
207978* ...	F0	0.42	0.150	...	...	≤ 6	K67
2454	F2	0.43	0.160	...	...	8	K67
3229	F2	0.44	0.216	...	...	≤ 10	W66
182101	F6	0.45	0.210	...	...	13	K67
187013* ...	F5	0.46	0.148	...	...	9	K67
194012	F5	0.51	0.194	...	...	6	K67
16673	F6	0.52	0.210	...	...	≤ 6	K67
212754* ...	F5	0.52	0.139	...	...	7	K67
25998	F7	0.54	0.282	2.6	23	22	K67
13421* ...	F8	0.56	0.125	...	...	≤ 10	W66
187691* ...	F8	0.56	0.146	...	...	≤ 6	K67
26923	G0	0.57	0.281	...	...	≤ 6	K67
154417	F8	0.57	0.259	7.6	7	5.5 ± 0.7	SO82
206860	G0	0.58	0.319	4.6	11	$11, 10.2 \pm 1.1$	K67, SO82
6920	F8	0.60	0.199	13.1	4	...	...
30495	G1	0.61	0.290	7.6	7	...	...
190406	G1	0.61	0.190	13.5	4	$3-5$	K67
12235	G1	0.62	0.160	...	...	≤ 10	W66
161239	G6	0.65	0.134	...	...	≤ 10	W66
Sun[c]	G2	0.66	0.223	26	2	1.84	SO82
1835	G2	0.66	0.336	7.7	6	7.0 ± 0.8	SO82
224930	G2	0.66	0.175	...	...	< 6	K67
217014	G5	0.68	0.148	...	...	1.7 ± 0.8	SO82
20630	G5	0.68	0.348	9.4	5	> 15	HS55
26913	G3	0.70	0.380	7.2	7	< 6	K67
10700* ...	G8	0.72	0.168	...	...	...	...
152391	G8	0.76	0.412	11.0	4	...	...
219834A...	G8	0.79	0.155	...	...	≤ 15	HS55
149661	K0	0.81	0.331	21.3	1.9	...	...
26965	K1	0.82	0.191	...	...	...	...
10476	K1	0.84	0.172	...	...	< 20	HS55
3651	K0	0.85	0.171	(48)	1	...	...
155885	K1	0.86	0.399	22.9	1.9	...	...
155886	K1	0.86	0.337	20.3	2.0	...	...
17925	K0	0.87	0.606	6.6	6	...	...
166620	K2	0.87	0.210	42	1	...	...
22049	K2	0.88	0.533	11.3	4	< 3	VSP83
4628	K4	0.89	0.194	38	1	...	...
219834B...	K2	0.91	0.201	42	1	...	...
160346	K3	0.96	0.314	33.5	1	...	...
16160	K4	0.97	0.231	45	0.8	< 3	VSP83
32147	K5	1.07	0.302	...	...	...	...
190007	K4	1.12	0.767	29.3	1.2	...	...
156026	K5	1.16	0.893	18.0	2.3	...	...
201091	K5	1.18	0.694	37.9	1.0	2,4	VF79, SM79
201092	K7	1.38	1.088	48	0.7	< 3	VSP83
Gl 685	M0	1.45	2.213	19.2	1.6	...	...
6903	G0 III	0.69	0.294	6.2	50	100, 95	FD70, A75
218658	G2 III	0.76	0.220	...	...	4.7	G82
27022	G5 III	0.81	0.181	...	...	< 20	HS55
148387	G8 III	0.91	0.110	...	...	2.2	G82
23249	K0 IV	0.92	0.133	...	...	2.2 ± 0.9	SD79
24555	G8 III	0.94	0.166	...	...	< 15	HS55
29317	K0 III	1.07	0.218	...	...	< 15	HS55
222107	G8 IV–III	1.07	0.931	56.4	5	< 20	HS55

[a]An asterisk indicates that the star is a standard.

[b]REFERENCES.—K67: Kraft 1967. W66: Wilson 1966. SO82: Soderblom 1982. HS55: Herbig and Spalding 1955. VSP83: Vogt, Soderblom, and Penrod 1983. VF79: Vogt and Fekel 1979. SM79: Smith 1979. FD70: Faber and Danziger 1970. A75: Alschuler 1975. G82: Gray 1982. SD79: Smith and Dominy 1979.

[c]The observed, solar synodic period listed in Table 2 has been converted to the sidereal period listed here.

where N is the number of autocorrelation peaks included in the summations. If only one peak is present, no standard deviation is given for the period.

For stationary data with multiple peaks, the estimates of significance $S'_p(k)$ of the individual peak heights are combined and presented as

$$\Sigma'_{\text{peak}} = \left[\Sigma S'_P{}^2(k)\right]^{1/2},$$

where the summation is carried over the N individual peaks.

It is worth further clarifying the estimates of the error in the period determination. An accurate determination of a period requires that neither the period nor the longitude of activity marking the period change during the span of the observations. While plausible, these assumptions may be physically inappropriate. The quoted standard deviation for the mean period, d_P, represents the precision to which the peaks of the autocorrelation coefficients can be measured. Furthermore, the value of the significance of the heights of the peaks in the autocorrelation coefficients, Σ' peak, represents the reality of a period in the data. These errors do not necessarily imply the accuracy of a given rotation period, although they are inherent in the accuracy. Insofar as our assumptions of the stability of the period and its phase are correct, than our estimate of the reality of the period and the precision of measuring it will be closely related to the accuracy. The veracity of a rotation period, however, can be partially assessed by comparing spectroscopically measured rotational velocities with equatorial velocities inferred from our periods, as discussed below.

Our new results are presented in Tables 2 and 3. Table 2 lists the stars in order of HD number, while Table 3 lists them in order of increasing $(B - V)$ color, along with supplementary information. (In Table 3, the small sample of evolved stars is listed after the dwarf stars.) In Table 2, the period from Paper I is listed (col. [3]), along with the period and standard deviation determined from the analysis here (col. [4]). The combined significance Σ'_{peak} of the heights of the measured peaks (col. [5]), the maximum lag used in determining the periods from the autocorrelation coefficients (col. [6]), and N, the number of peaks included in the period determination (col. [7]), are also listed. Additional remarks appear in column (8).

For those few stars exhibiting long-term trends, we have attempted to remove the trends by subtracting a least squares polynomial fit of up to third order from the data. The autocorrelation coefficients are computed from the corrected data. If a period is present, the period, standard deviation of the period fit, and significance of the height of the peaks are calculated as described above. This procedure produced series that appeared to be stationary for all but a few stars: HD 16673, 25998, 23249, 24555, and 29317. The remark "nonstationary" appears for all stars exhibiting this behavior. The plots of autocorrelation coefficients in Figure 1 are shown for the original data uncorrected for long-term variations in the data.

Several comments are necessary to clarify the listing of the periods in Table 2. When only one peak in the autocorrelation coefficients is measured, there is no corresponding standard deviation for the period. For two of the stars, HD 6920 and 160346, the standard deviation of the period is fortuitously small because only two peaks were measured in each case. The period of HD 3651 is listed in parentheses to indicate the low significance of the height of the peak. HD 25998 shows both a nonstationary trend which was not corrected by our analysis and obviously repetitive autocorrelation peaks. The period and standard deviation of the period fit are measured but listed in parentheses to indicate the likely but unquantified significance to the peak height. Additionally, no value of Σ'_{peak} is listed, and the remark "nonstationary" appears. As discussed below, the equatorial velocity inferred from this period agrees well with the spectroscopically-determined projected rotational velocity. The observed period for the evolved star HD 218658 is listed in parentheses and discussed below.

For stars with no period listed, the remarks column contains an entry which categorizes the lack of a period:

(a) "nonstationary"—severe trends that are not removed by fitting low-order polynomials dominate the data and no obvious peaks appear;

(b) "noise"—the autocorrelations, including those corrected to stationarity, are mostly noise within the error criteria; and

(c) "insufficient"—data train is too short either to see the period or to assign to categories (a) or (b) above.

These remarks are intended to distinguish those stars which may upon further observation and analysis reveal rotation periods, from those with predominantly random fluctuations.

For five stars (noted in col. [8]) which were observed during 1981 as well as 1980, we have calculated rotation periods for the 1980 data and 1981 data separately, to detect whether there was a significant change in the period or the longitude of the activity (see § VIb) over the typically 9 month interval between the midpoint of the two sets of observations. In no case did the period show a statistically significant change. Therefore the period quoted for these stars in Table 2 was determined from the autocorrelation function of the entire 1980–1981 data set. However, to avoid errors caused by possible shifts in longitude of activity between 1980 and 1981, we did not include peaks corresponding to time lags bridging the two seasons. We return to this point in the discussion.

The star HD 4628 requires special discussion. The data in Figure 1 indicate a period of $19^{\mathrm{d}}.0 \pm 0^{\mathrm{d}}.4$, as reported earlier in Paper I. As was noted in Paper I, this rotation period is about half that required to be consistent with the position of HD 4628 in the $(S, B-V)$ plane. Moreover, recent unpublished data obtained in 1981 (Vaughan *et al.* 1982) show a clear rotational modulation period of about 38 days. Apparently, as was suggested in Paper I, during 1980 the star had two active areas separated in longitude by about 180°, giving a spurious doubling of the frequency of rotational modulation; this doubling disappeared in 1981. The period reported in Tables 2 and 3 has been determined from the new 1981 data.

Table 3 lists the dwarf and evolved stars separately, in order of increasing $(B-V)$ color. Our standard stars are again denoted with an asterisk after the HD number (col. [1]), with spectral type and $(B-V)$ listed in columns (2) and (3). The mean value of S observed during this observing interval is given ($\langle S \rangle$; col. [4]). The periods, taken from Table 2, are listed in column (5). We have listed in column (6) estimated equatorial velocities, $v = 2\pi R/P$, from the measured period, P, and stellar radius R for the dwarf stars. The values of stellar radii were assumed from the mass-radius relationship for dwarf stars of Harris, Strand, and Worley (1963) or from the spectral types of the giant stars (Allen 1973). Measured values or upper limits of $v \sin i$ found in the literature are listed in column (7) along with the sources of these measurements (col. [8]). As discussed in Paper I, there is good agreement between the projected rotational velocities measured spectroscopically and the estimated equatorial velocities in the sense that $v = 2\pi R/P \geq v \sin i$.

IV. SOLAR MEASUREMENTS

The disk-integrated solar spectrum was observed during the late afternoon prior to each observing night. The telescope was pointed toward the bright afternoon sky, and ambient light entering the system was recorded. The solar data revealed a (synodic) period of $28^{\mathrm{d}}.0$, as indicated in Table 2.

The detection of the solar rotation is corroborated by the results of the comparison of our daily sky measurements with those of the solar magnetic flux, also recorded daily at Mount Wilson (Howard 1976). The total surface magnetic flux on the solar disk (Howard 1982) was compared to our S-values for the sky (Fig. 2). It is well known that Ca II H and K emission intensifies in areas of high magnetic field concentration on the Sun (Babcock and Babcock 1955; Leighton 1959). Therefore, our values of S should be highly correlated with those of the total solar magnetic flux.

The linear correlation coefficient between the daily S-values[5] and the total magnetic flux is poor, 0.38. The cross-correlation coefficients, however, show a correlation at a lag of zero days significant at the 4.1 σ level. The lack of a strong correlation between the two sets of data may possibly be attributable to the following facts:

(*a*) Our measurements of the sky include the effects of atmospheric scattering on the solar Ca II H and K profiles. As a result, the measured variation of the emission peaks relative to the "continuum" windows will be decreased. Moreover, day-to-day variations in the amount of scattering introduces noise into the observed signal.

(*b*) The relatively small (5%–9%) modulation of the solar signal is near our limit of sensitivity to variations.

V. RESULTS FOR EVOLVED STARS

Our sample of evolved stars represents an inhomogeneous group requiring separate discussion. Although the widths of the stellar Ca II H and K emission cores are slightly larger than the instrumental slit widths, relative measurements can be made with precision. Rotational velocities for some giants are expected to be slow, perhaps with periods as long as our observing interval. Such long periods would be difficult to confirm in our data. In addition, three are spectroscopic binaries, HD 29317, 218658, and 222107, as noted in Table 2. We compensated for the stellar orbital motion only while observing HD 222107.

We detected the established rotation period in HD 222107 (λ And = HR 8961), an RS CVn–type binary system whose primary star rotates with an average period of about 54 days, although the observed period can vary by a few days (Dorren, Guinan, and Paczkowski 1982). The rotation period has been inferred from photometric modulations observed to be as large as 30% in the V passband. The photometric variations have been interpreted as caused by starspots, dark at visible wavelengths (Hall 1976), and bright in chromospheric and coronal emissions (Baliunas and Dupree 1982).

Because its projected rotational velocity is about 100 km s^{-1}, HD 6903 (ψ^3 Psc = HR 339) should be classified as one of the FK Comae-type stars, rapidly-rotating G–K giant stars (Bopp and Stencel 1981). Our measured rotation period, $6^{\mathrm{d}}.2$, implies an equatorial velocity for a G0 III star which is too slow, by a factor of 2, to equal the projected rotational velocity. Either the radius has been underestimated, perhaps because the spectral type of a star with such broadened lines would

[5]For sky measurements brighter in the continuum level than a threshold count rate determined ex post facto, the values of S saturate. In subsequent analysis we used the corrected values of S, for which we thank Barto Oranje.

be difficult to classify, or our 6 day period is an alias of an expected shorter period.

The other two known spectroscopic binaries show gradual changes in S over the time span of the observation. The data for HD 29317 (3 Cam = HR 1467) vary in a way consistent with the calculated phases of its orbital motion over its period of about 120 days. Other shorter-term fluctuations appear, for example, near JD 2,444,476–490, and may represent ephemeral chromospheric activity in giant stars on this time scale. Another evolved star, HD 218658 (π Cep = HR 8819), is a long-period (556 days) single-line spectroscopic binary within a visual binary system (see Table 2). The phases of the orbit during our observations produce a change in radial velocity of at most 5 km s^{-1}. The orbital phases, and time scale and magnitude of their variation, cannot explain the smooth variation in S over about 80 days. In addition, a variation in S clearly appears with a period of 4.6 days. The observed projected rotational velocity $v \sin i$ is 4.7 km s^{-1} (Gray 1982), consistent with an equatorial velocity of 5 km s^{-1} deduced from the observed 80 day variation. However, if caused by rotation, the period of $4^{d}.6$ implies an equatorial velocity of about 70 km s^{-1}, which requires the rotation axis inclined to within about 10° of our line of sight to reduce the projected rotational velocity to about 5 km s^{-1}. A rapid rotation masked by a low inclination is unlikely in HD 218658 for two reasons. First, if the orbital and stellar rotation axes are parallel, the mass function derived from the radial velocity curve (0.624 $M_{\odot}$; Batten 1967) combined with a low inclination, would require an extremely massive yet unobserved secondary star. In addition, the strength of Ca II H and K emission is considerably weaker in HD 218658 than HD 6903, a giant of approximately the same spectral type rotating near 100 km s^{-1}. If, as in dwarf stars, giant stars show increased H and K emission with faster rotation, then a slow rotation is preferred for HD 218658. It seems unlikely that the fainter companions of either the spectroscopic or the visual binary system could significantly contribute to the measured chromospheric emission. The spectroscopic companion is undetected in the visible, and the visual binary companion has an inferred spectral type of F3 V (Edwards 1976). In the case of the spectroscopic companion, assumed to be a main-sequence star, an estimated low mass results in a radial velocity outside the instrumental passbands during the observed orbital phases. Further, spectra of Ca II H and K emission profiles show that the widths of the lines are consistent with the luminosity of the giant star (Wilson 1976), which indicates the flux originates from the giant. Thus, the persistent $4^{d}.6$ period remains unexplained. In comparison, the fundamental period of radial oscillations of stars of this spectral type is near 1 day, a period imperceptible in our observations, unless the $4^{d}.6$ period corresponds to an alias of a shorter period.

VI. DISCUSSION

a) Comparison to Paper I

A comparison between the periods determined here and those of Paper I reveals no substantial modifications. In several cases we were able to find new rotation periods (HD 3651, 6903, 30495, 218658, 219834B, plus the Sun). The only star for which the period in Paper I is not within the error limits in Gl 685: we now propose $19^{d}.1$ instead of the possible period of 9 days quoted in Paper I. The 9 day period was noted to be of marginal significance in the earlier paper. Of all our program stars, Gl 685 was faintest in the photospheric continuum. The half-period alias apparently arose from excessively noisy points caused by both statistical fluctuations and flare activity. Two stars with marginal periods listed in Paper I, HD 187691 and HD 212754, now show no period in Table 2. Both these standard stars have extremely weak chromospheric emission and the periods which were marginally significant are now considered insignificant.

b) Long-lived Activity

For the five stars observed in both 1980 and 1981, we analyzed the combined data trains to determine whether the activity observed in 1981 occurred at the same longitude or at a substantially different longitude on the star than it did in 1980. If at the same longitude, one

TABLE 4

PHASE AND PERIOD ANALYSIS FOR STARS OBSERVED IN 1980 AND 1981

Star (1)	Period (from Table 2) (days) (2)	$\Delta\phi$ (degrees) (3)	Period, assuming $\Delta\phi = 0$ (days) (4)
149661 ...	21.28 ± 0.72	−130 ± 110	20.77 ± 0.25
152391 ...	11.05 ± 0.10	−84 ± 55	10.98 ± 0.05
154417 ...	7.58 ± 0.18	−80 ± 24	...
155885 ...	22.93 ± 0.47	122° ± 71	23.29 ± 0.28
155886 ...	20.26 ± 0.43	13° ± 82	20.28 ± 0.24

may conclude that particular longitudes of activity, and possibly even individual active regions, live at least as long as the separation of the two observing seasons. We assume that the rotation period is unchanged over this time, and that it has the value quoted in Table 2. Furthermore, we assume that the error in the value lies within the measuring precision given in Table 2; these precisions require that the longitude of activity remain stable within each observing season. These assumptions allow us to determine the relative shift in longitude of the strongest contribution to chromospheric activity, and its probable error, between the two observing seasons. These determinations are given in column (3) of Table 4.

For all of the stars except HD 154417, the observed phase shift does not differ significantly (that is, at a level larger than two standard deviations) from zero (Table 4). Thus the data are consistent with a single active longitude which preserves its identity over the total observing period. More precise periods, calculated under this assumption and taking account of lags spanning the seasonal gap, are given for these stars in column (4) of Table 4. Of course, the accuracy of these more precise periods rests on the above assumption, for which there is no support other than lack of a significant observed phase shift over the two seasons.

For the star HD 154417, the phase change of $-80° \pm 24°$ given in Table 4 is marginally significant at the 3 σ level. Therefore a calculation of a more precise period using the assumption of constant longitude of activity is improper. Possible explanations of the data for HD 154417 are: (1) the marginally significant phase change is in fact not real; (2) the activity decayed between 1980 and 1981, to be replaced by new activity at a longitude leading the earlier activity by about 80°; (3) the chromospheric activity has at least two components—a short-lived one rotating with period about $7^{\mathrm{d}}.58$ and a relatively long-lived one rotating with a slightly shorter period of about $7^{\mathrm{d}}.52$. We note that a behavior similar to the last possibility has been reported for the solar magnetic field (Wilcox *et al.* 1970). However, the present data are far too few to draw any firm conclusions.

c) Success Statistics

Our technique of measuring the rotation period is remarkably successful for stars of later spectral types, and for stars with high mean chromospheric emission index $\langle S \rangle$. From Table 3, where program stars are ordered by increasing $(B-V)$, one can immediately see that most main-sequence stars with $(B-V) > 0.68$ have measurable periods. This fact is seen dramatically in Figure 3. Excluding stars for which the data trains are insufficient for analysis, the only stars in these cooler spectral types which show "noise" in the autocorrelation functions and hence no periods are HD 10700 and

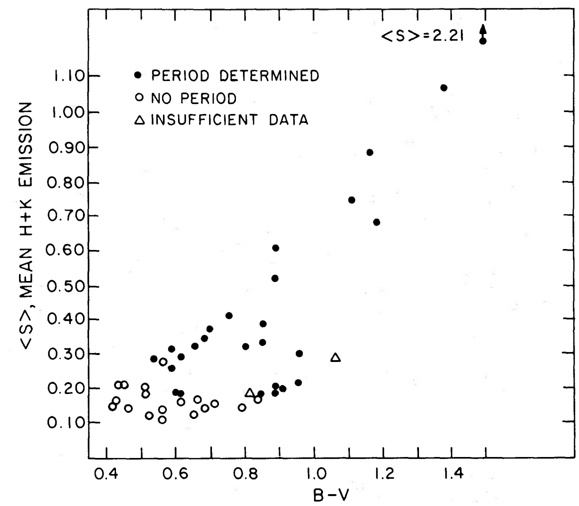

FIG. 3.—The mean value of the H and K emission strength, $\langle S \rangle$, as a function of $(B-V)$ color for our program main-sequence stars. While dots indicate that the period of a star was determined, circles show that a period was not present within our error criteria. Triangles denote that data trains were too short for analysis. It is evident that for $\langle S \rangle$ larger than about 0.2, rotation periods were usually determinable from our sample.

10476. Both these stars are among the weakest S-value stars in this group.

The bifurcation of the sample as a function of $\langle S \rangle$ shows remarkably that the success rate for stars with $\langle S \rangle$ larger than about 0.2 is about 95% exclusive of stars for which our data trains are of insufficient length. For the stars with strong emission, it is almost certain that we will observe a rotation period. Below $\langle S \rangle$ of about 0.2, the success rate for determining periods falls to $\sim 30\%$. The behavior of the success rate as a function of $\langle S \rangle$ implies that stars with strong emission are characterized by spatial emission asymmetry with high contrast, so that the rotational modulation $\Delta S/S$ is large compared to that for weak-emission stars. In addition, strong-emission stars tend to be rapid rotators, so that many rotation periods were included in our observing window. This enhances the detectability of rotational modulation. Further, the strong-emission stars tend to have persistent longitudes of activity, lasting in many cases at least as long as our sampling period. This may also enhance the detectability of a rotation period.

d) The Vaughan-Preston Gap

As Vaughan (1980) and Vaughan and Preston (1980) described from their survey of solar neighborhood dwarf stars, there appears to be a paucity of stars in the color range $0.40 \leq (B-V) \leq 1.00$ with intermediate-strength chromospheric emission. Two possible explanations of the gap can be given. Ca II emission is correlated with stellar age (Kraft 1967; Skumanich 1972), so that gaps in the local stellar population as a function of age will translate into gaps in chromospheric emission. The other explanation advanced is that dynamo activity changes rapidly at a critical dynamo number (Durney, Mihalas, and Robinson 1981; Knobloch, Rosner, and Weiss 1981), and so chromospheric emission can change dramatically for a relatively small change in stellar age and/or rotation rate. In this connection Middelkoop (1982) suggested from a plot of Ca II H and K flux as a function of projected rotational velocity for the solar neighborhood stars that indeed there is a break in chromospheric emission as a function of rotation. Although we have many fewer stars to work with than are in the solar neighborhood survey, it is of interest to look for such an effect in our data since the accuracy of the periods deduced by Ca II modulation is so much greater than for any other method. In Figure 4 we show the range of $\langle S \rangle$ as a function of rotational period for stars in the range $0.80 \leq B - V \leq 1.00$. The range has been restricted because the $\langle S \rangle$ index is not directly a simple function of the intrinsic chromospheric emission, but is the ratio of H and K emission to the continuum flux. Limiting our analysis to stars of similar $B - V$ reduces the need for calibration in order to intercompare stars. In addition, we have determined periods for only a relatively small number of weak-emission stars, most of which are in this $(B - V)$ range. The symbols are plotted at values of $\langle S \rangle$ as measured by us (Table 3), and the ranges given span the minimum and maximum values observed in Wilson's (1978) long-term survey of these same stars. The stars have been differentiated into two groups according to the strength of the Ca II chromospheric emission (Vaughan 1980). Presumably, the young, strong–emission-line stars (above the gap) evolve into slowly rotating, weak-emission stars lying below the gap. There is no evidence for a discontinuity in emission as a function of rotation period in these data. If anything, the increase in rotational period with decreasing strength of $\langle S \rangle$ appears to be a rather smooth transition between the two groups of stars. Although the statistics are much poorer than in the solar neighborhood survey, the difficulty of measuring projected rotational velocities of a few km s^{-1} and the uncertainty introduced by $\sin i$ leads us to conclude that the question of a discontinuity in emission as a function of rotation is still unanswered.

V. CONCLUSIONS

With time series measurements of chromospheric Ca II H and K emission fluxes, it is possible to measure the rotation period directly, independent of axial inclination, in many lower main-sequence stars. This technique of measuring rotation rates from the modulation of chromospheric emission is extremely fruitful, especially for slowly rotating stars for which traditional spectroscopic line-broadening techniques have been insensitive.

For main-sequence stars with relatively strong S, rotational modulation is almost always observed. In addition, these strong-emission–line stars tend to have long-lived longitudes of activity which, in a few cases, may persist through two observing seasons. For a small sample of main-sequence stars in a limited range of $(B - V)$ color, the strength of S appears to decline smoothly as a function of rotation period. This sample is too limited from which to draw conclusions concerning

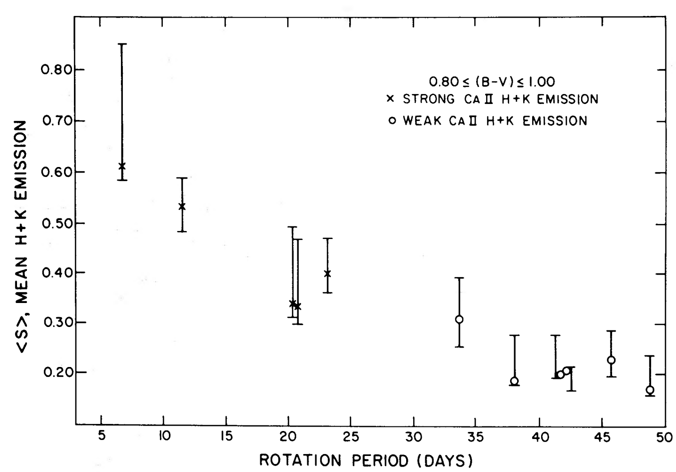

FIG. 4.—For main-sequence stars in the spectral type range $0.80 \leq (B - V) \leq 1.00$, whose rotation periods were determined in our survey, the mean value of the H and K emission strength $\langle S \rangle$ measured in this study is plotted as a function of rotation period. The stars are classified as old (*circles*) or young (X's) according to Vaughan (1980). The vertical bars cover the range from minimum to maximum value of S observed by Wilson (1978). In this plot, the transition from young, rapidly-rotating stars to older, slowly-rotating stars appears to be smooth.

the reported gap, or lack of stars with moderate S-strength in a restricted $(B-V)$ range within the Vaughan-Preston survey of solar neighborhood stars. In one of the evolved stars, we observe an unexplained, short ($4^d.6$) period apparently inconsistent with rotation. Another of our evolved stars is likely, although apparently unclassified as such, to be an FK Comae-type star, that is, a G–K giant with extremely rapid rotation. By continued monitoring of the rotational modulation, it should be possible to determine lifetimes and other properties of active areas on stars, or to investigate the behavior of rotational modulation as a function of phase in the activity cycle. By extending the sample to the solar neighborhood dwarfs, it may be possible to determine the reality, and explanation, of the bifurcation in chromospheric emission strength as a function of age, rotation rate, and spectral type.

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S. L. Baliunas, L. Hartmann, and R. W. Noyes: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

J. Frazer, H. Lanning, G. W. Preston, and A. H. Vaughan: Mount Wilson and Las Campanas Observatories, 813 Santa Barbara Street, Pasadena, CA 91101

F. Middelkoop: c/o C. Zwaan, Astronomical Institute at Utrecht, Zonnenburg 2, Utrecht, The Netherlands

D. Mihalas: NCAR/HAO, Box 3000, Boulder, CO 80307