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A SEARCH FOR Ap STARS WITH VERY LONG PERIODS

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Four-color (*uvby*) photoelectric observations have yielded new periods for three peculiar A-type stars. For HD 8441, the period P is equal to 69.5 days, for HD 12288, P = 34.9 days, and for HD 216533, P = 17.20 days. The period of 12.448 days derived by Preston (1972) for HD 24712 is confirmed. The periods of HD 18078 and HD 2453 are longer than one year. These results nearly double the number of Ap stars known to have periods longer than 25 days and add weight to the evidence that magnetic stars undergo rotational deceleration during their lifetimes.

Key words: photometry — peculiar A-type stars

I. Introduction

There has been, to date, no systematic attempt to discover Ap stars that vary on a time scale of years. However, two stars, HD 9996 (Preston and Wolff 1970) and HD 187474 (Babcock unpublished) are known to have periods in excess of five years. Preston (1970*a*) has recently published a list of 23 additional Ap stars for which $v \sin i$ is less than 10 km sec^{-1} and which may, on the oblique rotator hypothesis, also have very long periods. The present paper describes the results of *uvby* photometry of eleven of the stars in this list.

II. Observations

The observations were made with a 24-inch Boller and Chivens telescope on Mauna Kea. The telescope is equipped with a Tinsley photometer and a 9558 A photomultiplier cooled thermoelectrically to −20° C. In 1970 we used an unmodified GR amplifier and a strip chart recorder to make the observations; after July 1971 we used a photon counting system. The order of the observations has been described elsewhere (Wolff and Wolff 1971). Since few of the stars had been observed previously, suitable (nonvariable) comparison stars were not yet established. We therefore chose two comparison stars for each program star and observed them with equal frequency. From observations of the comparison stars, we estimate that the rms deviations of the differential photometry (variable − comparison) are approximately $0^m\!.003$ for Δy and $\Delta(b-y)$ and approximately $0^m\!.007$ for Δc_1 and Δm_1. We have also transformed the observed color indices of the comparison stars to the standard *uvby* system and have combined the results with the differential photometry to derive transformed color indices for the program stars. From a comparison of the transformed indices of the comparison stars with the results of other observers, we estimate that the standard deviations of the transformed values of $(b-y)$, m_1, and c_1 are approximately $0^m\!.01$, $0^m\!.015$, and $0^m\!.015$, respectively. The error in V may be as large as $0^m\!.04$. This estimate may be generous but represents an attempt to include uncertainties in the transformation of y to V, as well as errors that may arise because we do not monitor slow changes in the overall sensitivity of the photometric system and because we use mean extinction coefficients in reducing the observations.

III. Periodic Variables

Four of the stars observed are clearly variable on a time scale that is substantially less than one year, and we used the technique described by Lafler and Kinman (1965) to derive periods for these objects. The magnitudes and color indices of the comparison stars are listed in Table I and are given to three decimal places in order to

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TABLE I

PHOTOMETRY OF COMPARISON STARS

Variable Stars	Comparison Stars	V	Mean Color Indices $b-y$	m_1	c_1
HD 8441	HD 8710	6.881	0.232	0.183	0.598
	HD 8862	6.633	-0.028	0.116	0.874
HD 12288	HD 11395	7.284	0.026	0.104	0.952
	HD 11874	7.345	0.076	0.234	0.921
HD 24712	HD 25910	6.251	0.021	0.194	1.028
HD 216533	HD 214764	6.992	0.205	0.197	0.758
	HD 216912	7.045	-0.020	0.104	0.554

display with full precision the difference between the stars of each pair. The observations of the variable stars are listed in Tables II–V and are discussed in the sections that follow.

A. HD 8441

The star HD 8441 has been observed spectroscopically by Babcock (1958) and photoelectrically by van Genderen (1970). From an analysis of the radial velocities measured by Babcock, Renson (1965) determined a period of 106.27 days, and van Genderen's observations appeared to yield the same period. Our own observations of HD 8441 are best represented by the elements

$$\mathrm{JD}_{\odot}\ (\text{maximum light}) = \underset{\pm\,3.5}{2441244.0} + \underset{\pm\,1.2}{69.5}E\ ,$$

where the estimated errors are the largest allowed by the data. The resulting light curves are shown in Figure 1. The longer period of 106.27 days is clearly ruled out by the observations in 1970, which cover nearly two cycles of the 69.5-day period. The observations of van Genderen span an interval of 72 days in 1965 and begin and end near minimum light. In adopting the value of $P = 106.27$ days, van Genderen assumed that the duration of minimum light was much longer than it is. If we assume that maximum light at the effective wavelength of van Genderen's observations, λ5960, coincides in phase with maximum light in u, as our own observations at λ5450 suggest, then the elements given here adequately represent van Genderen's observations. Although the radial velocities are incompatible with this period, it is highly likely that they arise from orbital motion in a binary system. Therefore we conclude that the period of the photometric variability of HD 8441 is not equal to the orbital period, as is also the case, for example, for HD 9996 (Preston and Wolff

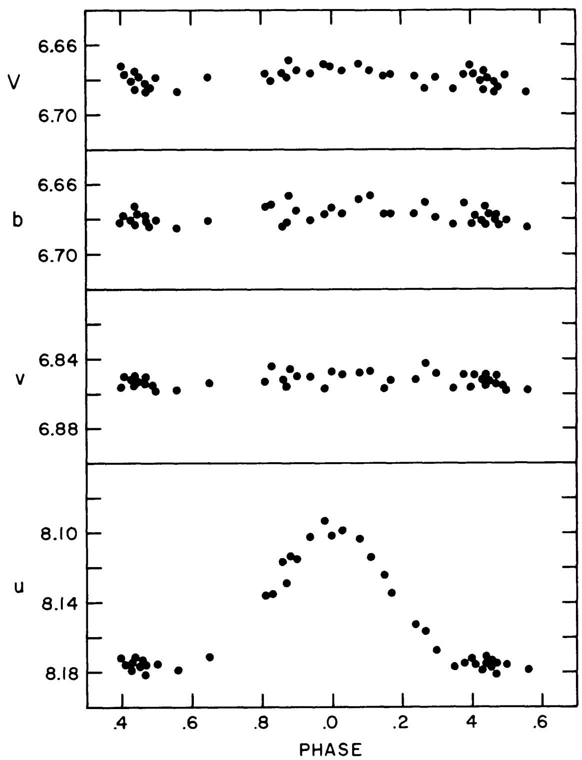

FIG. 1 — The light variations of HD 8441 plotted according to the ephemeris $\mathrm{JD}_{\odot}$ (maximum light) = 2441244.0 + 69.5E.

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TABLE II

PHOTOMETRY OF HD 8441

JD$_\odot$ 2440000+	Phase	V	$b-y$	m_1	c_1
782.08	0.35	6.685	-0.002	+0.176	+1.147
784.08	.38	6.677	- .006	.183	1.147
785.10	.40	6.672	+ .010	.164	1.142
786.08	.41	6.677	+ .002	.169	1.154
787.06	.43	6.681	+ .002	.169	1.156
788.09	.44	6.675	- .002	.179	1.144
789.07	.45	6.679	- .002	.177	1.146
790.07	.47	6.687	- .006	.179	1.146
814.00	.81	6.677	- .004	.184	1.102
818.99	.88	6.669	- .002	.181	1.088
819.99	.90	6.675	.000	.176	1.089
834.94	.11	6.675	- .008	.187	1.086
839.01	.17	6.677	- .002	.177	1.105
843.94	.24	6.678	- .002	.177	1.124
845.95	.27	6.685	- .014	.185	1.142
847.94	.30	6.679	.000	.168	1.151
853.90	.39	6.679	- .008	.185	1.144
859.94	.47	6.682	- .002	.176	1.146
865.88	.56	6.687	- .002	.175	1.147
871.85	.65	6.679	+ .002	.171	1.142
884.89	.83	6.681	- .008	.179	1.122
901.90	.08	6.671	- .001	.180	1.076
1170.10	.94	6.677	+ .004	.167	1.080
1185.12	.15	6.678	.000	.181	1.088
1205.02	.44	6.686	- .004	.177	1.146
1207.05	.47	6.685	- .001	.172	1.154
1209.03	.50	6.678	+ .004	.172	1.142
1233.98	.86	6.677	+ .007	.161	1.096
1234.96	.87	6.679	+ .002	.171	1.100
1242.95	.98	6.671	+ .006	.175	1.054
1243.98	.00	6.673	+ .002	.171	1.082
1245.97	0.03	6.675	+0.003	+0.169	+1.078

1970). Babcock's (1958) observations of the magnetic field of HD 8441 do not fit a period of 69.5 days. However, the observed magnetic range of about 800 gauss is not large compared with the errors associated with determinations of field strength (Preston 1969), and the fact that the magnetic data are not well represented by $P = 69.5$ days is probably due to uncertainties in the measurements of the magnetic field intensities.

B. HD 12288

The photoelectric observations of HD 12288 are shown in Figure 2, where they are plotted

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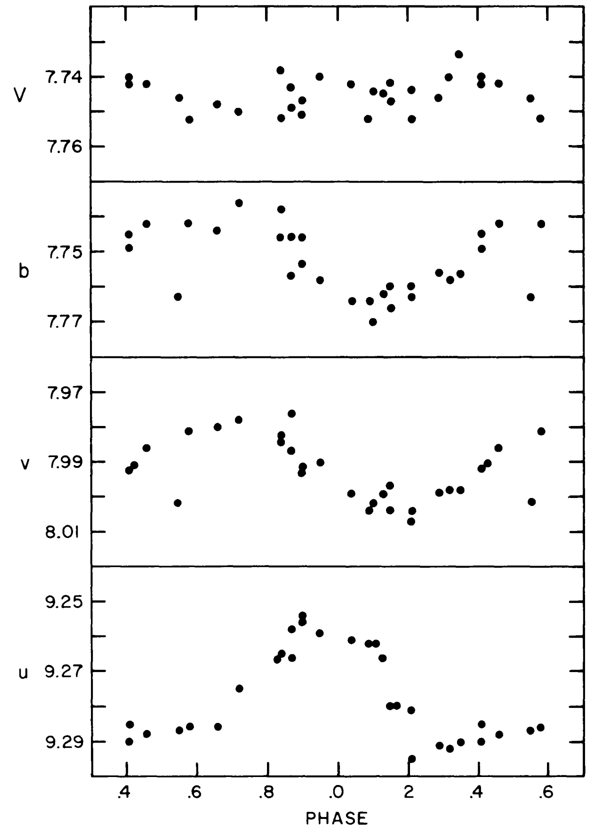

FIG. 2 — The light variations of HD 12288 plotted according to the ephemeris JD$_{\odot}$ (maximum light in u) = 2440854.7 + 34.9E.

according to the elements:

$$\begin{aligned} JD_{\odot} \text{ (maximum light in } u) \\ = 2440854.7 + 34.9E \\ \pm 3.5 \quad \pm 0.3 \end{aligned}$$

The b and v light curves each contain a single discrepant point. Since we can find no indication of any error in the observations, we have searched for a period that would eliminate the discrepancy. No other long period represents the data as well as $P = 34^{d}9$. However, because we observed HD 12288 only once per night and at about the same time each night, we cannot rule out periods near 1.03 days. For two periods, 1.0297 days and 1.0271 days, the data phase together as well as for the longer period, but at least one point disagrees badly with the others. On the basis of the oblique rotator model, we consider these short periods implausible because they imply a rotational velocity near 160 km sec^{-1}. To satisfy Preston's (1970*a*) measured upper limit, $v \sin i < 6$ km sec^{-1}, the star would have to be so nearly pole-on that only 4% of its surface would appear and disappear from view as the star rotated. Within the framework of our present understanding of the photometric variability of Ap stars (Preston 1971), it is difficult to see how the large amplitude of the light variation could then be produced.

Whether the light curves are plotted according to a long or a short period, the phase of maximum light appears to vary, possibly progressively, with wavelength. This star is the only Ap star known to us for which the light curves at different wavelengths are not very nearly in phase or in antiphase. More observations should be made to confirm both the proposed period and the apparent variation with wavelength of the phase of maximum light.

C. HD 24712

From an analysis of the spectrum variations of HD 24712 (HR 1217) Preston (1972) has derived the elements

$$JD_{\odot} \text{ (Eu maximum)} = 2440578.0 + 12.448E$$

Our photoelectric observations are plotted according to this ephemeris in Figure 3. These magnitudes were derived from measurements relative to a single comparison star, HD 25910. The second comparison star, HD 24832, proved to be variable. The constancy of HD 25910 was checked in 1970 by observations of HD 11874, one of the comparison stars for HD 12288, and in 1971 by observations of HD 23010.

As Figure 3 shows, the light curves of HD 24712 are in phase at all four wavelengths, and minimum light coincides with Eu maximum. This phase relationship between the spectrum and photometric variations directly contradicts the explanation given by Wolff and Wolff (1971) for the light variations of Ap stars with large overabundances of rare earths. The Wolffs pointed out that absorption due to lines of doubly ionized rare earths in the region λλ2000–3000 will cause a redistribution of flux into the visible, and they suggested that this backwarming effect is the primary cause of photometric variability in Ap stars that are rare-earth spectrum variables. If this explanation is correct, then rare-earth maximum should coincide with maximum brightness in V, and this phase relationship did obtain

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TABLE III

PHOTOMETRY OF HD 12288

JD⊙ 2440000+	Phase	V	b−y	m_1	c_1
832.06	0.35	7.734	+0.023	+0.219	+1.048
834.08	.41	7.740	+ .010	.234	1.052
835.97	.46	7.742	+ .001	.243	1.057
842.94	.66	7.748	- .004	.238	1.070
844.94	.72	7.750	- .014	.256	1.055
848.95	.84	7.738	+ .001	.242	1.040
852.95	.95	7.740	+ .018	.216	1.034
859.95	.15	7.742	+ .018	.220	1.044
883.90	.84	7.752	- .006	.244	1.044
884.93	.87	7.749	- .003	.233	1.060
899.82	.29	7.746	+ .010	.232	1.050
900.85	.32	7.740	+ .018	.224	1.052
903.91	.41	7.742	+ .002	.244	1.052
944.87	.58	7.752	- .010	.248	1.066
955.78	.90	7.751	+ .004	.234	1.024
1172.09	.09	7.752	+ .012	.228	1.018
1205.07	.04	7.742	+ .022	.213	1.027
1207.09	.10	7.744	+ .026	.208	1.026
1209.07	.15	7.747	+ .020	.220	1.036
1211.06	.21	7.744	+ .019	.225	1.030
1222.98	.55	7.746	+ .017	.222	1.045
1234.00	.87	7.743	+ .014	.216	1.040
1234.98	.90	7.747	- .001	.246	1.018
1242.97	.13	7.745	+ .017	.220	1.030
1245.99	0.21	7.752	+0.009	+0.234	+1.048

for all the stars observed up to that time (see also Preston 1971). Molnar's (1973) study of the variability of α^2 Canum Venaticorum in the region λλ2000–3000 strongly supported the Wolffs' suggestion. In attempting to reconcile the observations of HD 24712 with this proposal, we note that both the color indices and the spectrum (Preston 1972) indicate that this star is one of the coolest Ap stars known. The backwarming effect should be less important than in hotter stars, because the strength of the doubly ionized rare-earth lines and the continuous flux in the region λλ2000–3000 are both reduced. Changes in line blanketing in the visible regions of the spectrum, rather than backwarming, may therefore be the dominant cause of the light variations. This suggestion can be tested by measurements of the line blocking coefficients as a function of phase, and Bonsack (private communication) is making appropriate observations.

D. HD 216533

Babcock (1958) reported that HD 216533 shows pronounced variations in the strength of the lines of Sr II. We find that the star is a photometric variable as well, and the elements of the variation are:

$$\mathrm{JD}_\odot\,(\text{maximum light}) = \underset{\pm 1.5}{2440785.2} + \underset{\pm 0.09}{17.20}E$$

The data do not eliminate the possibility that

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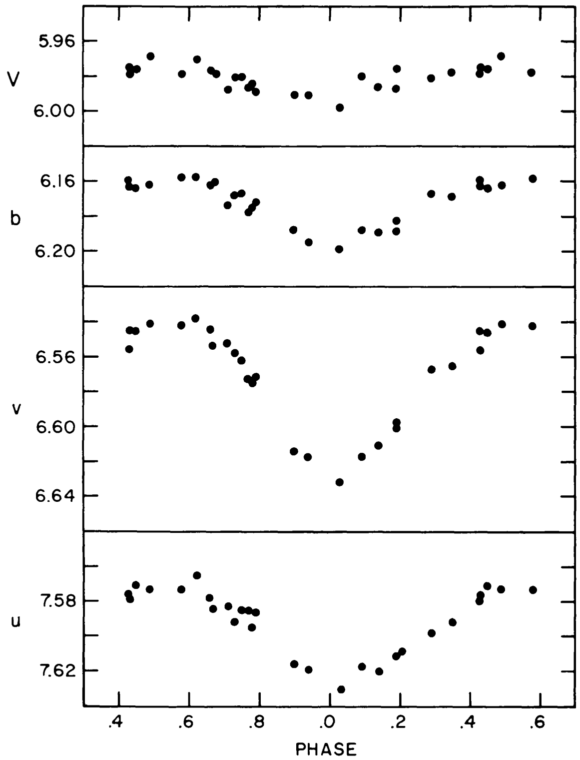

FIG. 3 — The light variations of HD 24712 plotted according to the ephemeris JD$_\odot$ (Eu maximum) = 2440578.0 + 12.448E.

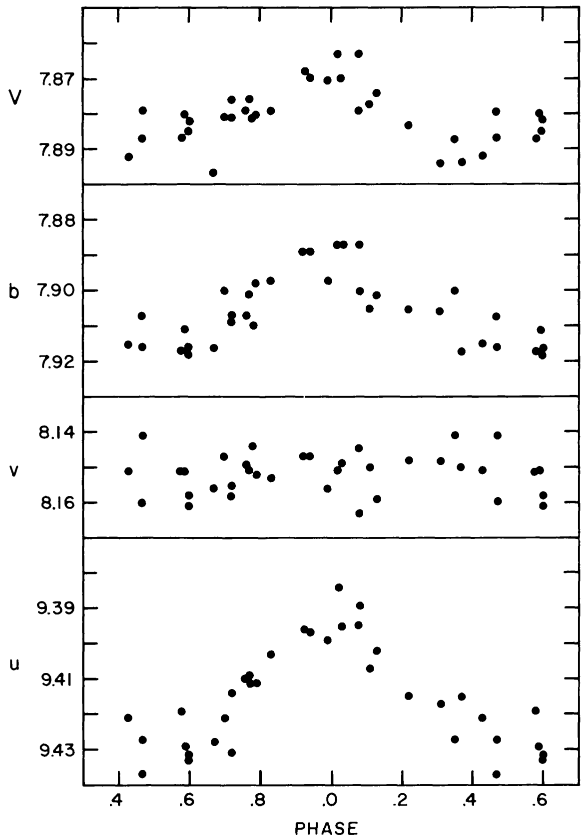

FIG. 4 — The light variations of HD 216533 plotted according to the ephemeris JD$_\odot$ (maximum light) = 2440785.2 + 17.20E.

P = 17.98 days, but the shorter period does provide a slightly better representation of the data. The light curves are shown in Figure 4. The variations in u, b, and y are in phase; the amplitude in v is less than 0^m01.

IV. Stars That Do Not Vary on a Short Time Scale

Seven of the eleven stars observed show no evidence of photometric variability during a single observing season and we have, therefore, searched for variability from one year to another. Table VI lists the transformed color indices of these seven stars, derived separately from observations in 1970 and 1971. In order to find whether the differences between entries for 1970 and 1971 are significant, we have computed magnitude and color differences, ΔV, $\Delta(b-y)$, etc., between pairs of comparison stars for 1970 and 1971 separately. Forming the differences between the two years and averaging over five pairs of comparison stars then yielded

$$\langle \Delta V_{1971} - \Delta V_{1970} \rangle = 0.000 \pm 0.002$$

$$\langle \Delta(b-y)_{1971} - \Delta(b-y)_{1970} \rangle = -0.001 \pm 0.005$$

$$\langle \Delta m_{1_{1971}} - \Delta m_{1_{1970}} \rangle = +0.003 \pm 0.007$$

$$\langle \Delta c_{1_{1971}} = \Delta c_{1_{1970}} \rangle = -0.001 \pm 0.007$$

Since the color indices in Table VI were obtained by combining differential photometry with the measured indices of the comparison stars, for which we adopted the transformed color indices derived from the observations made in 1971 only, we may compare Table VI directly with the above differences and standard deviations. The magnitudes and color indices observed for the Ap stars in 1970 differ from those in 1971 by more than twice these standard deviations only for HD 18078 and HD 2453. In the case of HD 18078, the difference is marginally significant, but HD 2453 is clearly variable.

In order to search for variability on a longer time scale, we have included in Table VI the *uvby* measurements of these stars obtained by

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TABLE IV
PHOTOMETRY OF HD 24712

JD$_\odot$ 2440000+	Phase	V	$b-y$	m_1	c_1
833.11	0.49	5.968	+0.194	+0.186	+0.652
834.12	.58	5.978	.180	.204	.646
836.04	.73	5.981	.186	.205	.642
843.02	.29	5.981	.185	.214	.630
845.01	.45	5.976	.188	.195	.641
849.01	.77	5.987	.191	.203	.618
852.99	.09	5.980	.208	.220	.570
860.02	.66	5.977	.184	.198	.651
865.99	.14	5.986	.202	.220	.585
871.96	.62	5.970	.188	.192	.647
899.04	.79	5.989	.183	.216	.614
900.96	.94	5.991	.204	.219	.577
901.96	.03	5.998	.201	.230	.566
903.96	.19	5.976	.205	.212	.595
935.82	.75	5.981	.186	.210	.626
953.78	.19	5.987	.201	.213	.594
955.84	.35	5.978	.191	.206	.630
956.80	.43	5.975	.187	.196	.646
1224.04	.90	5.991	.197	.230	.574
1234.08	.71	5.988	.185	.194	.651
1235.04	.78	5.985	.191	.206	.626
1243.04	.43	5.979	.181	.216	.629
1246.04	0.67	5.977	+0.182	+0.212	+0.636

Cameron (1966) in the early 1960s. In this case, stars can be considered variable only if the differences between Cameron's observations and our own exceed the uncertainties associated with the transformation to the standard *uvby* system. On this basis, HD 18078 and HD 2453 are the only stars that definitely vary. The period of HD 2453 may be as short as two years. If the difference between the 1970 and 1971 observations of HD 18078 represents the mean rate of change of m_1 and the difference between Cameron's value and our own represents the range of m_1, then it appears that the period of HD 18078 is in excess of ten years.

Stepień (1968) has derived periods of 9.8 days for 10 Aquilae and 18 days for HD 192678; in each case the observed amplitude was about 0^m015. If Stepień's periods are correct, our own observations cover the entire cycle of each star. We find that the amplitude of 10 Aql is less than 0^m004 in *u*, *v*, *b*, and *y* and that the total range observed for HD 192678 is less than 0^m008 at all four wavelengths. We also note that spectroscopic observations of 10 Aql made on ten consecutive nights by Preston (1970*a*) do not show any variations in either the spectrum or the strength of the magnetic field. We conclude, therefore, that the periods derived by Stepień for these two stars are probably incorrect.

V. Discussion

Periods are now known for eleven of the 25 stars in Preston's (1970*a*) list of Ap stars with $v \sin i < 10$ km sec^{-1}. Two additional stars, HD 2453 and HD 18078, have periods in excess of one year. Five more stars show no evidence

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TABLE V

PHOTOMETRY OF HD 216533

JD$_\odot$ 2440000+	Phase	V	$b-y$	m_1	c_1
782.04	0.82	7.876	+0.031	+0.220	+1.006
785.02	.99	7.871	.026	.234	0.982
787.01	.11	7.877	.027	.218	1.012
789.03	.22	7.883	.022	.222	1.028
820.90	.08	7.863	.037	.226	0.962
821.91	.13	7.874	.026	.230	0.985
829.95	.60	7.882	.034	.208	1.032
831.94	.72	7.881	.029	.216	1.030
832.91	.77	7.876	.024	.226	1.008
833.84	.83	7.879	.019	.236	0.994
835.84	.94	7.870	.020	.238	0.992
842.83	.35	7.887	.014	.225	1.043
844.81	.47	7.879	.028	.206	1.060
846.88	.59	7.880	.030	.210	1.036
848.84	.70	7.881	.019	.228	1.026
852.81	.93	7.868	.020	.238	0.991
871.79	.03	7.870	.016	.246	0.983
884.78	.79	7.880	.018	.236	1.005
898.76	.60	7.885	.033	.210	1.028
1170.03	.37	7.894	.023	.209	1.031
1170.97	.43	7.892	.022	.212	1.033
1181.06	.02	7.863	.024	.238	0.970
1186.06	.31	7.894	.012	.230	1.027
1206.01	.47	7.887	.029	.215	1.022
1208.00	.58	7.887	.030	.203	1.034
1211.00	.76	7.879	.028	.215	1.017
1233.82	.08	7.879	.008	.251	0.988
1243.86	.67	7.897	.018	.220	1.032
1245.86	0.78	7.881	+0.032	+0.209	+1.030

of photometric variability. The lack of variability could imply that the periods are very long, or, as seems equally probable, simply that the amplitudes are too small to be measurable. As Preston (1971) has pointed out, approximately 40% of the Ap stars that are known to be periodic variables have photometric amplitudes of 0^m02 or less. Because of the strong correlation between photometric and spectrum variability in the cooler Ap stars (Wolff and Wolff 1971; Preston 1971), there may be a strong bias against determining periods, either spectroscopically or photometrically, for low-amplitude light variables. Probably, therefore, more than 40% of all Ap stars vary by less than 0^m02, and it is not surprising that five of the eleven stars described here do not show definitely detectable (greater than $\sim 0^m01$) light variations.

Of the 13 stars in Preston's list for which periods are at least approximately known, only four have periods less than 25 days. Seven have periods greater than 100 days, and four of

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TABLE VI

PHOTOMETRY OF STARS THAT DO NOT VARY ON A TIME SCALE OF LESS THAN ONE YEAR

Star Name	Time of Observation	V	$b-y$	m_1	c_1
HD 2453	∿1963	6.91	-0.005	+0.271	+0.877
	1970	6.877	+0.015	+0.252	+0.924
	1971	6.867	+0.020	+0.273	+0.878
HD 18078	∿1963	8.25	+0.087	+0.251	+1.079
	1970	8.224	+0.133	+0.189	+1.097
	1971	8.235	+0.135	+0.172	+1.115
10 Aql	∿1963	5.93	+0.139	+0.215	+0.825
	1970	5.897	+0.138	+0.219	+0.829
	1971	5.901	+0.142	+0.217	+0.825
HD 191742	∿1963	7.13	+0.114	+0.232	+0.960
	1970	7.124	+0.116	+0.248	+0.939
	1971	7.126	+0.113	+0.251	+0.937
HD 192678	∿1963	7.38	-0.060	+0.263	+0.995
	1970	7.330	-0.057	+0.268	+1.014
	1971	7.333	-0.063	+0.280	+1.004
γ Equ	∿1963	4.70	+0.157	+0.242	+0.740
	1970	4.689	+0.141	+0.232	+0.768
	1971	4.699	+0.139	+0.239	+0.760
HD 204411	∿1963	5.30	+0.052	+0.179	+1.202
	1970	5.281	+0.053	+0.191	+1.216
	1971	5.283	+0.048	+0.197	+1.213

these definitely have periods exceeding one year. If the periods of these seven stars are, as the oblique rotator model requires, rotational periods, then the corresponding rotational velocities are all less than $\sim$1.5 km sec^{-1}. As Preston (1970*b*) has pointed out, the number of Ap stars with such low rotational velocities is much larger than any reasonable distribution function of rotational velocities would predict. The observed frequency of long periods and slow rotation can be reconciled with an oblique rotator model only if some deceleration mechanism plays a dominant role in determining the rotational velocities of the sharp-line Ap stars.

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