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PHOTOMETRIC BEHAVIOR OF MAGNETIC STARS*

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ABSTRACT

Detailed three-color observations of sixteen magnetic stars are presented, and a discussion of the photometric properties of twenty-three stars observed by the author is given. The results indicate that in virtually every case, if enough data are obtained, it is possible to find periodicities in the variations. Comparison with observations obtained by other investigators shows that there is no evidence for variability of periods, amplitudes, and shapes of light curves. It is shown that the extrema of the magnetic and light curves can be in phase as well as in antiphase. Two groups of magnetic stars are distinguished according to their photometric behavior: one consists of stars having V, $B - V$, and $U - B$ variations in phase, and the other consists of stars having a double wave in V and a peculiar $B - V$ curve with a broad, flat maximum. Variations of light in the first group can be explained in terms of variable effective temperature of a visible hemisphere The results of this paper seem to support the hypothesis that the rotation is a main cause of variations of the magnetic stars.

I. INTRODUCTION

Since the discovery by Guthnick and Prager (1914) that the peculiar A-type star α^2 CVn varies periodically in brightness with an amplitude of a few hundredths of a magnitude, some thirty peculiar stars were found to have similar variations. The interest in these stars increased considerably when Babcock discovered the existence of magnetic fields in many of them. At present it is believed that all the Ap stars possess magnetic fields. Because typical amplitudes of light variations are of the order of a few hundredths of a magnitude, the photoelectric method must be employed in detecting these variations. Nevertheless, the available observations are highly non-uniform. The overwhelming majority of them have been published in instrumental systems, and many of these systems have transmission bands considerably different from any widely accepted photometric system. Moreover, a large number of the stars were observed only in one color. All of this makes a discussion of photometric properties of the magnetic stars very difficult. For some of these stars periodic changes of the magnetic field were also found, and it became crucial for the understanding of phenomena taking place in them to establish phase relationships between light and magnetic curves. For this reason the two sets of observations should be as close in time as possible.

A few years ago a Zeeman analyzer was placed in operation by G. W. Preston at the Lick Observatory. Since then, many spectroscopic observations of magnetic stars have been obtained, and it became highly desirable to obtain concurrent series of photometric observations in one of the existing photometric systems. The *UBV* system has been chosen because many properties of stars are well worked out and understood in terms of this system.

Over twenty stars were chosen for photoelectric observations from the list of stars observed spectroscopically by Preston. In almost all cases concurrent or simultaneous series of observations have been obtained. In this paper detailed photometric data for sixteen stars are presented. Data for the others have been or will be published together with the spectroscopic observations in joint papers with Preston. Here, an over-all discussion of the general photometric properties of all these stars is given.

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II. OBSERVATIONS AND DESCRIPTION OF INDIVIDUAL STARS

The observations were made with the 24-inch reflector of Lick Observatory and standard *UBV* equipment. During August 1967 only, the observations were made with a different 1P21 photomultiplier. Between observing runs in October and December 1967 the mirror was aluminized. These two changes in the photometric system caused small systematic differences in the $U - B$ values of comparison stars (when tied up to the *UBV* system) obtained from different runs. These differences were generally smaller than 0.01 mag and were subsequently ignored in deriving mean values of color indices of the comparison stars. A complete observation usually consisted of a set: comparison 1–variable–variable–comparison 2. Such sets were repeated after about 1 hour and, sometimes, again after another 1 or more hours. The method of reduction was the same as described previously (Preston and Stępień 1968*a*). The probable error of one listed observation is, on the average, 0.005 mag. In the subsequent description stars are arranged in order of increasing right ascension. The values of amplitudes of light variations of the magnetic stars discussed in the text are always rounded to the nearest five thousandths of a magnitude.

HD 2453.—This star was observed on thirty-six nights between August 6, 1967, and January 5, 1968. Magnitudes and color indices of the comparison stars are given in Table 1. The star HD 1641 is a visual binary (ADS 285) with a separation of 2″ between components. The relatively large difference in $B - V$ between HD 2453 and the comparison stars might affect accuracy of observations. Nevertheless, the scatter of observations did not exceed the scatter of differences, HD 1641 *minus* HD 2688. It may be concluded that the star was constant during the period when it was observed. Mean values of V, $B - V$, and $U - B$ were formed over observing runs, and they are given in Table 2. Here N denotes the number of nights on which the star was observed. If the star varies in brightness, the period must be at least several months.

HD 9996 = HR 465.—This star was observed on eleven nights in the beginning of 1967 and on thirty-seven nights in the fall of 1967. Unfortunately a bad star, HD 10086, was used as a comparison star during the first eleven nights. It has too large a $B - V$, relative to HD 9996. As a result of this choice and large westerly hour angles during observations a systematic difference was found in the color indices of HD 9996 obtained from this set of nights and the others. This comparison star also affected the results obtained between July 25 and August 11, 1967. Later, two more favorable stars were chosen. Magnitudes and color indices of all the comparison stars are given in Table 1. The star HD 9935 is a visual binary (ADS 1273), and only one component was observed with a 17″ diaphragm. On nights with poor seeing only HD 10204 was used as a comparison star. The observations of HD 9996 show small scatter and indicate that the star was constant throughout the period when it was observed. Mean values of V, $B - V$, and $U - B$ taken over separate observing runs are presented in Table 3. It is apparent that the star was constant, at least in V, during one year. If it is a light variable its period must be at least a few years.

HD 10783.—A separate publication is being prepared which discusses in detail all the magnetic and photometric data. Babcock's (1958) magnetic and van Genderen's (1965) photometric observations agree well with recent concurrent magnetic and photometric data obtained at the Lick Observatory if the following elements are used:

$$\text{Maximum of } V = \text{J.D. } 2439757.91 + 4^{d}.1327E\,.$$

Light variations in V, $B - V$, and $U - B$ are in phase. The magnetic curve is in phase with the light curves, i.e., the maximum of the magnetic field corresponds to the maximum of light in all three colors.

HD 18296 = 21 Per.—This star was observed photometrically by Rakos (1962*a*)

TABLE 1

MAGNITUDES AND COLOR INDICES OF COMPARISON STARS

Variable (HD or Name)	Comp Stars (HD)	V (mag)	$B-V$ (mag)	$U-B$ (mag)
2453	1641	6 849	+0 451	−0 018
	2688	7 505	+ 464	+ .066
9996	9935	8 614	+ 086	+ 043
	10086	6 616	+ 696	+ 193
	10204	5 639	+ 213	+ 140
21 Per	17940	7 961	+ 246	+ 146
	18222	8 633	+ 379	+ 119
15 Cnc	66299	6 704	+ 065	+ .099
	68253	8 558	+ 134	+ 043
	68254	8 027	+ 035	+ 027
71866	71844	7 080	+ 161	+ .200
49 Cnc	73143	5 922	+ 088	+ 150
	74308	8 668	+ 238	+ 195
	74926	7 687	+ 099	+ .094
78 Vir	116160	5 693	+ 043	+ 033
	118005	8 893	+ 142	+ 132
153882	153809	7 256	+ 113	+ 095
	154228	5 913	+ 007	− 016
10 Aql	175579	7 033	+ 060	− .036
21 Aql	179343	6 939	+ 101	− 186
	180782	6 181	+ 027	− .002
192678	192679	7 019	+ 487	− 038
	194668	6 491	− 014	− 053
215038	215035	5 716	+ 019	+ .031
	216886	7 430	+ 252	− 183
215441	215501	8 351	+ 259	+ .144
	215757	6 852	+ 064	− .026
224801	3	6 712	+ 068	+ .078
	224906	6 254	−0 038	−0.349

TABLE 2

MAGNITUDES AND COLOR INDICES OF HD 2453

Period (U T)	N	$\langle V \rangle$ (mag)	$\langle B-V \rangle$ (mag)	$\langle U-B \rangle$ (mag)
August 6–August 23, 1967	13	6 879	+0 087	+0 031
September 10–October 9, 1967	13	6 879	081	.024
December 10–January 5, 1968	10	6 882	+0 080	+0 033

who found small amplitude variations with the period 1.7 days. The author observed this star on thirty-two nights between December 29, 1966, and January 5, 1968. In the 1966–1967 season the star HD 18222 was used as a comparison star. In the 1967–1968 season two new comparison stars were chosen in place of HD 18222: HD 17940 and HD 19216. In the course of reductions it turned out that HD 19216 is a variable itself. It was possible to find a period of 7.7 days for this star (see below). This variability left only one comparison star which is almost 3 mag fainter than 21 Per. This comparison star, HD 17940, has two optical companions on both sides (in right ascension). The companions were far from the edge of the 28″ diaphragm centered on the comparison star, but when the 59″ diaphragm was used the light from them may enter it. No systematic difference between measurements of HD 17940 with different diaphragms was found, but all these circumstances caused a larger scatter of observations of 21 Per. Magnitudes and color indices of the comparison stars are given in Table 1. The observations of 21 Per are given in Table 4. For the 1966–1967 season mean values of differences, comparison *minus* variable, were formed for each night because individual observations were of poorer quality. This is why only two decimal digits are retained in Julian Day. For the

TABLE 3

MAGNITUDES AND COLOR INDICES OF HD 9996

Period (U.T.)	N	Comp Stars (HD)	$\langle V\rangle$ (mag)	$\langle B-V\rangle$ (mag)	$\langle U-B\rangle$ (mag)
January 31–February 20, 1967.	11/9*	10086	6 400	−0 016	−0 113
July 25–August 11, 1967	6	10086+10204	6 406	027	095
August 14–August 23, 1967...	9	9935+10204	6 401	031	104
September 23–October 8, 1967.	10	9935+10204	6 402	034	.102
December 10, 1967—January 5, 1968	12	9935+10204	6 404	−0 035	−0 103

* V has been measured on eleven nights, and color indices on nine nights.

1967–1968 season the individual sets of observations are listed. The observations are not represented by a period of 1.7 days. When plotted against Julian Day, they show an apparent period of about 3 days. The best-fitting period is 2.883 days. All the observations are plotted in Figure 1 (*left*) using the following elements:

$$\text{Maximum of } V = \text{J.D. } 2439837.7 + 2^{d}883E\,.$$

Magnetic observations given by Babcock (1958) do not fit the above period, but it was possible to find a number of periods in the vicinity of 3 days which satisfy the magnetic observations very well (e.g., 2.928 or 3.288 days). Thus the problem of an accurate value of the period near 3 days for 21 Per is not settled. The amplitude of light variations is 0.020 mag in V: Color indices do not show apparent variability with the above period.

HD 19216.—The light variations of this star were detected accidentally. The star was chosen as one of the comparison stars for 21 Per (see above). It is not known whether HD 19216 shows the characteristics of a peculiar A-type star, but it is not listed as such in the *Henry Draper Catalogue*. The star was observed on nineteen nights between September 25, 1967, and January 5, 1968, using HD 17940 as a comparison star. HD 17940 was also used as a comparison star for 21 Per, and its magnitude and color indices are given in Table 1. The observations are listed in Table 4 and displayed in Figure 1 (*right*). Phases were calculated using the following elements:

$$\text{Maximum of } V = \text{J.D. } 2439860.7 + 7^{d}7E\,.$$

TABLE 4

PHOTOELECTRIC OBSERVATIONS OF MAGNETIC STARS

21 Per

JD$_\odot$ 2439000+	Phase	V (mag)	B-V (mag)	U-B (mag)
488.72	0.95	5.106	--	--
490.71	.64	5.109	--	--
491.65	.97	5.108	-0.036	-0.235
492.86	.39	5.134	.036	.242
496.71	.72	5.121	.032	.252
497.71	.07	5.100	.019	.258
498.67	.40	5.124	.027	.255
499.70	.76	5.121	.026	.258
527.70	.47	5.126	--	--
531.67	.85	5.116	.031	.248
535.64	.23	5.120	.040	.241
536.64	.57	5.119	.019	.255
541.65	.31	5.118	--	--
758.025	.36	5.121	.026	.245
759.002	.70	5.121	.017	.238
760.022	.06	5.091	.019	.230
761.010	.40	5.134	.031	.244
767.036	.49	5.112	.017	.242
767.835	.77	5.121	.027	.251
767.979	.82	5.110	.028	.241
768.036	.84	5.114	.029	.232
770.033	.53	5.119	.022	.251
771.017	.87	5.094	.028	.243
833.829	.66	5.130	.034	.250
833.867	.67	5.121	.021	.241
834.668	.95	5.110	.033	.241
834.823	.00	5.101	.034	.247
835.690	.30	5.116	.024	.250
836.723	.66	5.115	.021	.256
837.784	.03	5.105	.017	.246
837.831	.05	5.100	.016	.243
839.760	.71	5.117	.026	.243
839.794	.73	5.110	.017	.247
840.687	.04	5.101	.019	.252
840.763	.06	5.104	.032	.257
854.722	.90	5.106	.030	.245
854.746	.91	5.108	.027	.240
858.683	.28	5.117	.030	.237
858.714	.29	5.119	.027	.241
859.679	.62	5.115	.024	.252
859.700	.63	5.108	.018	.256
860.697	.98	5.108	.028	.251
860.721	.99	5.097	.020	.249
860.742	0.99	5.093	-0.016	-0.246

HD 19216

JD$_\odot$ 2439000+	Phase	V (mag)	B-V (mag)	U-B (mag)
759.00	0.80	7.868	-0.009	-0.151
760.02	.92	7.838	0.000	.156
761.01	.05	7.852	+0.002	.168
767.04	.84	7.853	+0.004	.151
767.95	.95	7.838	-0.007	.160
770.03	.22	7.858	0.000	.160
772.00	.48	7.866	-0.017	.146
833.85	.51	7.861	-0.009	.153
834.75	.63	7.845	-0.010	.159
835.69	.75	7.855	+0.001	.158
836.72	.89	7.843	+0.002	.169
837.80	.03	7.842	+0.005	.157
839.78	.28	7.859	-0.015	.169
840.73	.41	7.867	-0.013	.157
853.70	.09	7.840	+0.011	.163
854.73	.22	7.849	+0.002	.167
858.70	.74	7.843	-0.003	.156
859.69	.87	7.847	+0.003	.151
860.72	0.00	7.831	+0.004	-0.171

15 Cnc

JD$_\odot$ 2439000+	Phase	V (mag)	B-V (mag)	U-B (mag)
482.93	0.01	5.637	-0.082	-0.129
486.91	.97	5.638	.089	.126
490.93	.95	5.628	--	--
492.90	.43	5.621	.075	.116
496.89	.40	5.629	.066	.135
497.74	.61	5.628	.064	.119
498.83	.87	5.629	.091	.128
499.84	.12	5.629	.087	.131
527.88	.93	5.628	--	--
531.81	.88	5.635	.085	.117
535.68	.82	5.628	.075	.127
536.86	.11	5.628	.078	.112
541.76	.30	5.625	.080	.119
615.72	.27	5.631	.073	.113
617.70	.75	5.631	.087	.120
833.97	.29	5.632	.077	.130
834.92	.52	5.627	.073	.115
835.98	.78	5.634	.078	.109
836.88	.00	5.634	.086	.112
853.91	.14	5.622	.084	.119
854.83	.36	5.635	.074	.114
855.90	.62	5.627	.076	.115
856.94	0.87	5.628	-0.083	-0.124

TABLE 4 (Continued)

$JD_{\odot}$ 2439000+	Phase	V (mag)	B-V (mag)	U-B (mag)
		15 Cnc (Cont.)		
858.82	0.33	5.632	-0.074	-0.120
859.80	.57	5.629	.075	.115
860.80	0.81	5.630	-0.077	-0.117
		HD 71866		
833.96	0.18	6.742	+0.116	+0.002
834.91	.32	6.740	.107	.011
836.03	.49	6.756	.073	.031
836.92	.62	6.747	.070	.022
837.92	.77	6.744	.072	.030
853.97	.13	6.751	.104	.010
854.83	.25	6.740	.122	.004
855.91	.41	6.750	.086	.013
856.98	.57	6.755	.073	.024
858.84	.84	6.744	.069	.034
859.87	.99	6.748	.079	.018
860.85	0.14	6.747	+0.108	+0.015
		49 Cnc		
474.96	0.57	5.635	-0.093	-0.252
482.93	.04	5.665	.087	.241
486.96	.78	5.626	.092	.238
491.75	.66	5.636	.099	.241
496.89	.61	5.633	.094	.253
497.75	.77	5.660	.085	.245
498.83	.97	5.665	.096	.244
499.88	.16	5.660	.092	.258
527.90	.32	5.634	--	--
531.82	.04	5.660	.097	.248
535.69	.76	5.650	.095	.254
536.90	.98	5.655	.099	.250
540.92	.72	5.634	--	--
541.77	.88	5.658	.087	.256
542.89	.08	5.647	--	--
615.71	.49	5.637	.092	--
617.69	.86	5.654	.086	--
619.68	.22	5.641	--	--
835.00	.88	5.649	.103	.247
853.98	.37	5.640	.099	.252
855.92	.73	5.646	.099	.238
856.97	.92	5.653	.103	.237
859.95	.47	5.646	.095	.246
860.90	0.65	5.644	-0.096	-0.241

$JD_{\odot}$ 2439000+	Phase	V (mag)	B-V (mag)	U-B (mag)
		78 Vir		
527.98	0.92	4.928	+0.029	+0.003
532.07	.25	4.923	.034	.001
541.01	.98	4.931	.024	.010
543.01	.14	4.921	.023	.014
613.82	.92	4.935	.037	.008
615.79	.08	4.937	.035	.006
617.75	.24	4.924	.036	.005
619.78	.41	4.913	.027	.010
623.82	.74	4.925	.040	.007
624.79	.81	4.929	.033	.000
625.84	.90	4.928	.037	.008
630.70	.30	4.922	.025	.011
631.71	.38	4.924	.027	.008
649.71	.85	4.924	.037	.009
650.72	.93	4.926	.029	.009
651.70	.01	4.935	.027	.010
652.76	.10	4.926	.039	.013
854.07	.52	4.923	.028	.011
855.08	.60	4.925	.034	.007
856.08	.68	4.928	.031	.007
860.07	.01	4.936	.030	.011
861.07	0.09	4.929	+0.037	+0.007
		HD 153882		
674.75	0.84	6.307	+0.034	+0.044
696.85	.57	6.298	.036	.034
706.82	.23	6.280	.040	.046
707.69	.38	6.295	.045	.040
708.69	.54	6.291	.035	.030
711.70	.04	6.301	.040	.047
712.70	.21	6.289	.035	.051
713.69	.37	6.297	.039	.046
715.72	.71	6.301	.035	.030
716.72	.88	6.300	.040	.025
717.73	.05	6.299	.041	.042
718.73	.21	6.286	.040	.042
719.69	.37	6.301	.037	.031
720.71	.54	6.303	.038	.035
721.69	.71	6.304	.032	.029
722.72	.88	6.299	.042	.037
723.71	.04	6.298	.039	.047
724.77	.22	6.277	.039	.035
725.75	.38	6.294	.040	.033
726.72	0.54	6.294	+0.035	+0.035

TABLE 4 (Continued)

JD$_{\odot}$ 2439000+	Phase	V (mag)	B-V (mag)	U-B (mag)
		10 Aql		
719.75	0.79	5.902	+0.244	+0.106
720.77	.90	5.898	.247	.100
721.77	.00	5.893	.257	.100
722.77	.10	5.901	.250	.103
723.81	.21	5.904	.252	--
724.82	.31	5.903	.252	.100
743.76	.25	5.903	.246	.105
756.69	.57	5.903	.246	.111
757.68	.67	5.897	.244	.107
758.65	.77	5.907	.252	.098
759.67	.87	5.903	.257	.099
760.67	.97	5.894	.256	.095
767.64	.68	5.899	.247	.107
769.64	.89	5.888	.256	.107
770.66	.00	5.889	.259	.096
771.63	.10	5.894	.254	--
772.65	0.20	5.894	+0.256	+0.097
		21 Aql		
708.752	0.76	5.143	-0.065	-0.403
709.827	.39	5.153	.069	.401
710.777	.95	5.145	.075	.411
711.797	.54	5.154	.076	.403
712.778	.12	5.142	.073	.403
713.830	.73	5.145	.072	.402
714.785	.29	5.155	.076	.396
715.743	.85	5.149	.074	.399
716.747	.44	5.162	.069	.398
717.763	.03	5.149	.069	.396
718.736	.60	5.164	.068	.401
719.769	.20	5.150	.066	.409
720.779	.79	5.155	.072	.398
721.779	.38	5.156	.078	.401
722.778	.96	5.152	.071	.397
724.808	.15	5.140	.065	.399
743.743	.22	5.152	.070	.392
756.701	.80	5.144	.058	.407
757.664	.36	5.164	.079	.392
758.626	.93	5.150	.071	.399
759.652	.53	5.168	.063	.399
760.651	.11	5.155	.063	.393
761.624	.68	5.154	.061	.397
767.630	.19	5.164	.067	.406
769.628	.36	5.162	.065	.402
770.641	.95	5.155	.066	.401
771.611	0.52	5.160	-0.072	-0.406

JD$_{\odot}$ 2439000+	Phase	V (mag)	B-V (mag)	U-B (mag)
		HD 192678		
713.79	0.06	7.357	-0.009	-0.010
714.89	.12	7.354	.011	.001
715.83	.17	7.353	.011	.008
716.83	.23	7.351	.015	.010
717.81	.28	7.355	.013	.009
718.79	.34	7.352	.012	.005
719.80	.39	7.350	.018	.006
720.81	.45	7.357	.015	.006
721.80	.51	7.357	.017	.006
722.81	.56	7.351	.014	.016
723.81	.62	7.356	.017	.009
724.85	.68	7.351	.020	.013
743.86	.73	7.359	.021	.016
757.70	.50	7.355	.017	.016
758.74	.56	7.360	.017	.008
759.68	.61	7.347	.015	.017
760.68	.67	7.358	.023	.006
765.78	.95	7.369	.012	.017
767.76	.06	7.358	.012	.026
769.70	.17	7.346	.015	.014
770.66	.23	7.351	.012	.011
771.69	.28	7.349	.019	.002
772.68	.33	7.346	.021	.011
835.61	.83	7.361	.019	.017
836.63	.89	7.363	.016	.027
840.60	0.11	7.347	-0.005	-0.012
		HD 215038		
717.849	0.47	8.156	-0.052	-0.488
719.740	.40	8.156	.046	.482
719.885	.47	8.152	.052	.479
719.980	.52	8.162	.060	.478
720.716	.88	8.202	.039	.458
720.883	.96	8.220	.046	.451
720.986	.01	8.217	.036	.462
721.726	.38	8.167	.058	.476
721.876	.45	8.166	.055	.491
721.985	.50	8.162	.058	.482
722.719	.86	8.207	.045	.468
722.885	.95	8.208	.037	.460
723.001	.00	8.204	.036	.456
723.714	.35	8.162	.047	.486
723.879	.43	8.155	.048	.487
723.989	.49	8.145	.046	.476
725.960	.46	8.165	.045	.485
743.774	0.21	8.181	-0.044	-0.470

TABLE 4 (Continued)

JD⊙ 2439000+	Phase	V (mag)	B-V (mag)	U-B (mag)
		HD 215038 (Cont.)		
743.993	0.31	8.150	-0.048	-0.473
744.874	.75	8.166	.044	.475
744.961	.79	8.186	.045	.469
756.697	.55	8.153	.056	.489
756.843	.63	8.149	.042	.486
757.670	.03	8.221	.049	.468
757.998	.19	8.186	.043	.464
758.910	.64	8.162	.050	.472
759.709	.03	8.210	.042	.464
766.884	.56	8.148	.056	.482
767.810	.01	8.227	.047	.464
767.949	.08	8.202	.043	.463
769.703	.94	8.201	.035	.458
770.692	.43	8.151	.054	.474
771.913	.03	8.215	.040	.464
772.696	0.41	8.150	-0.059	-0.486
		HD 215441		
717.88	0.66	8.842	+0.038	-0.524
719.83	.87	8.786	.012	.539
720.87	.98	8.786	.007	.535
721.88	.09	8.791	.023	.531
722.89	.19	8.830	.029	.524
723.87	.30	8.875	.034	.504
724.88	.40	8.888	.038	.490
725.88	.51	8.879	.040	.496
743.98	.42	8.894	.036	.491
744.92	.51	8.890	.032	.492
756.80	.77	8.808	.022	.526
757.75	.87	8.789	.004	.529
758.90	.99	8.775	.023	.532
759.73	.08	8.806	.013	.528
760.90	0.20	8.850	+0.026	-0.506

JD⊙ 2439000+	Phase	B (mag)	B-V (mag)	U-B (mag)
		HD 215441 (Cont.)		
765.81	0.72	8.822	+0.025	-0.529
766.87	.83	8.799	.018	.534
767.81	.93	8.784	.012	.541
769.72	.13	8.816	.023	.526
770.72	.23	8.864	.024	.515
771.74	.34	8.888	.029	.476
772.83	0.46	8.897	+0.032	-0.485
		HD 224801		
696.942	0.75	6.373	-0.067	-0.352
697.983	.03	6.340	.045	.396
706.966	.43	6.366	.064	.365
715.922	.82	6.352	.057	.368
716.904	.09	6.351	.046	.382
717.931	.36	6.377	.066	.361
719.931	.90	6.347	.050	.366
720.924	.16	6.362	.059	.378
721.934	.43	6.382	.063	.350
722.934	.70	6.379	.062	.349
723.928	.96	6.328	.045	.386
724.949	.24	6.380	.061	.369
725.953	.51	6.368	.062	.351
758.914	.32	6.390	.072	.355
759.965	.60	6.377	.067	.337
760.953	.86	6.367	.065	.361
765.826	.17	6.364	.054	.376
766.912	.46	6.366	.066	.355
767.884	.72	6.374	.069	.347
769.768	.22	6.372	.063	.372
770.748	.48	6.369	.061	.352
771.924	.80	6.357	.068	.354
772.919	0.06	6.334	-0.049	-0.385

The accuracy of measurements suffered from the same difficulties as for 21 Per, and this is probably the main cause for the large scatter in Figure 1 (*right*). Freehand curves were drawn neglecting all the deviations, but the possibility cannot be ruled out that the V curve has a secondary maximum similar to that encountered in 73 Dra and HD 224801. The amplitude of variations is 0.030 mag in V, 0.015 mag in $B - V$ (the $B - V$ curve is in antiphase, relative to the V curve) and 0.015 mag in $U - B$ (in phase with V).

HD 32633.—Detailed magnetic and photometric data for this star have already been published (Preston and Stępień 1968*a*). The star shows a very strong magnetic field with reversals of polarity. Variations in V, $B - V$, and $U - B$ are in phase. Maxima of light in all the colors coincide with the minimum of the magnetic field.

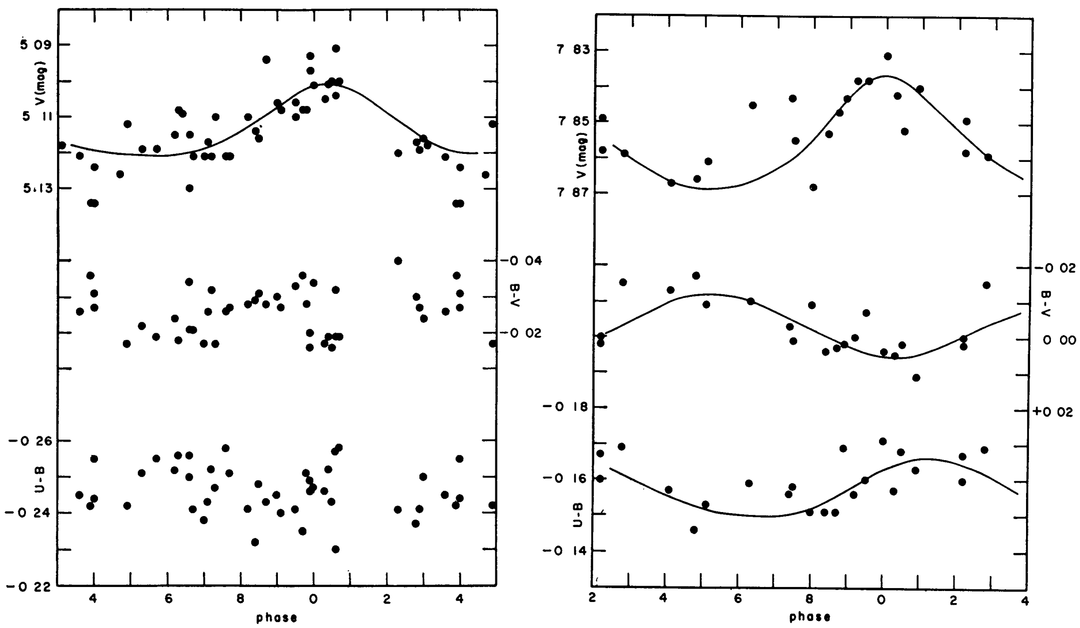

FIG. 1.—Photoelectric observations of 21 Per plotted with the period 2.883 days (*left*), and HD 19216 plotted with the period 7 7 days (*right*).

HD 65339 = 53 Cam.—This star has the largest known amplitude of magnetic variations. It has caused considerable interest in the past because it seemed to be an exception from the general rule of the coincidence of maxima of light variations with minima of the magnetic field (Jarzebowski 1960*a*, *c*). Jarzebowski (1960*c*) also reported a shift in phase between minima of light variations in different colors. Recent concurrent series of magnetic and photometric observations (Preston and Stępień 1968*b*) clarified the situation with regard to the phase relationship between the magnetic and the light variations. The star shows only a small variation in V. The maximum of these variations coincides with the minimum of the magnetic field. The variations in $B - V$ are in antiphase relative to V variations, and $U - B$ varies in phase with $B - V$. As a result the U curve is in antiphase to the V curve.

HD 68351 = 15 Cnc.—According to Babcock (1958), the spectrum of this star has relatively broad lines, showing evidence of a magnetic field of positive polarity. The star was measured photoelectrically on twenty-six nights between December 23, 1966, and January 5, 1968. Three comparison stars were used: HD 68253 in the 1966–1967 season and HD 66299 and HD 66254 in the 1967–1968 season. Magnitudes and color indices of the comparison stars are given in Table 1. The observations of 15 Cnc are given in Table 4. The light variations of 15 Cnc are small, but a periodicity of around 4 days is indicated by changes in $B - V$. The best period is 4.116 days. Figure 2 (*left*) gives all the observations of 15 Cnc plotted using the following elements:

$$\text{Maximum of } B - V = \text{J.D. } 2439482.9 + 4^{d}116E\,.$$

The star is constant in V and in $U - B$, while the amplitude of $B - V$ variations is 0.015 mag.

HD 71866.—This magnetic variable has been studied in the past by a number of investigators. Provin (1953*b*) first reported small light variations, but he had not enough data to carry out any discussion of these variations. Babcock (1956) found a period of

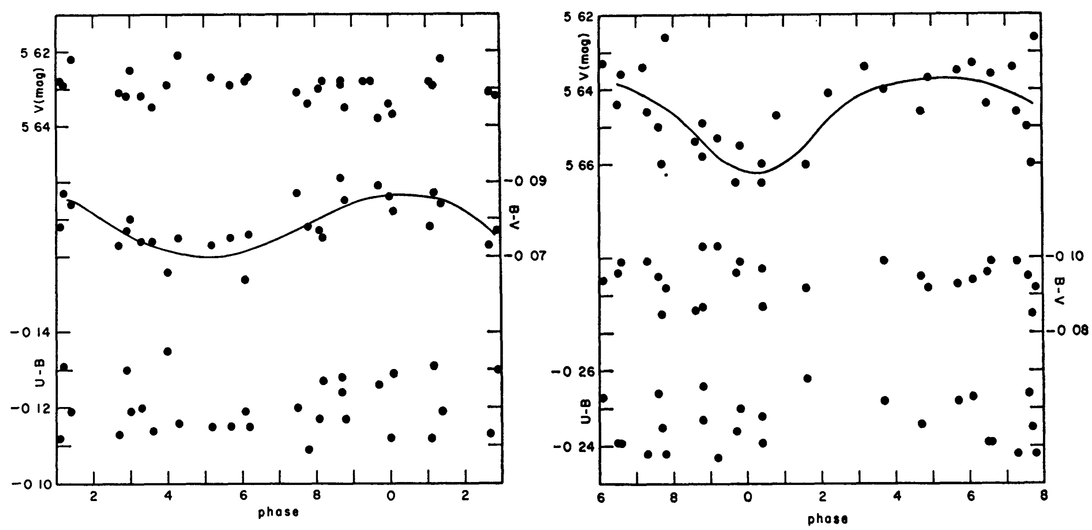

Fig. 2.—Photoelectric observations of 15 Cnc plotted with the period 4.116 days (*left*), and 49 Cnc plotted with the period 5.43 days (*right*).

around 6.8 days from the magnetic data. Detailed investigations of light variations were made by Jarzebowski (1960*a*, *c*) and Rakos (1962*b*). Because a discrepancy existed between Jarzebowski's and Rakos' conclusions regarding the phase relationships among variations in different colors, the star was included in the present investigation. It was observed on twelve nights between December 9, 1967, and January 5, 1968. Excellent weather and a very convenient comparison star HD 71844 situated only 10′ from the variable (also used by other investigators) resulted in accurate measurements of HD 71866. The photometric data of HD 71844 are given in Table 1. The observations of HD 71866 are listed in Table 4 and shown in Figure 3 (*left*). Phases were computed using the elements derived by Preston and Pyper (1965):

$$\text{Positive cross-over} = \text{J.D. } 2432957.90 + 6^{d}80001\,.$$

The observations in V show a double wave similar to those found in HD 224801 and 73 Dra except that, in this case, both maxima are equal. Because the observations are not sufficiently numerous to prove beyond doubt the existence of such a double wave, Rakos' yellow observations were plotted in the same figure with the above elements and with the vertical shift of +7.090. Only observations obtained at the Lowell Observatory were used, and mean values for each night were formed. They confirm the existence of the double wave. Both maxima have an amplitude of 0.015 mag, and one minimum is probably deeper than the other. The $B - V$ curve is also strikingly similar to $B - V$ curves obtained for HD 224801, 73 Dra, and α^2 CVn (Pyper, unpublished). The amplitude of the $B - V$ curve is 0.050 mag, and the minimum coincides with one of the maxima of the V curve. By analogy with HD 224801 and 73 Dra we shall call this maximum the primary maximum. The shapes of V and $B - V$ curves explain a discrepancy between the results obtained by Jarzebowski (1960*c*) and Rakos (1962*b*) concerning the phase relationship between light curves in yellow and blue light. Rakos' photometric

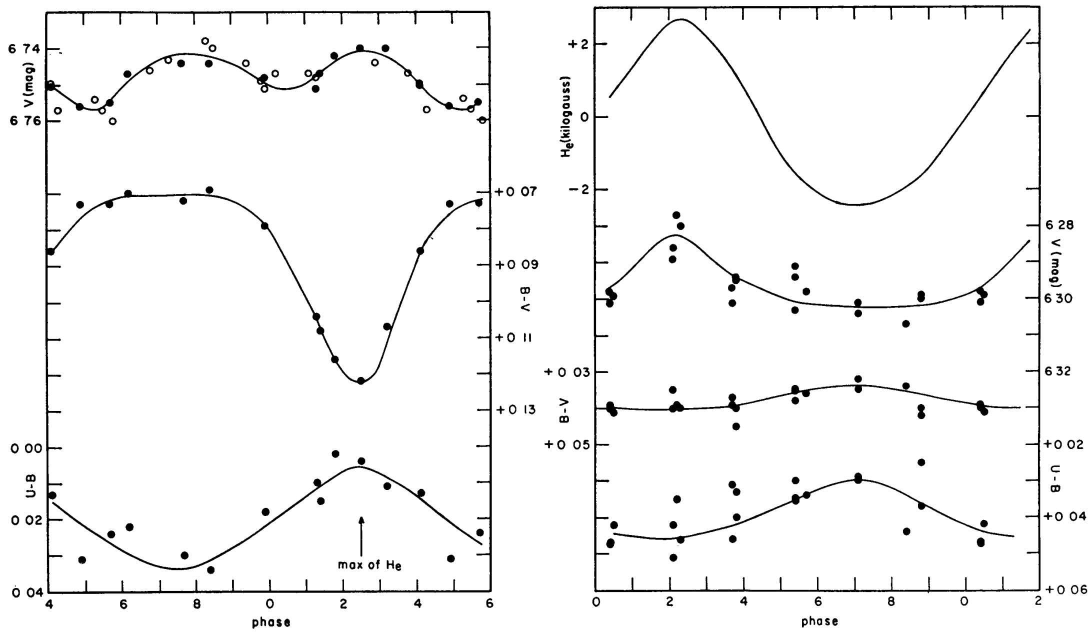

FIG. 3.—Photoelectric observations of HD 71866 plotted with the ephemeris given by Preston and Pyper (1965) as given in the text (*left*). Filled circles denote observations obtained in the present investigation, and open circles denote observations by Rakos (1962*b*). The phase of the maximum of the magnetic field is marked with an arrow Photoelectric observations of HD 153882 plotted with the ephemeris given by Preston and Pyper (1965) as given in the text (*right*). The smooth magnetic curve given by Preston and Pyper is shown at the top.

system was close to the *UBV* system, while the sensitivity of Jarzebowski's yellow filter was shifted to the blue, relative to the V band. As a result he obtained the curve which describes light variations somewhere between the effective wavelengths of the V and B bands and which was in phase with the curve in blue light. HD 71866 also shows variations in $U - B$ which are in antiphase relative to the $B - V$ variations and have an amplitude of 0.025 mag. The maximum of the magnetic field coincides with the minimum of the $B - V$ curve (or with the primary maximum of the V curve). Thus the relationship is just opposite to that in the case of 73 Dra.

HD 74521 = 49 Cnc.—Spectra of this star show the presence of a magnetic field of constant polarity. Photoelectric measurements of 49 Cnc were made on twenty-four nights between December 15, 1966, and January 5, 1968. Three comparison stars were used: HD 74308 in the 1966–1967 season and HD 73143 and HD 74926 in the 1967–1968 season. Magnitudes and color indices of these stars are given in Table 1. The star HD 74926 is a visual binary (ADS 6995), and the values given for this star refer to both components. The observations of 49 Cnc are given in Table 4 and plotted in Figure 2 (*right*) with the following elements:

$$\text{Minimum of } V = \text{J.D. } 2439499 + 5\overset{d}{.}43E\,.$$

HD 78316 = *κ Cnc*.—A separate publication will give a full discussion of all the magnetic and photometric data obtained at the Lick Observatory. The magnetic field is weak, and the light variations are also very small, which make any conclusion about periodicity quite uncertain. A period of around 7 days has been found from all the available data. The magnetic curve has a peculiar shape resembling that of α^2 CVn. The amplitude of light variations is 0.01 mag in V. Color indices do not show variability in the above period.

HD 108662 = *17 Com A*.—The detailed magnetic and photometric data will be published elsewhere. This star shows periodic variations of luminosity and the magnetic field with the period around 5 days. The variations in V, $B - V$, and $U - B$ seem to be in phase, although a small shift between the maxima in V and $B - V$ may exist. The phase relationship between light and magnetic curves is uncertain. The magnetic field is relatively weak, and individual measurements give considerable scatter. Extrema of the magnetic and light curves do not coincide if the observations are plotted with the period found from the photometric data alone. It seems, however, that by changing the period a little one could force the extrema to coincide.

HD 111133.—This star was observed on twenty-five nights in the 1966–1967 and 1967–1968 seasons. Two stars, HD 110423 and HD 111470, were used as comparison stars. A period of around 11 days was found for HD 111133, with the largest amplitude of variations in blue light. It turned out, however, that HD 110423 is probably also slightly variable and had to be rejected. Unfortunately, in the 1967–1968 season HD 111470 appeared brighter by more than 0.02 mag in ultraviolet compared with the 1966–1967 season. Whether this difference is of stellar or instrumental origin is not known. Subsequently it was decided not to publish detailed data.

HD 118022 = *78 Vir*.—This star has one of the most numerous sets of magnetic observations published by Babcock (1958). So far it was impossible, however, to find a regularity in the magnetic variations. The author observed 78 Vir on twenty-two nights between February 6, 1967, and January 5, 1968. Two stars, HD 116160 and HD 118005, were used as comparison stars, and their magnitudes and color indices are given in Table 1. The second star is too faint for photometry of the required accuracy, but it was necessary to use this nearby star because of lack of stars with comparable magnitudes and color indices in the vicinity of 78 Vir. The accuracy of measurements undoubtedly suffered as a result. An analysis of the observations indicated a possible period near 13 days. With this preliminary period an improved period of 12.26 days was found from the magnetic data given by Babcock (1958). All of Babcock's observations are plotted in Figure 4 (*left*) using the above period and an arbitrary epoch J.D. 2430000. Open circles at the level $H_e = 0$ indicate eye estimates that the magnetic field was weak. Horizontal bars drawn through some of the filled circles indicate the presence of cross-over effect when Babcock did not note the sign of it. Bars inclined upward and downward to the right indicate positive and negative cross-over, respectively.

The scatter of observations is quite large but, as pointed out by Babcock, the magnetic field varies rather erratically, changing sometimes by several hundred gauss on consecutive nights. Moreover, an observation at $H_\epsilon = -1680$ gauss indicates also that the expected scatter of individual observations is of the order of a few hundred gauss. All the eye estimates but one lie in the half-cycle where the maximum occurs. The cross-over effect is not confined to any particular phase. The sign of cross-over is indicated for only a few observations, but even here no apparent regularity throughout the cycle is apparent. Finally, it does not seem that the plates with cross-over effect give values of the magnetic field which deviate more than the others from the smooth curve. The radial velocity of 78 Vir (not plotted here) does not show regular variations with the period 12.26 days.

The photometric observations of 78 Vir are given in Table 4 and shown in Figure 4 (*right*) using the following elements:

$$\text{Minimum of } V = \text{J.D. } 2439860 + 12\overset{\text{d}}{.}26E\,.$$

Although the amplitude of variations is only 0.015 mag, one can see that variations in V follow the above period. Color indices seem to be constant. Because eleven years passed between the last published magnetic observations and photoelectric observations presented here, it is not possible to establish a phase relationship between the V curve and the magnetic curve.

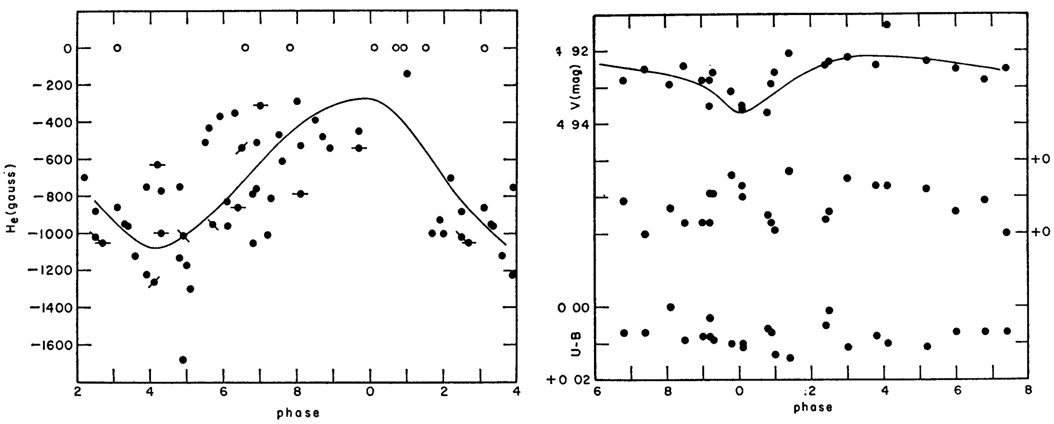

FIG. 4.—Magnetic observations of 78 Vir given by Babcock (1958) plotted with the period 12.26 days (*left*). Open circles indicate eye estimates. Short bars across filled circles indicate cross-over effect (*horizontal bar:* no sign given; *bar inclined upward to the right:* positive cross-over; *bar inclined downward to the right:* negative cross-over). Photoelectric observations of 78 Vir plotted with the same period (*right*).

HD 152107 = 52 Her.—A separate discussion of the magnetic and photometric data for this star is in preparation. A period slightly less than 1 day has been found. It satisfies all the available data, but for many reasons discussed in detail in the paper mentioned above there is large scatter in the photometric and magnetic observations. If the proposed period is correct, it is the shortest known period among magnetic variables. The amplitude of light variations amounts to 0.015 mag in V with the possibility of a small variation in $B - V$ in antiphase, relative to the V curve. No regular variations in $U - B$ were found. A gap in time between the magnetic and photometric series of observations makes it impossible at present to establish the relationship between the magnetic and light curves.

HD 153882.—This star has a strong magnetic field with reversals of polarity. It has been found by Gjellestad and Babcock (1953) to be a periodic variable. Recently the magnetic field of HD 153882 has been observed by Preston and Pyper (1965), who improved the period given by Gjellestad and Babcock. Jarzebowski (1960*a*) has obtained the photoelectric observations of this star and found light variations with the amplitude 0.02 mag. In the present investigation the star was observed on twenty nights between July 3 and August 24, 1967. Two comparison stars were used, and their magnitudes and color indices are given in Table 1. The observations of HD 153882 are given in Table 4 and plotted in Figure 3 (*right*) using the following elements given by Preston and Pyper (1965):

$$\text{Positive cross-over} = \text{J.D. } 2432752.73 + 6\overset{\text{d}}{.}00925E\,.$$

The magnetic curve obtained by Preston and Pyper is given at the top. Many comments follow the inspection of Figure 3 (*right*). The most interesting conclusion is that the maximum of the V curve coincides with the maximum of the magnetic curve. The time interval between the magnetic and photoelectric observations is three years, but this relationship seems to be certain. The new period satisfies all the published magnetic data made over sixteen years. Moreover, in August 1967 seven plates were taken by Preston with the 120-inch telescope, and visual inspection of them showed that the magnetic field follows the ephemeris predicted by the above elements (Preston, private communication). The amplitude of the V variations is 0.020 mag. The variations of $B - V$ and $U - B$ are in antiphase, relative to the V curve, and their amplitudes are 0.005 and 0.015 mag, respectively. The scatter of observations is large. It may be due

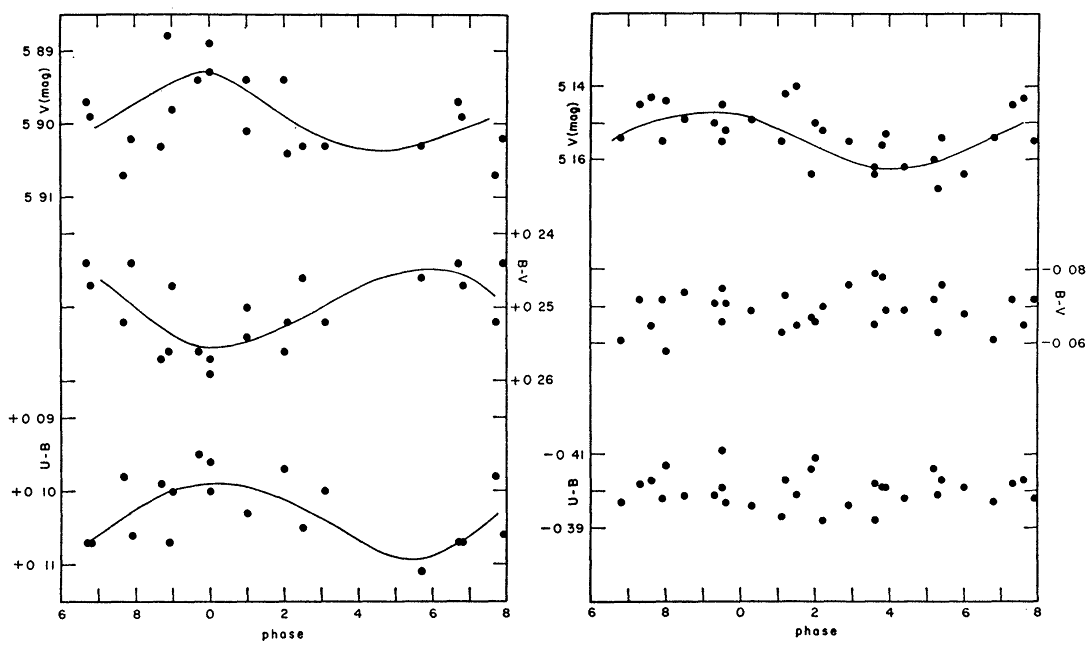

FIG. 5.—Photoelectric observations of 10 Aql plotted with the period 9.78 days (*left*). The vertical scale is expanded by a factor of 2, relative to the other figures. Photoelectric observations of 21 Aql plotted with the period 1.71 days (*right*).

partly to the fact that HD 153882 is a visual binary, and a 17″ diaphragm had to be used to cut off the light of the fainter component, while a 28″ diaphragm was used for observations of the comparison stars. This difficulty, irregularities in the drive system of the telescope, and poor seeing undoubtedly affected the accuracy of measurements for this variable. Nevertheless, the possibility that the star shows intrinsic short-term fluctuations cannot be ruled out.

HD 176232 = 10 Aql.—According to Babcock (1958), this star has a moderate magnetic field with alternating polarity. Because of very narrow lines and a relatively rich spectrum, the magnetic field can be measured with high precision. This star was measured photoelectrically on seventeen nights between August 18 and October 9, 1967. Only one star, HD 175579, was used as a comparison star. Mean values of V, $B - V$, and $U - B$ for this star are given in Table 1. The constancy of brightness of HD 175579 was not checked, but the scatter of V, $B - V$, and $U - B$ obtained from individual nights does not exceed that for other constant stars. Differences, variable *minus* comparison, show variability with small amplitude. It is assumed here that this variability is due to

10 Aql. The period 9.78 days was found. The observations of 10 Aql are given in Table 4 and plotted in Figure 5 (*left*) using the following elements:

$$\text{Maximum of } V = \text{J.D. } 2439721.8 + 9^{\text{d}}78E\,.$$

All three curves have the amplitude 0.010 mag. The variation in $B - V$ is in antiphase with the V curve while the $U - B$ variation is in phase with the V curve. The small amplitudes of the variations make conclusions about the variability and period of 10 Aql rather uncertain. The observations are not very numerous, and a gap exists between phase 0.3 and 0.6. In August 1967 Preston obtained nine plates of this star on ten consecutive nights. They indicate that the magnetic field of 10 Aql was constant and had a value of approximately +500 gauss (Preston, unpublished).

HD 179761 = 21 Aql.—This star is a component of a visual binary, which makes photoelectric observations more difficult than for other stars because of the necessity of using a small diaphragm. The variable was always observed with a 17″ diaphragm, while a 28″ diaphragm was used for observations of the comparison stars. This circumstance and possible intrinsic fluctuations of the star caused relatively large scatter of individual sets of observations on nights when more than one such set was obtained. The star was observed on twenty-seven nights between August 6, 1967, and October 8, 1967. Magnitudes and color indices of comparison stars are given in Table 1. The observations of 21 Aql are given in Table 4. When plotted against Julian Day, they show an apparent periodicity of about 2 days. However, because of the small amplitude of the variations and the considerable scatter, the derived period is rather uncertain. The observations are displayed in Figure 5 (*left*), with the period of 1.71 days and the following elements:

$$\text{Maximum of } V = \text{J.D. } 2439817.71 + 1.71E\,.$$

An associated period of about 2.3 days satisfies this set of data equally well and cannot be ruled out. The amplitude of the variation is 0.015 mag in V, and the observations show no clear evidence of variability in the color indices.

HD 192678.—According to Babcock (1958), this star shows a strong magnetic field of positive polarity. Photoelectric observations of HD 192678 were made on twenty-six nights between August 11, 1967, and December 16, 1967. Magnitudes and color indices of comparison stars are given in Table 1. One of the comparison stars, HD 192679, is a visual binary (ADS 13560). Both components were always included in the diaphragm. The observations of HD 192678 are given in Table 4. The star shows a periodicity near 18 days. All the observations are presented in Figure 6 (*left*), where phases were computed from the following elements:

$$\text{Minimum of } V = \text{J.D. } 2439766.7 + 18^{\text{d}}E\,.$$

The V and $B - V$ curves are in phase while the $U - B$ curve is in antiphase, relative to them. The amplitudes in V, $B - V$, and $U - B$ are 0.015, 0.010, and 0.015 mag, respectively. Thus, in spite of the strong magnetic field, the amplitudes of the photometric variations are quite small. The coverage of a cycle by magnetic observations was not adequate to 1967, but a few plates taken on consecutive nights do not show rapid variations of the magnetic field (Preston, private communication).

HD 196502 = 73 Dra.—This star was believed for a long time to be an irregular magnetic variable with constant polarity. Recent observations by Preston (1967) showed that this is a periodic magnetic variable. Its magnetic field reverses polarity, and the period is equal to the period of spectral variations. Photometric observations of 73 Dra have been published elsewhere (Stępień 1968*b*). They were not obtained in the same season as the magnetic observations, but because the length of the period of this star is known accurately, they can be phased with the magnetic observations. This comparison confirms the conclusion drawn by Berg (1967) that the minimum of the magnetic field coincides with the primary maximum of the V curve. The variations in V show also a secondary maximum with an amplitude equal to half that of the primary maximum. This double wave was already detected by Provin (1953*a*). The variations in $B - V$ are in antiphase, relative to V, and have an amplitude equal to the amplitude of the primary maximum in V. As a result only the secondary maximum is visible in B. The $U - B$ index shows little or no variation.

HD 215038.—According to Babcock (1958), two magnetic observations of this star on consecutive nights showed a large field of positive polarity. It was observed photoelectrically by Jarzebowski (1961), who found light variations with a period of 2.0357 days and an amplitude of 0.07 mag. The author observed HD 215038 on nineteen nights

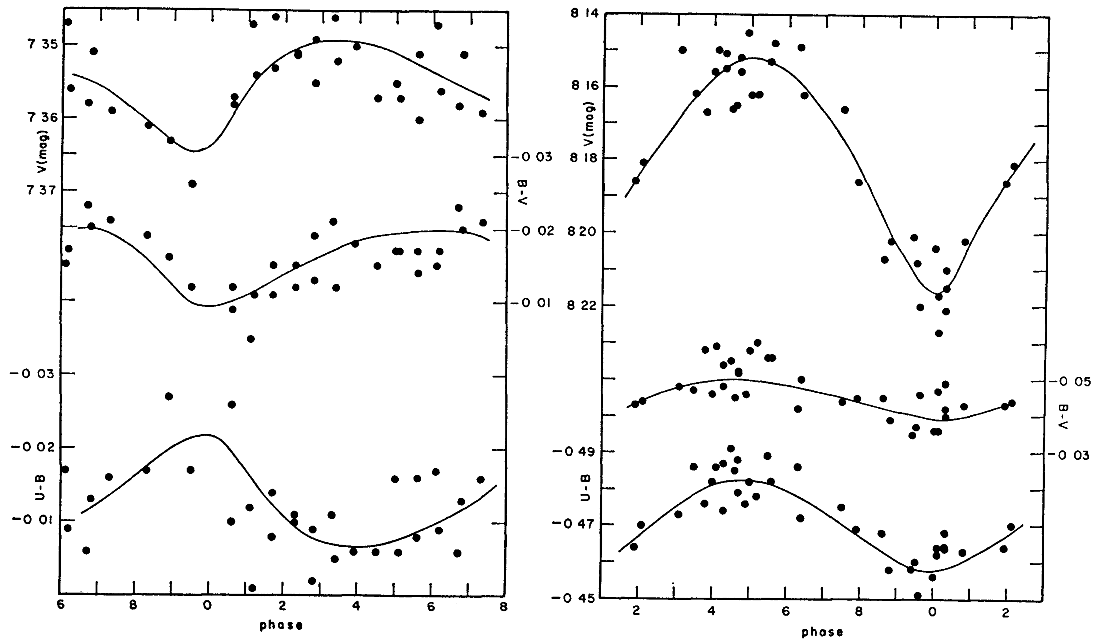

FIG. 6.—Photoelectric observations of HD 192678 plotted with the period 18 days (*left*). The vertical scale is expanded by a factor of 2, relative to the other figures. Photoelectric observations of HD 215038 plotted with the period 2.036 days (*right*).

between August 15, 1967, and October 9, 1967. Magnitudes and color indices of comparison stars are given in Table 1. The star HD 216886 is a visual binary (ADS 16371), and values given in Table 1 refer to both components. The observations of the variable are given in Table 4 and displayed in Figure 6 (*right*). A large gap in time between Jarzebowski's and the author's observations makes it difficult to improve the period. According to the ephemeris given by Jarzebowski, the presently observed minimum falls at phase 0.21. By assuming that no cycles were lost and by forcing minima to coincide, the period was changed to 2.036 days. The following elements were used to calculate the phases in Table 4:

$$\text{Minimum of light} = \text{J.D. } 2437271.65 + 2^{d}036E .$$

The amplitudes of the light variations in V, $B - V$, and $U - B$ are 0.065, 0.010, and 0.025 mag, respectively. All the curves are symmetrical and in phase. The main reason for the relatively large scatter of observations in Figure 6 (*left*) is that each point corresponds to an individual set of observations.

HD 215441.—This is the magnetic variable (Babcock 1960) with the largest known magnetic field: $H_e \approx 12$ kilogauss. The star has fairly sharp lines; some of them were resolved into separate Zeeman components, the separations of which indicate a surface magnetic field of 34 kilogauss. This star has also the largest known light variations among magnetic variables. These variations were detected by Jarzebowski (1960*b*), who found a period of 9.5 days. The author observed HD 215441 on twenty-two nights between August 15, 1967, and October 9, 1967. Magnitudes and color indices of comparison stars are given in Table 1. The observations of HD 215441 are given in Table 4. As in the case of HD 215038, it is not possible to improve the period without ambiguity. By forcing maxima observed by both authors to coincide, a set of new periods in the vicinity of 9.5 days can be derived. Of these, $P = 9.488$ days is closest to the period found by Jarzebowski (1960*b*) and seems to fit his data best. This period was used in new elements of HD 215441:

$$\text{Maximum of light} = \text{J.D. } 2436865.0 + 9^{d}488E\,.$$

The observations are plotted in Figure 7 (*left*). The V, $B - V$, and $U - B$ curves are in phase, and their amplitudes are 0.110, 0.030, and 0.045 mag, respectively.

HD 224801.—This star was observed photoelectrically by Provin (1953*b*) and Rakos (1963). Both sets of observations indicate that the yellow light curve has a peculiar shape with two unequal maxima. The author observed HD 224801 on twenty-three nights between July 25, 1967, and October 9, 1967. Magnitudes and color indices of the comparison stars are given in Table 1. The observations of the variable are given in Table 4. The observational material for this star is sufficient to justify an attempt to improve the period. The best agreement for all the existing data was obtained with the period 3.73983 days. All the data obtained in the visual pass band are plotted in the upper part of Figure 7 (*right*), using as elements the time of maximum given by Provin (1953*b*) and the above period:

$$\text{Maximum of } V = \text{J.D. } 2434222.77 + 3^{d}73983E\,.$$

To obtain agreement between zero points to the present set of data and sets obtained by Provin (1953*b*) and Rakos (1963), a value of 6.705 mag was added to differences, variable *minus* comparison, listed by these investigators. It is apparent from the good agreement of all the sets of data that the shape of the light curve has remained constant over the past sixteen years. The two lower curves in Figure 7 (*right*) give the variations of color indices. The variations of the color indices obtained by the other investigators were not plotted because a scale factor is involved in the transformation of instrumental indices to the UBV system. This factor does not occur in the case of V. Shapes of $B - V$ and $U - B$ variations are similar to those obtained by Provin and Rakos. The star HD 224801 is similar to 73 Dra and HD 71866 with regard to its photometric behavior.

III. DISCUSSION

a) General Properties

A summary of the photometric properties of stars, observed by the author and possessing light variations, is given in Table 5. The consecutive columns give HD number; name or HR number; mean values of V, $B - V$, and $U - B$, taken as arithmetic means of the appropriate quantities at minimum and maximum; unreddened color index $(B - V)_0$, obtained from the standard relation between $U - B$ and $B - V$ for main-sequence stars given by Johnson (1963); approximate period; amplitudes of variations in V, $B - V$, and $U - B$; and the phase relationship between the V curve and the magnetic curve, if known. The last digits of the mean values and amplitudes of V, $B - V$, and $U - B$ are rounded to the nearest 5. Signs associated with the amplitudes in $B - V$ and $U - B$ show the phase relationships of the variations in color indices relative to the V variations: a plus sign means that the appropriate curve is in phase with the V curve, and a minus sign means that it is in antiphase. To obtain amplitudes of variations in B (and U), one has to add the amplitudes in $B - V$ (and $U - B$) to the amplitude in V *taking into account the signs*. The resulting sign will give the phase relationship relative to the V curve. The same sign convention is applied to indicate the phase relationship between the V curve and the magnetic curve. A colon indicates that the appropriate quantity is uncertain. It should be noted that, although the existence of light variations and lengths of periods are established in many cases, there are stars (e.g., 15 Cnc, 49 Cnc, 10 Aql, 21 Aql) for which the variations are small and the observations not very numerous. Results for such stars should be treated with caution and need photometric and/or spectroscopic confirmation. The star 21 Aql is not even regarded as peculiar by Sargent and Searle (1962).

The stars from Table 5 are arranged in order of decreasing $(B - V)_0$. The last entry

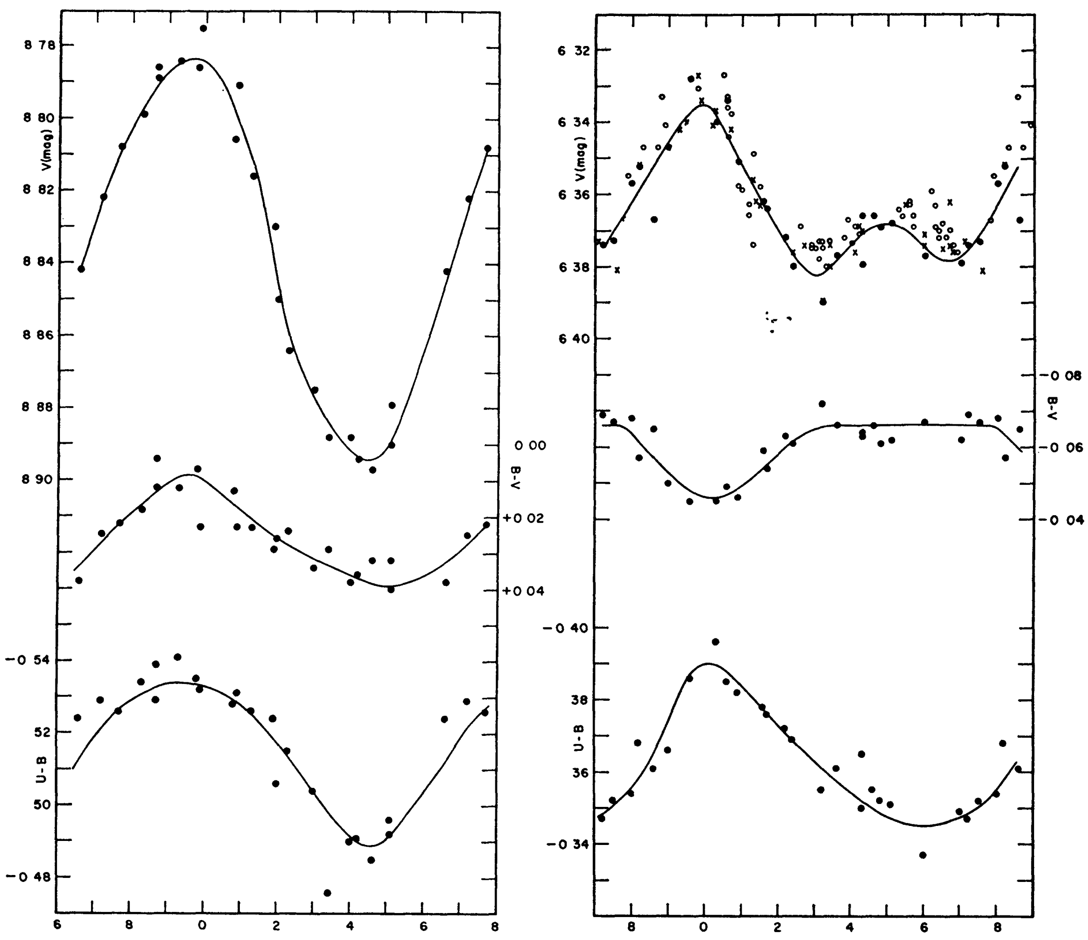

FIG. 7.—Photoelectric observations of HD 215441 plotted with the period 9.488 days (*left*), and HD 224801 plotted with the period 3.73983 days (*right*). Filled circles denote observations obtained in the present investigation, open circles denote observations obtained by Rakos (1963), and crosses denote observations obtained by Provin (1953*b*).

is 73 Dra, for which $(B - V)_0$ cannot be determined unambiguously because of its position in the $U - B$, $B - V$ diagram. All the stars from Table 5 are displayed in Figure 8. The main sequence defined by Johnson (1963) is given as a solid line. Straight lines of various lengths indicate the observed ranges of variations of $B - V$ and $U - B$. Small shifts and differences in shapes of the $B - V$ and $U - B$ curves which may exist for some of the stars are ignored. They would result in loops rather than straight lines in Figure 8. The filled circles at the center of each line give $\langle B - V \rangle$ and $\langle U - B \rangle$.

TABLE 5

PHOTOMETRIC PARAMETERS OF MAGNETIC STARS

HD	Name or HR	$\langle V \rangle$ (mag)	$\langle B-V \rangle$ (mag)	$\langle U-B \rangle$ (mag)	$(B-V)_0$ (mag)	P (days)	ΔV (mag)	$\Delta(B-V)$ (mag)	$\Delta(U-B)$ (mag)	Phase Relation between H_e and V
215441 .		8 840	+0 025	−0 515	−0 175	9 49	+0 110	+0 030	+0 045	. .
215038.	.	8 185	− 045	− .470	− 145	2 04	.065	+ 010	+ .025	.
32633 .	.	7 060	− 050	− 420	− 125	6 43	.025	+ 010	+ 020	−
78316 .	κ Cnc	5 230	− 105	− .445	− 125	6 91	010	0:	0:	.
179761 .	21 Aql	5 155	− 070	− 400	− 115	1 7:	.015	0:	0:	
224801 .	9080	6 360	− 055	− 365	− .105	3 74	045*	− 020	+ 045	
74521 .	49 Cnc	5 650	− 095	− 245	− .095	5 43	025	0:	0:	
18296 .	21 Per	5 110	− 025	− 240	− 075	2 88	020	0:	0:	
68351	15 Cnc	5 630	− 080	− 120	− 080	4 12	0:	.015	0:	
10783	.	6 560	− 055	− .160	− 055	4 13	.020	+ 015	+ .010	+
19216	. . .	7 850	− 005	− 160	− 050	7 7	030	− 015	+ 015	.
108662..	17 Com	5 255	− 040	− 115	− 040	5 09	015	+ 010	+ 015	−?
65339	53 Cam	6 030	+ 150	+ 030	− 025:	8 03	010:	− 015:	− 015:	−
192678	.	7 355	− 015	− 015	− 015	18	015	+ 010	− 015	
71866 .	. . . .	6 750	+ 095	+ 020	− 015	6 80	015*	− 050	+ 025	+
152107	52 Her	4 810	+ 095	+ 050	− 010	0 96	015	− 005	0:	
118022	78 Vir	4 930	+ 030	+ 010	− 005	12 3	015	0:	0:	
153882..	6326	6 295	+ 035	+ 040	+ 010	6 01	020:	− 005:	− 015:	+
176232 .	10 Aql	5 900	+ 250	+ 105	+0 220	9 78	010	− 010	+0 010	.
196502	73 Dra	5 205	+0 090	+0 105		20 3	+0 030*	−0 030	0:	−

* There is a secondary maximum on the V variation.

Recently Eggen (1967) presented results of his photometry of bright peculiar A-type stars. Figure 9 gives the comparison of his photometry with $\langle V \rangle$, $\langle B - V \rangle$, and $\langle U - V \rangle$ taken from Table 5. Taking into account that the stars are slightly variable, the agreement is satisfactory.

b) *Constancy of Periods and Shapes of Light Curves*

Until recently α^2 CVn was the only peculiar A-type star for which there were enough observations in the past to discuss possible variations of period; the period proved to be constant. Now, we have a few more stars for which observations indicate lack of secular variations of period and shape of light curves, among them 73 Dra, HD 224801, and HD 71866. For a few other stars, sets of observations obtained in two different epochs can be easily phased with one period without any necessity of introducing secular variations. Therefore, the conclusion seems to be justified that at present there is no evidence for secular variability of period or shape of light curves of magnetic stars. Further, the shapes of the magnetic curves seem to be constant for many magnetic stars.

c) *Phase Relationship between Light and Magnetic Curves*

For a long time it was believed that in all cases where the relationship between magnetic and light variations could be established, the minimum of the magnetic curve coincided with the maximum of light curve. It has already been shown elsewhere (Stępień 1968*b*) that in some cases variations in different colors are in antiphase. This means that the discussion of the phase relationship between light and magnetic curves is meaningless without specification of color. It still seemed, however, to be true that in all known cases the minimum of the magnetic curve coincided with the maximum of the *V* curve (or with the primary maximum if two existed). Subsequent investigations showed that even this is not the case. The observations of HD 153882 show that in the case of this star the maximum of the magnetic curve coincides with the maximum of the *V* curve, and recent concurrent magnetic and photometric observations of HD 10783 proved that the same holds for this star. In the latter case variations in all colors are in phase, i.e., the maximum of the magnetic curve coincides with maxima of light curves in all colors. The star HD 71866 was considered as an example of a star for which the maximum of

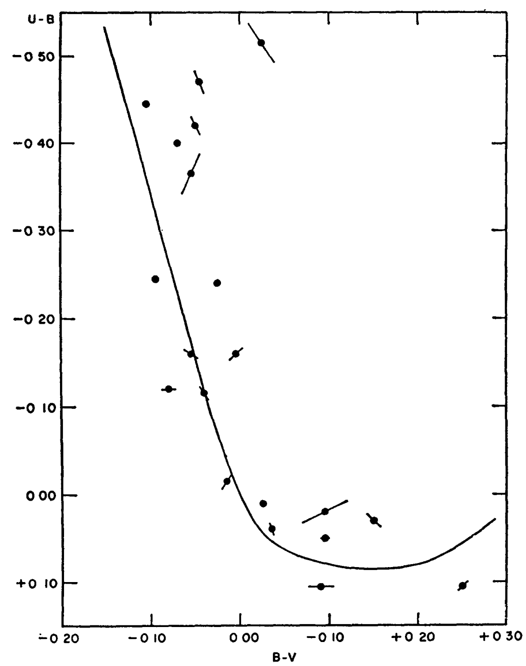

FIG 8.—Observed range of color indices of the magnetic stars during a cycle Solid line gives the main sequence according to Johnson (1963).

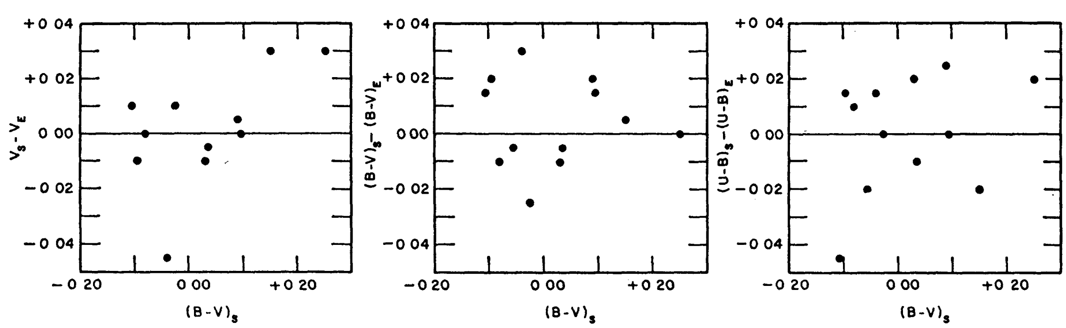

FIG. 9.—Comparison of mean values of V, $B - V$, and $U - B$ obtained in the present investigation with the photometry of Eggen (1967).

the magnetic field coincides with the minimum of the light variations. The confusion arose because the term "light variations" referred to variations in a wavelength region shifted toward the blue, relative to the V band. The observations of HD 71866 presented here show that the phase relationship is just opposite that for 73 Dra (which shows light variations of the same type). Hence HD 71866 should be considered as the star for which maximum of the magnetic curve coincides with the primary maximum of the V curve. The conclusion to be drawn from the data in Table 5 is that there is no preference for antiphase as opposed to in-phase relationships between light curves and magnetic curves.

d) Range of Light Variations

Generally, the range of light variations in one color is of the order of a few hundredths of a magnitude. The largest known amplitude occurs in the case of HD 215441 which varies in the ultraviolet by almost 0.2 mag. This star also has the strongest known magnetic field. The star with the second largest known magnetic field, 53 Cam (and with the

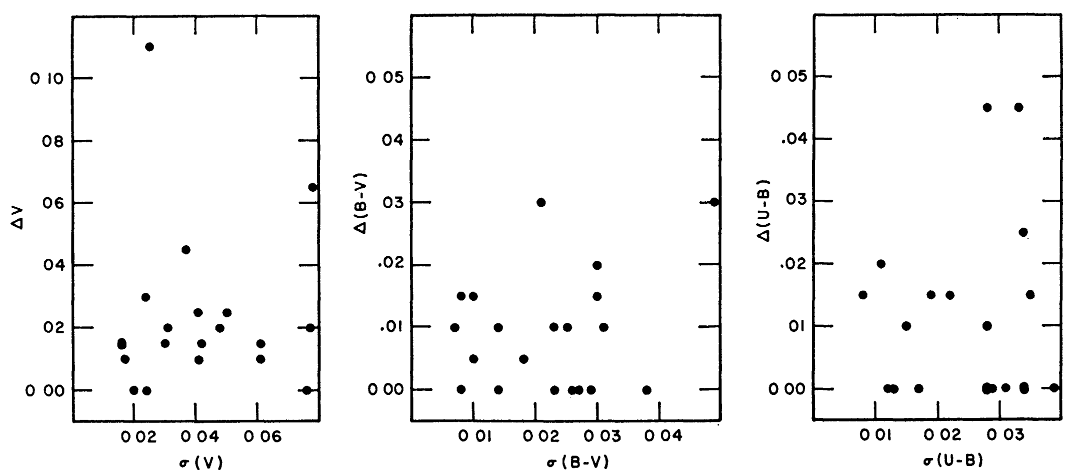

FIG. 10.—Comparison of observed light amplitudes of the magnetic stars with dispersions of individual observations obtained by Abt and Golson (1962).

largest range of magnetic variations), has quite small light variations, the largest being 0.02 mag in ultraviolet. The smallest known amplitude of light variations in all the measured colors occurs for 10 Aql where variations in no color exceed 0.01 mag. Moreover, two stars, HD 2453 and HD 9996, proved to be constant to within the errors of measurement during the time of observation. Because of the possibility of periods of the order of a few years, lack of variation in a limited time interval cannot be considered as proof that some magnetic stars are constant in brightness, though this may indeed be the case. The amplitude of light variations does not always change monotonically with wavelength. It often goes through an extremum in B.

The problem of variability of the magnetic stars was investigated statistically some time ago by Abt and Golson (1962). Their conclusion was that all the magnetic stars show slight variability and that dispersion of individual measurements obtained by them was correlated with the actual amplitude of light variations. Figure 10 presents the comparison of dispersions obtained by Abt and Golson (1962) with amplitudes obtained in the present investigation. It is apparent that no correlation exists. Although their basic conclusion, that the magnetic stars as a group are variable, remains unaffected, the dispersion for a particular star is not an indicator of the expected range of variations.

e) An Attempt of Classification of the Magnetic Stars

It is apparent from Figures 1–7 that a great variety of photometric behavior is present among the magnetic stars. It seems to be possible, however, to distinguish at least two groups of stars according to some general features present in their light curves. The first group consists of stars whose variations in V, $B - V$, and $U - B$ are in phase. Lines in Figure 8 corresponding to variations of these stars are parallel or nearly parallel to the main sequence, and the maximum in V corresponds to the upper-left end of a line. The following stars can be classified to this group: HD 215441, HD 32633, HD 215038, 17 Com, and possibly HD 10783. Two other stars: HD 124224 (Hardie 1958) and 56 Ari (Hardie and Schroeder 1963) seem also to belong in this group, although curves of 56 Ari show peculiar features which are not present in other stars of this group. From the incomplete results it seemed that approximately one-third of all the investigated stars belong to this group (Stępień 1968*a*). New observations showed, however, that the actual percentage is lower. The amplitude of light variations seems to be correlated with effective temperatures of stars of this group. This is shown in Figure 11, where the amplitude

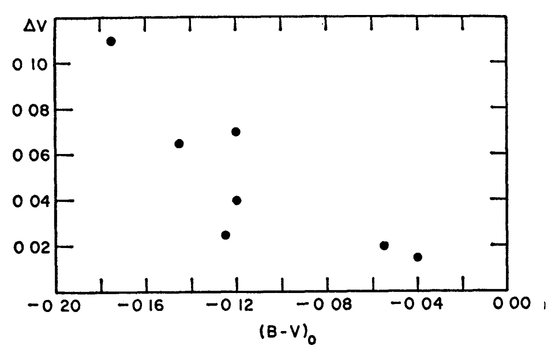

FIG. 11.—Dependence of the amplitude of the V variations on $(B - V)_0$ for stars of the first group (see text).

of the V variations is plotted against $(B - V)_0$. The sample is small, but the correlation seems to be real. The stars from this group do not show any preference for a particular kind of spectroscopic or magnetic behavior. The star HD 32633 has a strong magnetic field of alternating polarity, and the maximum of light variations (in all colors) coincides with the minimum of the magnetic field. The star HD 10783 has also a strong magnetic field of alternating polarity, but the light and magnetic curves vary in phase. The star HD 215441 has constant magnetic polarity of the magnetic field, and the magnetic range is small (Preston, private communication). Two stars of this group, HD 10783 and 17 Com, are Sr-Cr-Eu stars, while the rest are Si stars. The simplest explanation of the light variations of these stars is in terms of slight variations of effective temperature as described in § IV below.

Another group of stars presents light curves with the following characteristics: the V curve has two maxima; the $B - V$ curve has a narrow minimum, corresponding to the primary maximum of the V curve and a broad, flat maximum; and the $U - B$ curve (if $U - B$ is variable) is in phase with the V curve. Three stars from the sample observed by the author belong to this group: 73 Dra (Stępień 1968*b*), HD 224801, and HD 71866. In all cases the minimum of the V curve that occurs after the primary minimum seems to be deeper than the other. There may be an indication that the secondary maximum is shifted toward the rising branch of the primary maximum. In fact, this shift was observed in the V curve of 73 Dra, but the result is not conclusive. One more star, α^2 CVn, probably also belongs in this group. It was observed recently by Pyper (unpublished) in the three-color system. The $B - V$ and $U - B$ curves are similar to those of HD 224801, and the V curve has a hump on the rising branch which may be a trace of the secondary maximum shifted far toward the primary maximum. All four of these stars have magnetic fields of alternating polarity, but HD 71866 has a phase relationship between the magnetic and light curves opposite to those of 73 Dra and α^2 CVn. The magnetic curve of HD 224801 is not known. This last star is a Si star, while the others are Sr-Cr-Eu stars.

The rest of the observed stars show generally small amplitudes of light variations and, sometimes, considerable scatter of observations. Classification of them is, in consequence, very difficult.

IV. REMARKS CONCERNING THE MODEL OF A MAGNETIC STAR

Recent investigations of the magnetic stars seem to lean toward the oblique-rotator model (Stibbs 1950, Deutsch 1954, 1958). One of the arguments against this theory was that on its basis all the magnetic stars should show periodicity, and this was not observed. This investigation has shown that a periodicity can be found for virtually every peculiar A-type star for which light variations have been detected, and in no case have magnetic variations been in demonstrable contradiction with the period derived from the light variation. Therefore, the results of this investigation do not contradict the oblique-rotator theory. When the amplitude of light variations does not exceed 0.01 mag, and the period is several days (or more), chances of detecting such periodicity are small. The most profitable way of finding new periodic variables seems to lie in concurrent photometric, magnetic, and spectroscopic observations. If all kinds of measurements follow the same period, one may assume that the periodicity is established even if each set of observations separately is not conclusive.

When the radial velocity of a star varies in the photometric and magnetic period, the radial-velocity curve generally is 90° out of phase, as the variations would be if a spot of different brightness or elemental abundance were associated with an extremum of the magnetic field. This is in accord with the oblique-rotator theory. And, finally, newfound periods do not violate the well-known relation between line width and period. Pulsations of some sort coupled with the rotation may also take place (Ledoux 1967), but in any case the rotation seems to be the primary cause of variations of the magnetic stars. The question then arises as to what mechanism causes the observed light variations. Stars of the first group discussed earlier seem to present the simplest case. If the surface of the star is divided into two (or more) regions with different temperatures, and the division is not symmetrical with respect to the axis of rotation, the effective temperature of the visible hemisphere will vary with time. From the photometric data it is possible to estimate these variations. It will be done under the following assumptions: the figure of the star is symmetrical, relative to axis of rotation; the radius of the star is constant; and the star remains on the main sequence during all phases of a cycle.

We have a relation (Harris 1963)

$$M_{\rm bol} = 42.31 - 5 \log R - 10 \log T_e \,, \tag{1}$$

where $M_{\rm bol}$ is the bolometric magnitude of the star and R and T_e are the radius and effective temperature expressed in solar units, respectively. On the other hand, according to our assumptions,

$$M_{\rm bol}{}^{\rm max} = V_0{}^{\rm max} + ({\rm B.C.})^{\rm max}, \qquad M_{\rm bol}{}^{\rm min} = V_0{}^{\rm min} + ({\rm B.C.})^{\rm min} \,, \tag{2}$$

where V_0 is the absolute visual magnitude and B.C. is the bolometric correction for a star on the main sequence. Indices "max" and "min" refer to maximum and minimum light, respectively. From equations (1) and (2) we have

$$10 \log (T_e{}^{\rm max}/T_e{}^{\rm min}) = \Delta V + ({\rm B.C.})^{\rm min} - ({\rm B.C.})^{\rm max} \,, \tag{3}$$

where ΔV is the amplitude of light variations in V.

The scale of bolometric corrections has been revised recently by Morton and Adams (1968). The relation between bolometric correction and $B - V$ is linear in the range of $B - V$ between -0.03 and -0.20 mag, with the slope 7.235. Hence we have

$$10 \log (T_e^{\max}/T_e^{\min}) = -\Delta V - 7.235\, \Delta(B - V)\,, \qquad (4)$$

where $\Delta(B - V)$ is the amplitude of $B - V$. Assuming that the star has an effective temperature corresponding to its $(B - V)_0$ and using equation (4), one can calculate $\Delta T_e = T_e^{\max} - T_e^{\min}$. The values of ΔT_e for stars of the first group are given in Table 6.

The calculations were carried out as if the effective temperature of the whole star and, consequently, the bolometric magnitude varied. For the "two-spot" model, total flux of radiation emitted by a star is always constant. It is not, however, distributed isotropically. In such a case all the discussed quantities refer only to a visible hemisphere. If only a part of the visible hemisphere had a different temperature, the difference would have to be larger than that listed in Table 6.

TABLE 6

CALCULATED VARIATIONS OF EFFECTIVE TEMPERATURE OF SOME MAGNETIC STARS

Name or HD	ΔT_e
215441	1300
215038	450
32633	300
124224	700
56 Ari	450
10783	300
17 Com	200

Such a simple model cannot, however, explain all the kinds of observed light curves. Such stars as 21 Aql, 78 Vir, 21 Per, and 49 Cnc seem not to change their color indices while V varies. This means that all the colors vary in the same way. The simplest explanation of such variations is in terms of a small distortion of the star which is not symmetrical around the rotational axis. Neglecting possible small variations of effective temperature resulting from such a distortion, one can assume that the difference in brightness between maximum and minimum is caused by the difference in the surface of the visible disk. The third cause of light variations may lie in variations of the blanketing effect. The total blanketing effect for stars in this spectral region may be considerable, and variations in strength of spectral lines may, perhaps, cause variations of the order of 1–2 per cent in the flux in a given color. Detailed analysis of light variations of the magnetic stars is beyond the scope of this paper. It is, however, clear that, to explain the variety of shapes, amplitudes, and phase relationships of light curves that are observed, it will be necessary, in general, to consider more than one of the above mechanisms.

V. CONCLUSIONS

The results of the present survey indicate that, in almost every case, if a magnetic star is observed carefully and long enough a periodicity of variations can be found. New periods do not violate, so far, the relation between line width and period. Although the magnetic stars are light variable as a group, in some cases variations may be very small, even beyond present possibility of detection. A few stars have been observed often enough and carefully enough to establish that secular variations of periods, amplitudes, and shapes of light curves do not occur for them. The results of concurrent magnetic and photometric investigations show that the maximum of the magnetic field can coincide with the maximum as well as with the minimum of the light curve in any color. On the basis of the photometric behavior two groups of variables can be distinguished: in one of them the V, $B - V$, and $U - B$ variations are in phase, and in the other a double wave in the V curve is present accompanied by a $B - V$ curve with a broad, flat maximum and a narrow minimum. It is relatively simple to propose a possible mechanism of light variations for stars of the first group in terms of variable effective temperature. The variations of all the other stars are, however, so different from each other that probably more than one mechanism is involved.

More specialized observations can add much information to our present knowledge of the physical behavior of the magnetic stars. Scanner observations made throughout a cycle could yield valuable information about effective temperature and gravity variations. Strömgren photometry would be particularly useful because variations in the blanketing effect and gravity can be determined in less time than is required for scanner observations. The amplitude of light variations often passes through an extremum in the visible region, but for some stars there is a monotonic change of amplitude with wavelength. Therefore, multicolor observations of the magnetic stars can be expected to provide much information on the manner in which the amplitude varies over an extended spectral region.

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