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MAGNETIC FIELDS OF THE A-TYPE STARS

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ABSTRACT

A discussion of rotational line broadening in the spectra of A-type stars tends to confirm the view that strong coherent magnetic fields are a property of all rapid rotators having convective zones but that fields are observable only in the small proportion of such stars that happen to be observed nearly pole-on.

The A stars with observable fields are classed as α-variables (showing periodic magnetic variations); β-variables (irregular magnetic variations with reversal of polarity); γ-variables (irregular magnetic fluctuations without reversal of polarity); and δ-variables (erratic spectrum variables with irregular magnetic variations). All groups have "peculiar" spectra (abundance anomalies), undoubtedly arising from magnetic activity. The irregular magnetic fluctuations must occur through intrinsic magnetohydrodynamic motions of the stellar material that carries the magnetic lines of force. Irregular atmospheric mixing in the β- and γ-groups results in peculiar spectra but relatively invariant line intensities; a higher degree of organization in the magnetically periodic α-variables results in peculiar spectra with synchronous variations in line intensity

A basic physical process must underlie the extraordinary properties of the typical α-variables: they show large-amplitude, nearly symmetric magnetic reversals in periods ranging from 4 to 9 days; they display selective variations in line intensity, as well as the crossover effect and variations in luminosity The proposal is made that this process is a vastly amplified and accelerated magnetohydrodynamic oscillation analogous to the 22-year solar magnetic cycle An alternative model, the oblique rotator, is also discussed

Observational data on 89 stars showing evidence of magnetic fields through the Zeeman effect in their spectra have recently been compiled in the form of a catalog (Babcock 1958). Most of these stars have been observed repeatedly in order to derive data on the magnetic variations. The catalog includes notes on spectral peculiarities and line profiles, together with the results on magnetic-field intensity, polarity, and radial velocity; supplementary tables list 65 stars with weaker fields or slightly broader lines that probably show the Zeeman effect, 55 sharp-line stars giving little or no direct evidence for magnetic fields, and 112 stars that have lines too broad to show Zeeman displacements. The principal data on the 89 magnetic stars of the catalog are collected, in highly condensed form, in Table 1 of this paper.

In the course of the observing program, stars in various parts of the Hertzsprung-Russell diagram were tested for the presence of observable magnetic fields. Sharp-line stars of type A, on or near the main sequence, were found to show strong coherent magnetic fields almost consistently, although a few exceptions are known. The known magnetic A stars, numbering 70, make up the bulk of Table 1, which also includes 6 "metallic-line" stars, 3 giant M stars, 2 of type S, 1 subdwarf, 1 cluster-type variable(RR Lyrae), and a few unusual objects such as AG Pegasi and HD 45677.

One of the obvious results of primary interest is that virtually all stellar magnetic fields are variable (an exception may be No. 71, HD 187474) and that the great majority vary irregularly, thus demonstrating that intrinsic hydromagnetic fluctuations are occurring in the surface layers of these stars. Because of the enormous induction effects in the highly conducting plasma that constitutes a star, the magnetic lines of force can move only very slowly with respect to the material. Consequently, the lines of force imbedded in a given volume of material, or "magnetic regime," constituting a portion of a star, serve as a tag or tracer, from the observation of which we can hope to derive information about patterns of material flow.

TABLE 1

MAGNETIC STARS (SHORT FORM)

No.	Star or HD	R.A.*	Dec.*	m_v	Sp.	*w*†	No. Obs.‡	H_e Extremes§	Per.‖	Remarks#
1.	2453	$0^h 25^m 50^s$	+32° 09′	6.7	A2p	0.14	6/15	− 425 − 710	.	Like HD 188041
2.	4174	0 41 53	+40 24	7.5	M2e	.	11/41	−1200 +1100	Irreg.	[Ne III], [O III], *H*
3	8441	1 21 23	+42 53	6.6	A2p	0 08	13/31	− 750 + 400	Irreg.	Sr, Gd; sp. binary
4.	9996	1 35 30	+45 09	6.3	A0	0.1.	2/6	− 990 + 135	.	Sp. binary
5	43 Cas	1 38 36	+67 47	5.5	A0p	0 7	1/2	−1200 +	.	Si, Sr
6	10783	1 43 04	+ 8 18	6.6	A2p	0.3·	18/53	−1200 +2200	Irreg.	Si, Sr, Cr, (Eu, Gd)
7	11187	1 48 10	+54 40	7.1	A0p	0.27	7/10	− 70 +1250	.	Si, λ 4201
8.	HR 710	2 23 37	−15 34	5.8	A4p	0.15	39/50	−1080 − 320	Irreg.	Sr, Eu, Cr; sp. binary
9	21 Per	2 54 15	+31 44	5.2	A0p	0 6:	13/44	−1270 +1350	Irreg.	Si, Mn, Sr, Eu, λ 4200; variable profiles
10	19445	3 05 28	+26 09	8.0	F6	.	1/3	+ 415	.	High-velocity subdwarf
11	20210	3 12 53	+34 30	6.4	A7	0 4	1/4	− 260 +	.	Ba; sp. binary
12.	9 Tau	3 34 01	+23 03	6 7	A2p	0.15	1/7	+ 140	.	Si
13	HR 1105	3 37 48	+63 03	5.3	S	.	2/9	0: + 450	.	Heavy elements
14.	25354	3 59 52	+37 55	7.9	A0p	0.2*v*	4/8	− 380 x 0·	.	*Eu*, *Cr*, Mn, λ 4201, var. profiles
15	41 Tau	4 03 32	+27 28	5.3	A0p	0 43	3/8	− 530 + 700	.	Sr, Si, λ 4201, pec. profiles; sp. binary
16.	68 Tau	4 22 36	+17 49	4.2	A2V	0.2	1/4	− 400	.	Metallic-line star
17	30466	4 46 06	+29 29	7.2	A0p	0.5*v*	2/8	− ? +2320	.	Si, λ 4201; var. profiles
18.	32633	5 02 51	+33 51	6.9	B9p	0 4.	24/24	−3960 x +2220	4.0	Si, Cr; rapid reversal
19	16 Ori	5 06 34	+ 9 46	5 4	F2	0.3	2/4	− 420 + 375	.	Metallic-line star
20.	μ Lep	5 10 41	−16 16	3.3	B9p	0.3	5/28	− 170 + 325	.	Si, Mn, Y
21.	WY Gem	6 08 54	+23 14	7 4	M3p		1/8	− + 540	.	[Fe II]
22.	42616	6 10 10	+41 43	6.9	A2p	0 4.	4/12	− 840 0·		Sr; K-profile pec.; varies
23	45677	6 25 59	−13 01	7.5	B2e	0.3·	1/7	−1600	.	*H*, Fe II, [Fe II], [S II] in emission; K pec., varies
24.	49976	6 48 18	− 7 59	6.2	A0p	0 4*v*	1/14	− 810 +	.	*Sr*, *Ca;* profiles diverse, vary irregularly
25	50169	6 49 25	− 1 35	8.9	A4p	0.12	6/11	+ 670 +2120	.	Sr, (Eu); resembles HD 188041
26.	R Gem	7 04 21	+22 47	6+	Se		2/2	+ 370 + 400	.	
27	56495	7 14 33	− 7 26	7.5	A3p	0 4*v*	2/7	− ? + 570	.	Sr, *Cr*, *Mg* I
28.	53 Cam	7 57 27	+60 28	6 0	A2p	$\frac{1}{4}$–1*v*	20/20	−5120 x +3700	8.0	*Ti*, Sr, Cr, Eu, *Mg* II
29	15 Cnc	8 10 03	+29 48	5 6	A0p	0 7	0/9	0· + str	.	Si; profile of K varies
30.	71866	8 27 52	+40 24	6.7	A0p	0.26	61/65	−1700 x +2000	6.80	*Eu*, *Gd*, Sr
31.	3 Hya	8 33 02	− 7 48	5 6	A2p	0.31	16/22	− 480 + 740	Irreg.	Sr; velocity varies; sp. binary?
32.	49 Cnc	8 42 02	+10 16	5 6	A0p	0.26	9/26	− 200 +1450	.	Si, Sr, (*Eu?*)

* Position for 1950.

† Index of line width, *w*.

‡ Number of plates measured/number of plates taken.

§ H_e = effective field intensity in gauss; crossover effect indicated by x.

‖ Period in days, or irregular. Most not indicated are irregular.

\# Elements showing abnormal line intensity, italicized if variable.

TABLE 1—*Continued*

No.	Star or HD	R.A.*	Dec.*	m_v	Sp.	w†	No. Obs.‡	H_e Extremes§	Per.‖	Remarks#
33	ν Cnc	$8^h59^m49^s$	+24° 39′	5 4	B9p	0.5:	2/2	+ 105 + 470		Si, Sr, Cr; pec. profiles
34.	κ Cnc	9 05 02	+10 52	5.1	B8p	0.13	8/17	− 640 + 460		Mn, Si; sp. binary ($6\overset{d}{.}4$)
35	30 UMa	10 20 33	+65 49	4.9	A0p	0 08	2/3	− 290 + 340		Si, Sr, (Mn); sp. binary ($11\overset{d}{.}6$)
36.	45 Leo	10 25 01	+10 01	5.9	A2p	0.2*v*	5/14	− + 400		Many profiles peculiar and variable; $\underline{x}$
37	98088	11 14 26	− 6 52	6 0	A2p	0 4.	12/15	−1000 + 800	5.905	*Sr*, *Ba*, *Ti;* no. $\underline{x}$; sp. binary
38.	17 Com A	12 26 25	+26 11	5 4	A0p	0 4.	9/21	−1150 + 360		Sr, Cr, (Eu); profiles-vary
39	17 Com B	12 26 25	+26 11	6.7	A3		0/2	+mod.		Metallic-line star
40.	110066	12 36 51	+36 14	6.3	A4p	0.1:	5/7	− 55 + 300		Sr, Cr; λ 4210 wide
41	*l* Cen	12 37 10	−39 43	4.8	B8p	0.2:	1/1	+ 580		Mn, Si
42.	γ Vir	12 39 07	− 1 10	2.9	F0V		1/3	− 390		Standard F0
43	111133	12 44 30	+ 6 13	6.4	A4p	0.14	1/2	− 990		Sr, Cr
44.	α^2 CVn	12 53 42	+38 35	2.9	A0p	0.3*v*	28/96	−1400 $\underline{x}$ +1600	5 469	*Eu*, *Cr*, Sr; profiles vary
45	115708	13 16 11	+26 38	8.3	A2p	0.2:	1/3	+ 740		Sr, Eu
46.	78 Vir	13 31 35	+ 3 55	4.9	A2p	0.2	50/76	−1680 $\underline{x}$ − 140	Irreg.	Sr, Cr, Eu
47	BD1913	13 53 50	+45 59	9 7	Ap	0.2:	/1	+ 500:		BD+46°
48.	125248	14 15 52	−18 29	5 7	A0p	0.2*v*	33/40	−1900 $\underline{x}$ +2100	9.29	*Eu*, *Cr;* long-period sp. binary
49	126515	14 23 23	+ 1 13	7.0	A2p	0.1+	1/4	− +1310		Cr, Si, Sr; ($\underline{x}$); pec. profiles
50	π Boo A	14 38 22	+16 37	4.9	B8p	0 4	2/12	− 75 + 190		Si, Mn, Y, Sc
51.	μ Lib A	14 46 34	−13 56	5 4	A0p	0.3	7/13	−1300 − 200		Sr, Cr
52.	133029	14 58 56	+47 28	6.2	A0p	0 4	50/74	+1150 +3270	Irreg.	Si, Cr, λ 4201
53	134793	15 09 05	+ 8 43	8.2	A3p	0.3+*v*	4/11	− 530 + 450		*Eu*, *Sr*, Cr; widths vary
54.	135297	15 11 48	+ 0 33	8.0	A0p	0.3	1/3	−1110 +		Sr, Cr
55	β CrB	15 25 46	+29 17	3 7	F0p	0.15	61/89	− 960 +1020	Irreg.	Sr, Eu; sp. binary
56.	33 Lib	15 26 45	−17 16	7.2	F0p	0.15	1/2	+1120		Sr, Eu
57	ι CrB	15 59 26	+29 59	4.9	A0p	0 07	6/10	− 340 + 75		Mn, Si, Sr, Zr, Y
58.	ω Oph	16 29 10	−21 21	4.6	A7p	0 6	0/19	− +		Sr, Cr; pec. profiles
59	45 Her	16 45 19	+ 5 20	5.3	A0p	0 4+*v*	0/6	−		*Eu*, Sr, Si; profiles vary
60	52 Her	16 47 46	+46 04	4.9	A4p	0 4	2/19	+ 840 +1430		Sr, (Eu)
61.	153286	16 54 41	+47 26	6.9	F		2/3	− 500		Sr; metallic-line star
62.	153882	16 59 16	+15 01	6.2	A4p	0 4.	32/38	−1200 $\underline{x}$ +1440	6 01	(*Sr*, Cr, Mn); profiles vary
63	165474	18 03 25	+12 00	7 4	A7p	0.15	1/3	+ 900		Eu, Sr
64.	171586	18 33 08	+ 4 54	6.7	A2p	0.8.	1/4	− 740		Sr, Cr
65	173650	18 43 28	+21 55	6.4	A0p	0.2+	20/43	− 540 + 700	Irreg.	*Sr*, *Eu*, Si, Mn, Cr, Gd, λ 4201; pec. variable profiles
66.	10 Aql	18 56 29	+13 50	5.9	A4p	0.1.	5/10	− 315 + 440		Sr, Eu, Mn
67	21 Aql	19 11 11	+ 2 12	5.2	B8	0 4	4/6	− 590 + 170		Si
68.	RR Lyr	19 23 52	+42 41	7-8	F		18/47	−1580 +1170	?	

TABLE 1—*Continued*

No.	Star or HD	R.A.*	Dec.*	m_v	Sp.	w†	No. Obs.‡	H_e Extremes§		Per.‖	Remarks#
69	51 Sgr	$19^h33^m00^s$	−24°50′	5 7	F	.	1/3	− 230		.	Sr, Eu. Metallic-line star; sp. binary
70	184905	19 33 09	+43 50	6.6	A0p	1:v	0/26	−		.	*Si, Eu, Ca;* profiles vary
71.	187474	19 48 27	−40 01	5 4	A0p	0.1+	5/5	−1870	const.?		Eu, Si, Ti, Fe, (Mn, Al)
72.	188041	19 50 42	− 3 15	5 6	A5p	0.11	75/84	− 230	+1470	226	*Gd, Eu, Sr;* secular changes; variable amplitude
73	190073	20 00 31	+ 5 36	7.9	Aep	0.2+	1/12	+ 120		.	*Ca*
74.	191742	20 08 04	+42 24	7.8	A7p	0.12	2/5	− 510	− 175	.	Sr, (Si, Eu)
75	192678	20 12 18	+53 30	7.1	A4p	0.2:	0/1		+2000:	.	Cr
76.	192913	20 14 23	+27 37	6 7	A0p	0.2:	4/10	− 670	+ 380	.	Si, λ 4201
77	73 Dra	20 32 11	+74 47	5.2	A2p	0.13	9/14	− 700	+ 200:	Irreg.	*Ti, Eu, Sr;* sp. variations periodic?
78.	γ Equ	21 07 55	+ 9 56	4.8	A7p	0 09	21/31	+ 180	+ 880	Irreg.	Eu, Mg, Sr, (Si)
79	θ^1 Mic	21 17 34	−41 01	4.9	A2p	0 6−	1/3	− 650		.	*Eu, Sr,* Cr; diverse profiles
80	AG Peg	21 48 37	+12 23	7 6	B+M	.	14/30	−1000	+ 500	.	
81	VV Cep	21 55 14	+63 23	5–6	M+B	.	5/17	− 360	+ 850	.	Sp. binary
82.	215038	22 38 18	+75 24	8 0	A0p	0.8.	0/2	−3000:		.	Si, λ 4201
83	216533	22 50 36	+58 33	7.9	A2p	0.15	5/6	− 650	0	.	*Sr,* Cr, Eu, (Si)
84.	κ Psc	23 24 22	+ 5 58	4.9	A2p	0.8v	0/17	−	+	.	*Sr, Ca, Eu,* Cr
85	β Scl	23 30 18	−38 06	4.5	B9p	0.3·	1/3		+ 660	.	Mn, Si; Y has neg. polarity
86	ι Phe	23 32 23	−42 54	4.8	A2p	0 4.	0/2		+	.	Sr, Cr; pec. profiles
87	108 Aqr	23 48 46	−19 11	5.3	A0p	0.8.	0/12	−	+	.	*Sr, Ca, Eu,* Si, λ 4201; pec.
88.	224801	23 58 10	+44 58	6.2	A0p	0.8.	2/22	−	+2300	.	*Eu,* Si, Sr, λ 4201
89	4778	0 47 30	+44 44	6.1	A0p	½–1	0/4	−	+	.	*Eu, Mg,* Sr, Cr

Measurements of the differential line shifts resulting from the longitudinal Zeeman effect are readily made only if the lines are broadened to no more than about 0.3 A by the Doppler effect of axial rotation or turbulence. This follows from the fact that the Zeeman splitting for a normal triplet amounts to only about 0.2 A in a field of 10000 gauss and the strongest observed field, that of 53 Camelopardalis (No. 28), is about 5100 gauss. Furthermore, only coherent fields (of one outstanding polarity) can be measured by the displacement method in the integrated light of a star; thus, if the stellar surface is covered with limited regions of mixed magnetic polarity, the result is only a slight broadening of the profiles plus selective intensification. In view of the difficulties of observation and the likelihood that stars with fields of mixed polarity far outnumber those with coherent fields, there is now strong support for the contention that magnetic fields of physically significant intensity probably occur in virtually all stars. This view is strengthened by the scattering of observed fields among various spectral types, apart from type A, as listed in Table 1; by our knowledge of weak fields on the sun; and by the occurrence of flares on certain red dwarf stars. Stellar magnetic fields are probably ubiquitous.

The fact that the preponderance of strong coherent magnetic fields, as well as the variable fields of large amplitude, are found among the A-type stars may be tentatively attributed to the occurrence in this group of two conditions which we may suppose to be mutually necessary: rapid axial rotation and the presence of an outer convective zone. Among hotter stars the convective zone is lacking, while among stars cooler than type F0 rotation is usually slow. Convection and rotation in the A stars together favor the occurrence of regenerative dynamo processes of the kind proposed by Elsasser (1956) and by Parker (1955).

LINE WIDTH AND OBLIQUITY OF ROTATING A-TYPE STARS

The visibility of metallic lines in the spectra of main-sequence A stars depends very strongly on the degree of rotational broadening—i.e., on $v_e \sin i$, where v_e is the equatorial velocity and i is the obliquity of the rotational axis to the line of sight. This becomes particularly evident if one arranges a number of A-type spectrograms in a sequence of line width, from ultra-sharp ($w = 0.07$) as in ι CrB (No. 57), through sharp ($w = 0.18$) as in 78 Virginis (No. 46), to normal ($w \approx 4$) as in the majority of A stars. The rich spectrum of weak metallic lines seen in ultra-sharp-line spectra is largely obliterated with increasing obliquity as the profiles become shallow and broad. Indeed, in the typical A-type spectrum viewed at large obliquity, one sees, in addition to the hydrogen lines, only the K line, Mg II λ 4481, and perhaps, with difficulty, a few others. (There is also a marked increase in the equivalent widths of the metallic lines in passing from type B8 through the various subdivisions of type A to F0.) Typically, the line widths in the photographic region are in the vicinity of 4 A, indicating that $v_e \sin i$ is about 150 km/sec. If randomness of orientation prevails for the axes of the rapid rotators that make up the bulk of the A stars, then a small proportion of these rapid rotators must be observable at very small obliquity and must show sharp lines.

The following paragraphs bear out the contention that most of the sharp-line A stars are rapid rotators seen almost pole-on; that these are the stars in which magnetic fields can be observed; that these same sharp-line A stars are known as "peculiar stars"; that the strong coherent magnetic fields and the spectral "peculiarities" arise as a result of rapid axial rotation; that the visibility of the peculiarities, as well as of the metallic-line spectrum in general, decreases with increasing obliquity; and that the relatively numerous broad-line A stars probably also possess magnetic fields and "peculiar" spectra that are unobservable only because the axial obliquity happens to be large.

Before considering the statistics of line width, it may be remarked that there is no known evidence that the "peculiar" A stars (those with abnormally strong lines of Mn, Si, λ 4201, Eu, Cr, or Sr, as identified by Morgan 1935) are distributed differently from the "normal" A stars in the Galaxy or in clusters. It has also been shown by Provin (1953) that, when plotted in a $U - B$, $B - V$ color diagram, the peculiar A stars lie on the sequence defined by the ordinary A stars.

Rotational velocities for B8–A2 stars have been published by Slettebak (1954). For 87 normal, main-sequence stars he found $\bar{v}_e = 177$ km/sec, and for 16 "peculiar" A-stars $\bar{v}_e = 52$ km/sec. For the present purpose we group these together, obtaining a weighted mean of $v_e = 158$ km/sec. (Correspondingly, $\langle v \sin i \rangle = 124$ km/sec.) In theory, the distribution function can be obtained according to the methods of Chandrasekhar and Münch (1950) or of K.-H. Böhm (1952). However, a comparison of the observational data (obtained with a dispersion of about 30 A/mm) with newer measures of line width on high-dispersion, high-resolution spectrograms (4.5 A/mm) shows that considerable revisions are required for the sharper-line stars, i.e., for line widths in the range up to at least 0 5 A. There are fewer stars with very small line broadening than indicated by the low-dispersion observations. This is in part because the line λ 4481, used in the low-dispersion work, is virtually the only line available when $v \sin i$ is large; yet this line is too strong and its apparent width is too strongly dependent upon equivalent width to be suitable when $v \sin i$ is small. This "line," incidentally, is a doublet that is resolved in the spectra of several ultra-sharp-line stars when high dispersion is used.

The data are inadequate to define an accurate distribution function of v_e, but, for various values of v_e, the fraction of the group having rotational broadening less than a specified value can be found. On the assumption of random orientation of axes, the fraction of stars with obliquity less than i_0 is $F = 1 - \cos i_0$. We arbitrarily set 0.48 A as an upper limit of line width for the stars of interest.

If all A stars were like the average, with $v = 158$ km/sec, and if $i = 90°$, the line width w would be 4.5 A in the vicinity of λ 4200. For the limit $w = 0.48$ A, the corresponding i is $6\overset{\circ}{.}1$ and $\cos i_0 = 0.994$. Therefore, 0.6 per cent, or about 12 stars of the approximately 2000 type A stars brighter than magnitude 6.0, would have rotational broadening less than our limit of 0.48 A.

Because of the real distribution of velocities, the observed group with $w < 0.48$ A will include all slow rotators with $v < 16.8$ km/sec, as well as a decreasing fraction of those in more rapid rotation (Fig. 1). For different values of v_e, the fraction, F, of stars having $w < 0\ 48$ is given in Table 2. The period of rotation, P, is also listed.

Evidently the number of sharp-line, extremely rapid rotators ($v_e \geq 200$ km/sec) will be quite small, but we may expect to find a few dozen A stars brighter than the sixth magnitude, with lines sharper than 0.5 A, that are rotating with $v_e > 75$ km/sec, and a comparable number with slower rotation.

Inspection of lines on plates of 4.5 A/mm dispersion shows not only that the earlier results are subject to considerable modification but that many of the sharp-line stars display profiles that are somewhat diverse and variable in width. It is evident that, for lines sharper than about 0.4 A, rotational Doppler broadening falls to a level that is comparable with Zeeman broadening and that the problem is complicated. The profiles are affected by the specific Zeeman patterns and by the magnetic-field intensity, as well as by peculiar atmospheric motions in some cases. Therefore, precise measurements of line width have not been attempted. Rather, the "index of line width," w, has been measured or estimated for most of the stars of Table 1. This is simply the apparent width of typical metallic lines, as measured on the plate and corrected for the projected slit-width (usually 0.07 A). Since the measurements were made on plates taken with the double polarizing analyzer, a part of the Zeeman broadening that results from any coherent field has been eliminated. For most of the stars under discussion, the edges of the sharp metallic lines are rather well defined, and w is of real significance, although subject to improvement.

The extended search for sharp-line A stars that has resulted in the bulk of entries in the catalog is believed to be reasonably complete, although not exhaustive, down to a limit between the sixth and seventh magnitudes; a few eighth-magnitude stars are included. The results show that a few dozen such bright stars exist and that most of these have observable magnetic fields and anomalous line intensities. Some of the relevant data have been collected in Table 3, in which the A-type stars (B8–F0) of Table 1 have been rearranged according to line width, from $w = 0.07$ to $w = 0.48$. These groups have been further divided to separate the stars, 30 in number, that are brighter than magnitude 6.0. These magnetic stars constitute the bulk of the bright, sharp-line, A-type stars. A few others can be added by scanning Tables 2 and 3 of the catalog. From Table 2 (magnetic field possibly present), selecting A stars brighter than magnitude 6.0, with $w < 0.4$ A, and excluding "metallic-line" objects as well as high-luminosity stars of classes I, II, and III, we have: ϵ Ari, A4p (composite); θ Leo, A2 V; υ Her, B9p (Mn); and ρ Her, B9p (Mn). Similarly, from Table 3 of the catalog (sharp-line stars with no observable field), we select the 8 stars in the present Table 4.

To summarize, there are 33 sharp-line A-type stars brighter than magnitude 6.0 with the designation "peculiar," all but 3 of which show the Zeeman effect, plus 10 apparently

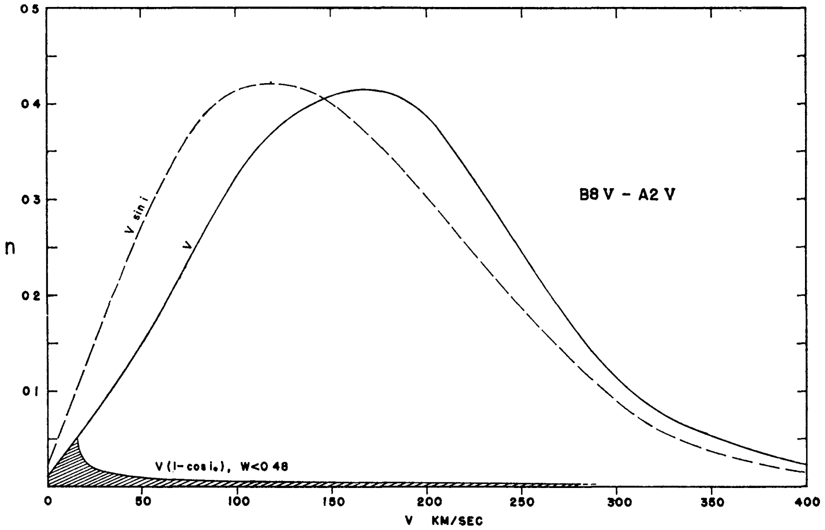

FIG. 1.—Curves showing distribution of equatorial velocity, v, and $v \sin i$, among the stars of types B8 V–A2 V. The curves have been adapted from the results of Slettebak (1954), but n has been arbitrarily diminished for $v < 50$ in accord with results from high-dispersion plates. The area under the lowest curve represents stars with $w < 0.48$.

TABLE 2*

STATISTICS OF LINE WIDTH

v_e (km/sec)	F	P (days)	v_e (km/sec)	F	P (days)	v_e (km/sec)	F	P (days)
16 8	1 000	6 4	50	0 059	2 2	150	0 007	0 72
20	0 461	5 4	75	026	1 4	200	003	54
25	0 262	4 3	100	014	1 1	250	0 001	0 43
30	0 173	3 6	125	0 009	0 86			

* On the assumption that spin axes are oriented at random, F represents the fraction of A stars showing rotational broadening less than 0 48 A, for various values of v_e

TABLE 3*

Sharp-Line Stars from Table 1

w	Brighter than 6$^{\rm m}$0		Fainter than 6$^{\rm m}$0	
	No	Name	No	Name
0 07–0 12	35	30 UMa	3	8441
	40	110066	4	9996
	57	ι CrB	25	50169
	66	10 Aql	74	191842
	72	188041		
	77	γ Equ		
13– 17	8	HR 710	1	2453
	34	κ Cnc	12	9 Tau
	43	111133	49	126515
	55	β CrB	56	33 Lib
	71	187474	63	165474
	76	73 Dra	81	216533
18– 22	36	45 Leo	14	25354
	41	l Cen	45	115708
	46	78 Vir	65	173650
	48	125248(v)	73	190073
			75	192913
23– 27	32	49 Cnc	6	10783
			7	11187
			30	71866
28– 37	20	μ Lep	28	53 Cam(v)
	31	3 Hya	54	135297
	44	α^2 CVn(v)	53	134793(v)
	51	μ Lib A		
	83	β Scl		
38–0 47	15	41 Tau	18	32633
	37	98088	22	42616
	38	17 Com A	24	49976
	50	π Boo A	27	56495
	59	45 Her	52	133029
	60	52 Her	67	21 Aql
	62	153882		
	84	ι Phe		
0 48+	5	ω Cas	17	30466
	9	21 Per	64	171586
	29	15 Cnc	70	184906
	33	ν Cnc	66	224801
	58	ω Oph		
	78	θ^1 Mic		
	82	κ Psc		
	85	108 Aqr		

* This list is limited to B8p, B9p, and Ap stars, "metallic-line" stars being excluded

normal main-sequence stars showing no field. The number of sharp-line A stars actually found after a diligent search and the proportion of peculiar and normal sharp-line spectra are statistically in good accord with the predictions of the foregoing paragraphs and with Figure 1.

Not only the line widths but the total intensities must be functions of latitude on a rapidly rotating star. Considering that the magnetic field as well as the temperature and surface gravity vary between the equator and the poles of rotation, it is a reasonable inference from observation that certain of the spectral peculiarities found in the A stars arise preferentially near the poles and that not only the profile depths but also the equivalent widths of the peculiar lines become suppressed with increasing obliquity. Line intensities will be diminished by limb darkening and by dilution of the profiles by the continuum of the low latitudes. With moderate obliquity, there is also the possibility of accounting for diverse line widths if various lines arise in differing latitudes.

The oblateness resulting from rapid rotation gives the star a greater effective area for small obliquity, and the relatively greater surface gravity near the poles will result in a higher effective temperature and greater surface brightness. Variations in ionization as a function of latitude will accentuate the obliquity effect as regards spectrum differences.

TABLE 4

SHARP-LINE A-TYPE STARS SHOWING NO MAGNETIC FIELD

Star	Sp	m_v	π	M	$M-M_0$
γ Gem	A0 IV	+1 9	0″047	+0 2	−0 7
α CMa	A0 V	−1 6	375	+1 2	+0 3
21 Lyn	A1 V	+4 4	020	+1 0	−0 3
95 Leo	A4	+5 5	013	+1 1	−1 0
HD 186568	B9	+5 9	. . .	.	. .
ν Cap	B9 IV	+4 8	018	+1 1	+0 8 (w=0 4:)
o Peg	A1 V	+4 8	017	+0 9	−0 4
σ Aqr	A0 IV	+4 9	0 014	+0 6	−0 3 (w=0 3:)

These considerations were discussed by Baldwin (1944) with particular reference to the rapidly rotating B stars. Similar, though somewhat diminished, effects would be expected for stars of type A. If an ordinary, rapidly rotating star could be observed as the obliquity diminished toward small values, the star would become slightly brighter and bluer, while the line spectrum would become characteristic of higher temperature and pressure. Not only would the lines become sharper, but the anomalies originating in high astrographic latitudes would grow more important. A strong axisymmetric magnetic field, through its influence on energy transport in the presence of turbulence and through selective intensification of lines, would enhance the obliquity effect, but quantitative predictions are impossible in the present situation.

The obliquity effect on spectral type is qualitatively in accord with observation, for it is known that, as a group, the peculiar A stars lie on the upper fringe of the main sequence when absolute magnitude is plotted against spectral type in the H-R diagram. These results were discussed by Deutsch (1947).

The few slow rotators of type A, on the other hand, would not be expected to show any appreciable obliquity effect. They should lie on or close to the main sequence. The number of such stars in Table 4 is only 8, although we might include θ Leonis. Absolute magnitudes are listed in Table 4 for 7 of these stars for which trigonometric parallaxes are available. Also listed is the difference, $M - M_0$, between the absolute magnitude of the star and the absolute magnitude, M_0, of a main-sequence star of corresponding spectral type. The values of M_0 have been taken from the work of Trumpler (1930). The mean $M - M_0$ is -0.2. Therefore, the evidence indicates that the few stars supposed to be slow rotators lie on, or close to, the main sequence, along with the numerous oblique rapid rotators, while the pole-on rapid rotators tend to lie on the upper fringes of the main sequence.

If the foregoing considerations are correct, the ordinary, typical, broad-line A star is a rapid rotator with a strong magnetic field, which, if it could be observed pole-on, would show a peculiar spectrum. The sharp-line stars with normal spectra, limited in number, are presumably slow rotators with weak fields. It appears reasonable to associate strong coherent magnetic fields with axial rotation and perhaps to infer that the strongest magnetic fields are likely to be found in the most rapid rotators. The conclusion sometimes expressed in the past—that the peculiar A stars have small axial rotation—may require modification. One might say, rather, that the stars referred to as peculiar have small $v_e \sin i$ because i is small. When we consider similar stars with increasing i, the spectrum anomalies decrease, along with the visibility of the metallic lines in general, as the lines become very broad and shallow.

If the foregoing arguments regarding obliquity are in error and if, alternatively, the magnetic stars as a group are to be regarded as slow rotators observed at large obliquity, it is plausible to attribute their slow rotation to a transfer of angular momentum, through the agency of the magnetic field, to an outlying or circumstellar gas cloud. But in the low proportion of spectroscopic binaries observed among the stars of Table 1 (10 spectroscopic binaries out of 70 A stars) there is little evidence that such a transfer has occurred. In an independent study of 124 peculiar A stars, M. Jaschek and C. Jaschek (1958) found that 21 systems, or 17 per cent, are spectroscopic binaries. But they found that the percentage of binaries is 43 in "normal" A stars with $v \sin i$ no greater than 75 km/sec and in luminosity classes between II and V.

MAGNETIC FIELDS

The stellar Zeeman effect is measured in terms of the mutual displacement of line profiles observed through analyzers of opposite sign for rotatory polarization. Each elemental area, da, of the visible disk of the star contributes to the final blended profile in proportion to $WJda$, where W is the local equivalent width of the line and J is the local surface brightness of the star in the direction of observation. The Zeeman displacement is proportional to the component of the magnetic field in the line of sight. These factors were taken into account (Babcock 1947) when it was shown that a pole-on star, with typical limb darkening, having a regular axisymmetric dipolar field, would produce an observable Zeeman effect corresponding to an "effective" field, H_e. This was shown to be, for an A-type star, about 0.3 times as great as H_p, the field intensity at the pole, and to have the same polarity.

The data that have since been collected on the magnetic fields of stars and of the sun show that stellar fields are in general not simple, permanent, dipolar fields. All stellar fields that have been adequately observed (with the possible exception of HD 187474) are found to vary, and the great majority vary irregularly. While periodic variations might be accounted for by axial rotation of a star having an oblique aspect and carrying an asymmetric or irregular distribution of magnetic regions, rapid irregular magnetic variations can arise only through intrinsic hydromagnetic changes involving displacements of the stellar material in the photosphere, together with its associated magnetic field. The apparent field of a star undergoing intrinsic irregular hydromagnetic fluctuations can, of course, be modulated by axial rotation. The complicated effects that are observed in the spectra of the sharp-line A stars indicate that, while the dipolar component of the field predominates in many instances, the field pattern is probably a complex one with considerable fine structure; indeed, this is only to be expected if some form of convection is effective in these stars. It is also inferred by analogy with the pattern of magnetic fields on the sun (Babcock and Babcock 1955).

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Because the pattern of the magnetic-field distribution on the surface of a star is complex and variable, the earlier practice of reporting field intensity in terms of H_p has been abandoned, and results are now given simply in terms of the effective field, H_e.

As was pointed out in the investigation of the magnetic variable HD 125248 (Babcock 1951), the profile broadening in this and most other sharp-line magnetic stars is of the same order as the Zeeman displacements of the polarized components of the line profiles. The profiles do not indicate broadening that would result from averaging of extremely strong and very weak distributed fields. Although Zeeman broadening is often one of the prime contributors to line width in stars with $w < 0.4$ A, the metallic lines are usually without appreciable wings. The profiles tend to be sharp-edged, indicating that the effective field has approximately uniform intensity over the extended photospheric area in which the lines are produced. In measuring a stellar field of 2 kilogauss, we are not measuring the mean of a field-free photosphere averaged with an area of 2 per cent of the stellar disk that carries a concentrated field of 10^5 gauss. Thus there is no direct evidence from the observations either for or against the occurrence of small, localized dark spots, similar to sunspots, but with superstrong fields. The observations refer, rather, to photospheric fields. Particularly among the later subdivisions of type A, the line intensity and the considerable depth of the affected profiles indicate that the magnetic field necessarily affects most, if not all, of the surface. Among the magnetic stars near type A0, however, the line intensities are generally smaller and the profiles are often shallower, suggesting that, while the magnetic field may affect the whole stellar surface the lines may possibly arise in magnetic regions constituting no more than a considerable fraction of the visible surface. The profiles may be "diluted" by continuous radiation. Such limited regions with fields of the order of a few kilogauss are considered to be analogous to widely extended magnetic regions or zones on the sun, such as the magnetic polar caps, rather than to sunspots.

Among the magnetic stars, lines of most of the chemical elements usually agree moderately well in indicating consistently the same field intensity at any given time. This is particularly so in ultra-sharp-line stars having slowly varying fields, such as are characteristic of the later subdivisions of type A. Examples are 10 Aquilae, γ Equulei, and HD 110066, for which probable errors of only about ± 30 gauss are derived for H_e from measures of numerous lines of several elements.

For the star 53 Cam, a typical plot of Δs_c, the measured Zeeman displacement, against z, the mean displacement of the σ components of the Zeeman pattern, is given in Figure 2. The resulting field strength is $H_e = +3225 \pm 78$ gauss.

In some other stars with more rapidly varying fields, differences in measured field intensity are found for particular elements as compared to the mean, or differences may be detectable in the field measured for the ionized, as compared to neutral, atoms. For example, chromium lines in HD 125248 near the phase of negative maximum intensity show a stronger field than do other elements. In some of the "Si" stars (e.g., κ Cancri) lines of Si II occasionally yield divergent results. Occasional weak lines of Sc II or Y II found in certain stars are usually discordant. Divergent field intensities, with indications that the field is partly of mixed polarity, are particularly evident in such stars as 21 Persei, HD 173650, HD 42616, and HD 56495.

MAGNETIC CLASSIFICATION

The sharp-line A-type stars of Table 1 may be grouped, according to the characteristics of their magnetic variation, into three classes, denoted as α, β, and γ, after the type stars α^2 Canum Venaticorum, β Coronae Borealis, and γ Equulei. Those of the α group, 8 in number, show cyclic or essentially periodic magnetic variations, often with considerable deviations from the mean amplitude. Those of the β group, numbering 7, show magnetic fields with irregular fluctuations, including reversals of polarity. Stars of the

γ group, 5 in number, display irregular magnetic variations and always show the same polarity. The α-, β-, and γ-stars, as selected from Table 1, are listed in Tables 5, 6, and 7, respectively.

The α-variables are distinguished not only by periodicity but by large magnetic amplitudes and (except in the case of HD 32633) by variations of line intensity that are synchronous with the magnetic changes. Two of the α-variables are atypical, in that HD 98088 is a short-period spectroscopic binary and HD 188041 has a period far longer than the others; also, neither of these two stars shows the crossover effect. The typical stars of the α-group, however, all have magnetic fields of large amplitude that show nearly symmetrical reversals of polarity, and they all show the crossover effect in the line profiles. (For a description of this effect see Babcock 1956) The irregular variables

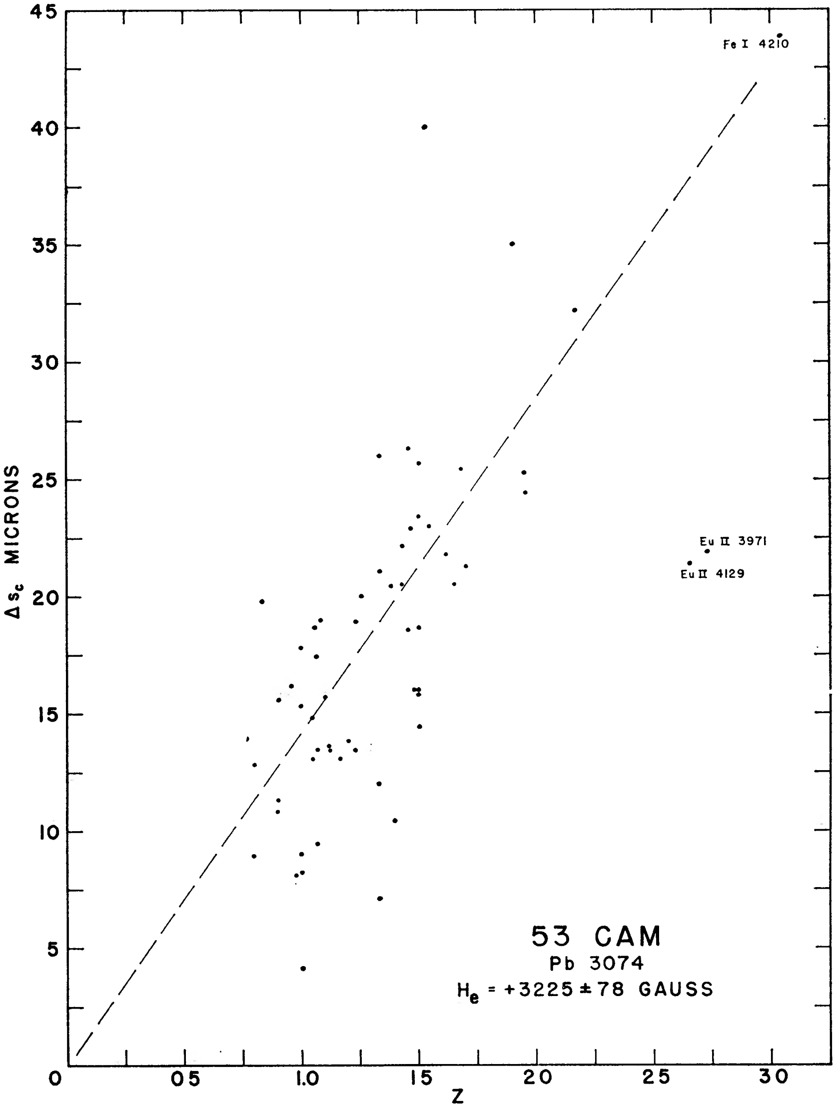

FIG. 2.—Plot of measurements from one spectrogram of the star 53 Cam. Each point represents one line, where z is the mean displacement of the normal (σ) components of the Zeeman pattern in terms of the normal Lorentz triplet ($z = 1$), and Δs_c is the measured displacement, in microns, between the components of the line in strips of the spectrum analyzed for right-handed and left-handed polarization.

TABLE 5

ALPHA VARIABLES

(Arranged in Order of Increasing Period)

Star	Sp	w	H_e Extremes (gauss)	P (days)	3 6/P	Remarks*
HD 32633	B9p	0 3–0 5	−3960 +2220	4 003	0 9	Si, Cr, Eu; irregular amplitude; random crossover
α^2 CVn...	A0p	3v	−1400 $\underline{x}$ +1600	5 469	66	*Cr*, *Eu*, Sr; profiles vary
HD 98088.	A2p	4:	−1000 + 800	5 905	61	*Sr*, *Ba*, *Ti;* no $\underline{x}$; Sp binary
HD 153882	A4p	4:	−1200 $\underline{x}$ +1440	6 01	60	(*Sr*, *Cr*, *Mn*); profiles vary
HD 71866	A0p	26	−1700 $\underline{x}$ +2000	6 80	53	*Eu*, *Gd*, Sr
53 Cam	A2p	25–1v	−5120 $\underline{x}$ +3510	7 986	45	*Ti*, *Mg*, Sr, Cr, Eu; profiles vary
HD 125248	A0p	2v	−1900 $\underline{x}$ +2100	9 295	39	*Eu*, *Cr*
HD 188041. .	A5p	0 11	− 230 +1470	226	0 01	*Gd*, *Eu*, *Sr;* secular changes; non-uniform amplitude

* Elements showing anomalous line intensities are listed Italics indicate that intensity varies

TABLE 6

BETA VARIABLES

(Irregular, Reversing Polarity)

Star	Sp	w	H_e Extremes (gauss)	Remarks
21 Per .	A0p	0 6:	−1270 +1350	Si, Mn, Sr, Eu, λ 4201; var. profiles
HD 173650 .	A0p	2+	− 540 + 700	*Sr*, Si, Mn, Cr, *Eu*, Gd, 4201; peculiar var profiles
HD 8441. .	A2p	08	− 750 + 400	Sr, Gd; sp. binary
HD 10783	A2p	3:	−1200 +2200	Si, Sr, Cr (Eu, Gd)
3 Hya	A2p	31	− 480 + 740	Sr (Sp binary?)
73 Dra	A2p	13	− 700 + 200 est	*Eu*, *Sr*, *Ti*
β CrB	F0p	0 15	− 960 +1020	Sr, Eu; sp binary

TABLE 7

GAMMA VARIABLES

(Irregular Amplitude, Constant Polarity)

Star	Sp	w	H_e Extremes (gauss)	Remarks
HD 133029	A0p	0 4	+1150 +3270	Si, Cr, λ 4201
78 Vir	A2p	2	−1680 $\underline{x}$ − 140	Sr, Cr, Eu
HR 710	A4p	15	−1080 − 320	Sr, Cr, Eu; sp binary
52 Her	A4p	4	+ 840 +1430	Sr, (Eu)
γ Equ	A7p	0 09	+ 180 + 880	Eu, Mg, Sr (Si)

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of groups β and γ have generally lower magnetic amplitudes and usually do not show spectrum variations or the crossover effect. Curves of magnetic variation for the α-variables are shown in Figures 3–10, and sections of their spectra are reproduced in Figure 11.

It is characteristic of the magnetic results that, after allowing for errors of observation, deviations from the mean in amplitude or in phase are to be found. Such deviations are perhaps least evident in the spectroscopic binary HD 98088 and are most obvious in HD 32633 and HD 188041, which have, respectively, the shortest and longest periods in the group. A second characteristic is that the mean curves of magnetic variation are not of the simple harmonic type. In general, the magnetic maximum of one polarity tends to be broader than that of the other, and in α^2 CVn, HD 71866, and HD 188041, there are indications of a dip or notch in the top of the broader maximum. In HD 125248 and in α^2 CVn, the line profiles tend to be considerably narrower at the phase of the broader of the magnetic maxima (i.e., when the rare-earth elements, rather than chromium, are at maximum intensity). In 53 Cam, the variation in line width is most extreme, as is the field intensity.

The range of magnetic variation for various subdivisions of spectral type is shown in

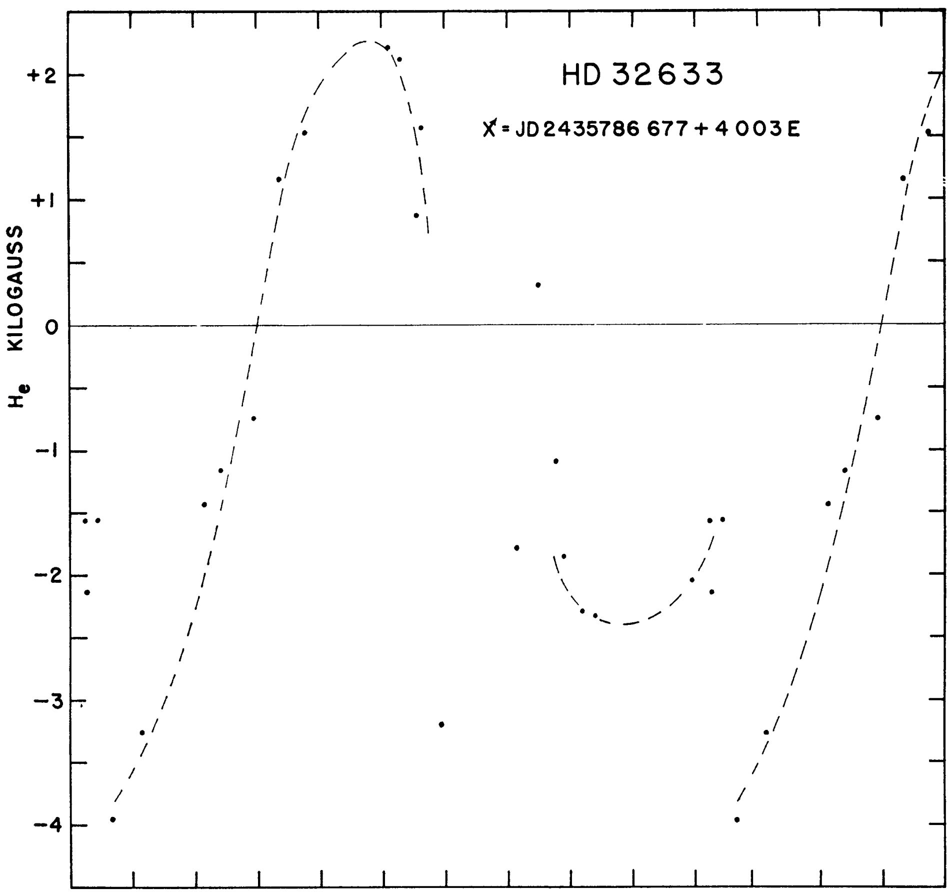

FIG. 3.—Magnetic variations of HD 32633 (No. 18). The steep rise and the positive maximum seem to recur regularly in the 4-day period, but the field intensity near mid-period shows unusually large random deviations, which probably account for the fact that the star is not a spectrum variable. The lines are wider when the polarity is negative. The crossover effect is obvious on only one plate. Probable errors of individual points are in the range 0.08–0.16 kilogauss.

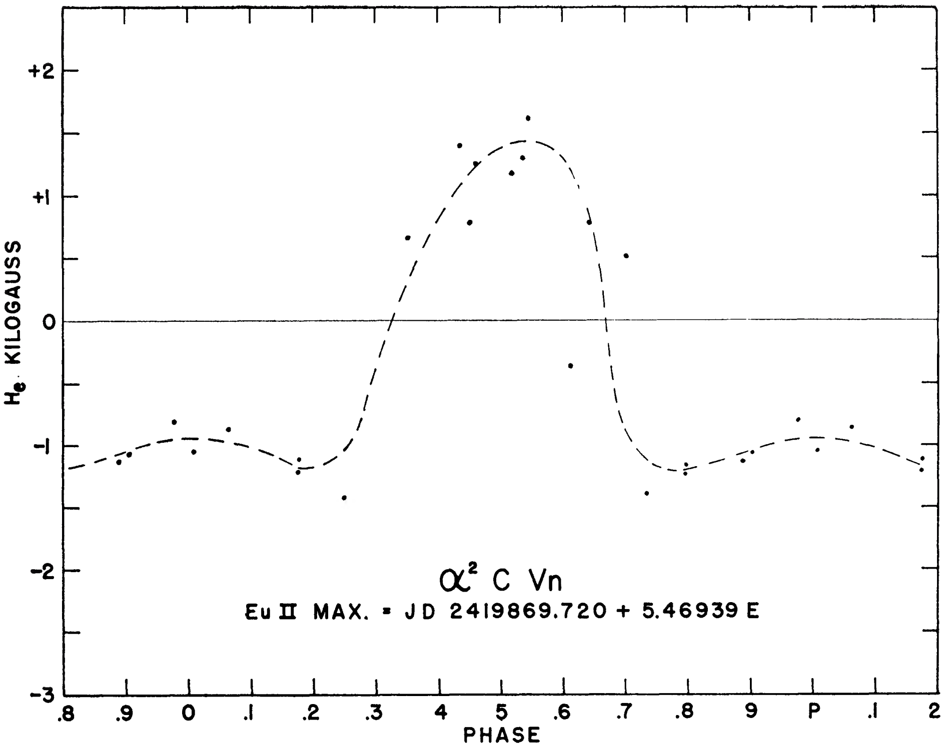

FIG. 4.—Magnetic variations of α^2 CVn (No 44). Intensity of the Eu II lines varies in antiphase with the intensity of lines of Cr I and Cr II, which are at maximum when the magnetic field has positive polarity. There occur marked deviations from the mean magnetic curve, particularly near the phase of negative crossover.

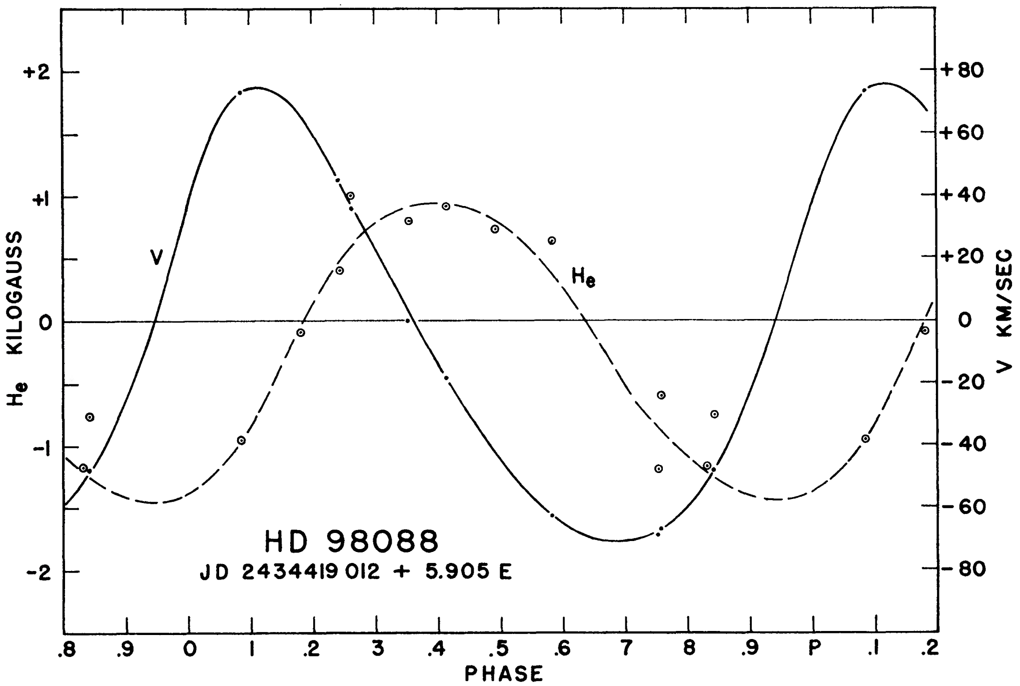

FIG. 5 —Curves of magnetic-field intensity (*dashed line*) and of velocity (*solid line*) for the unique α-variable HD 98088 (No. 37) The magnetic variations occur in the period of orbital revolution. The star is also a spectrum variable.

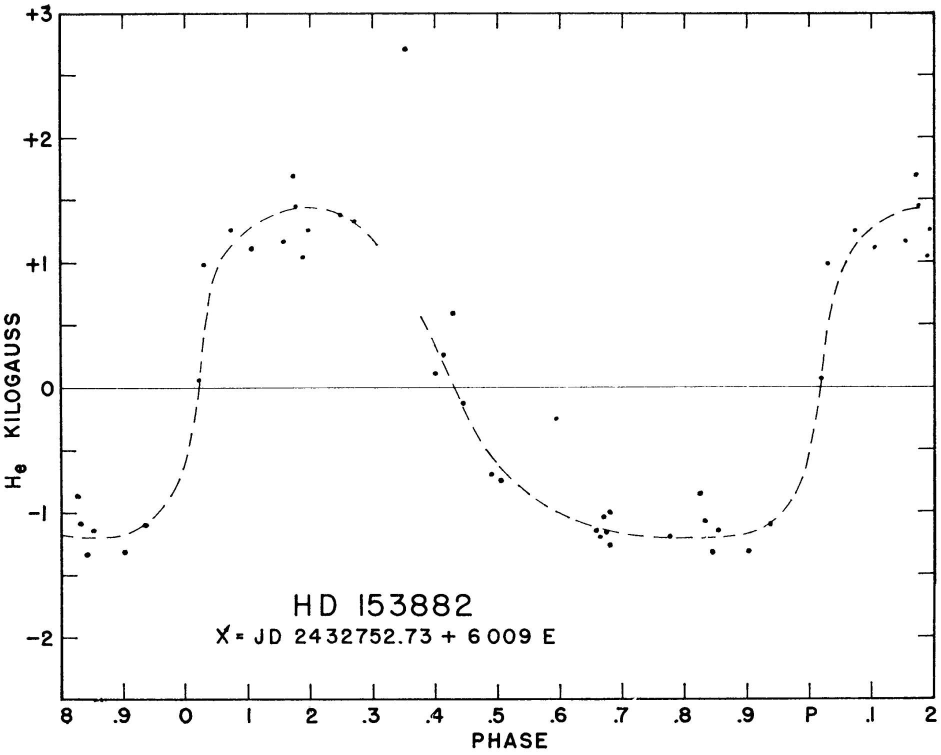

Fig 6 —Magnetic variation of HD 153882 (No 62). The probable error of each determination is about ±0 1 kilogauss Note the anomalous, very strong, field indicated by one plate near phase 0 36 The spectrum shows the crossover effect and certain peculiar profiles, but with little indication of changes in equivalent width

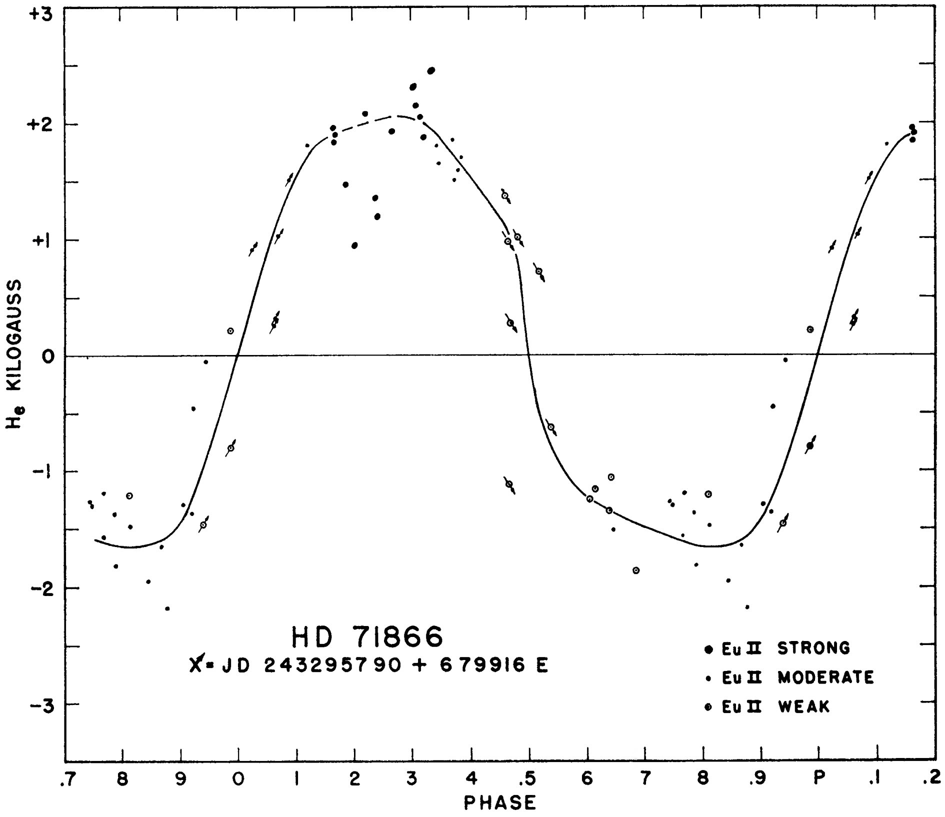

Fig 7.—Magnetic variation of HD 71866 (No. 30). Near phases 0 0 and 0.5, as indicated by the arrows, the crossover effect is uniquely prominent in the spectrum of this star. The intensity of the Eu II lines shows a double maximum, being strongest near positive magnetic maximum, moderately strong near negative magnetic maximum, and weakest at the crossover phases. There are pronounced deviations from the mean magnetic curve. Radial velocities from various plates are randomly scattered within a range of about 7 km/sec.

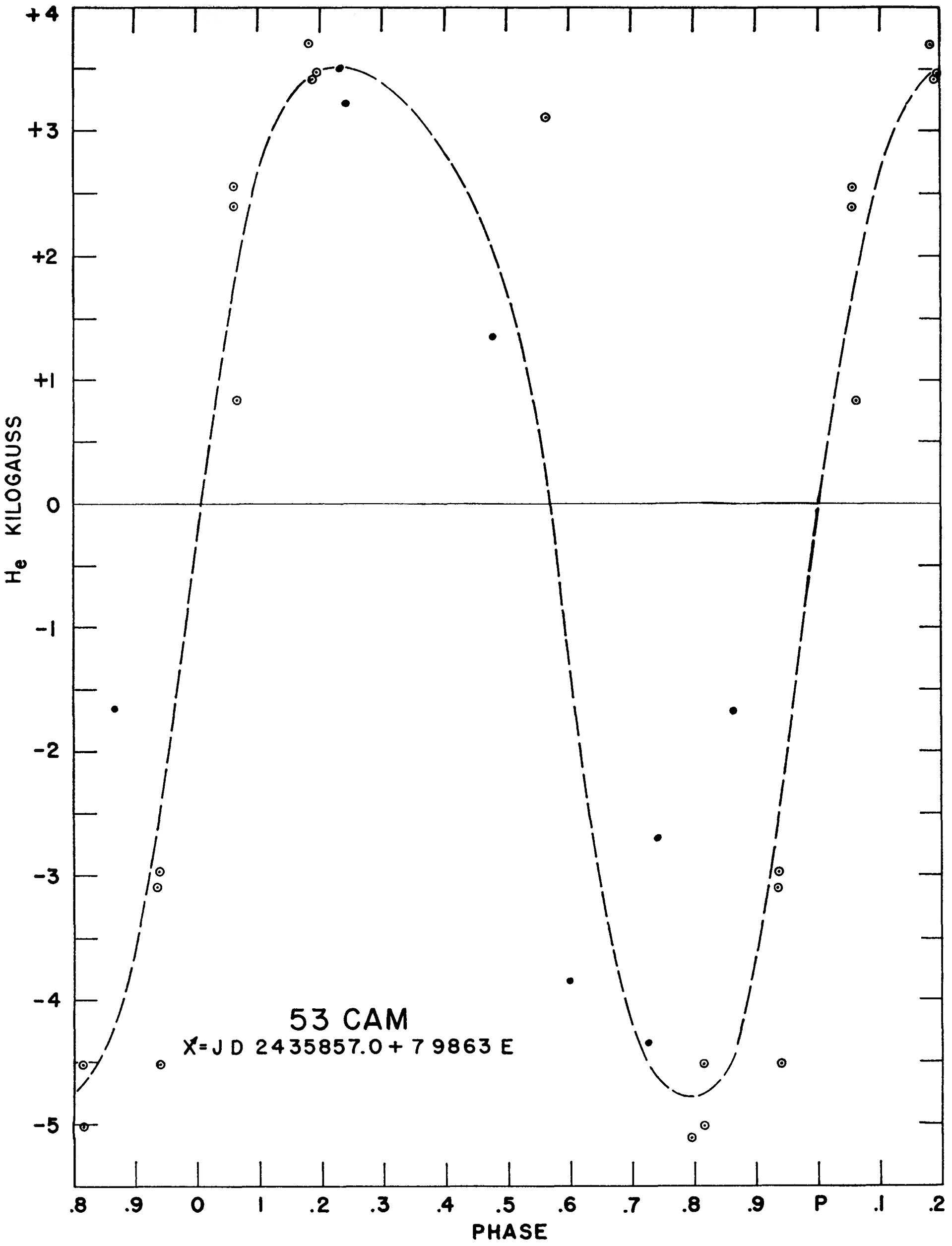

FIG 8 —The magnetic variable 53 Cam has a uniquely strong field and a uniquely large amplitude of variation. Probable errors of individual plates are between 0.1 and 0.2 kilogauss. The lines are much wider, and those of Ti II are stronger, when the field is of negative polarity. Dots represent observations in the first 5 months of 1957; dots with circles represent observations between October, 1957, and February, 1958. As in other α-variables, there are marked deviations from the mean curve, suggesting that large-scale hydromagnetic turbulence is effective.

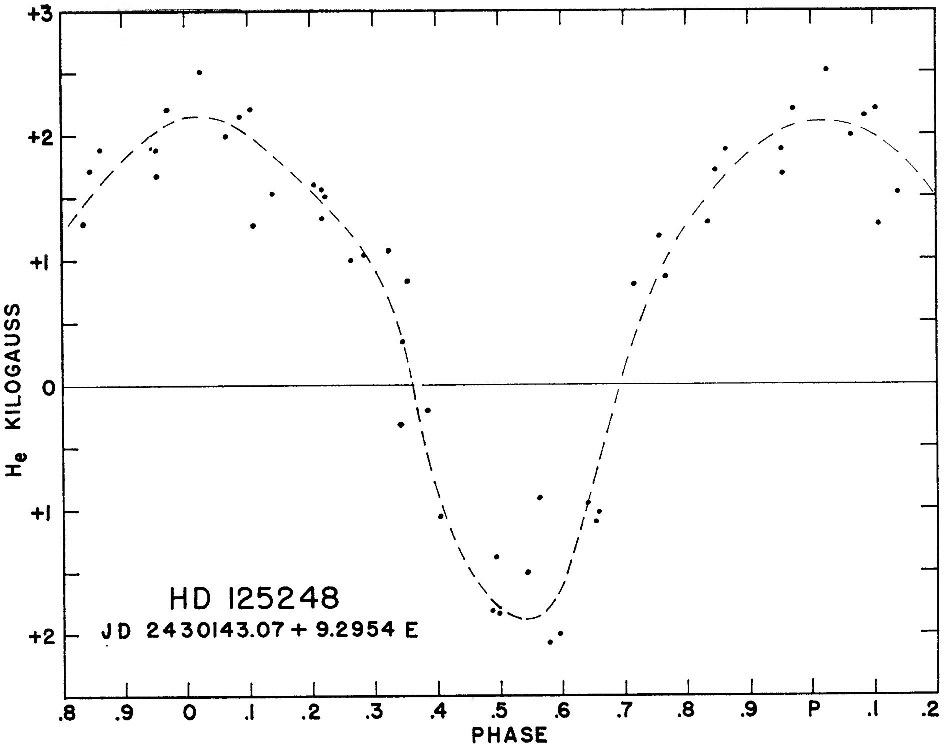

FIG 9 —Curve of magnetic variations for HD 125248 (No. 48) Zero phase is at maximum positive field intensity, which is also the phase of maximum intensity of the Eu II lines As in α^2 CVn, the lines of Cr, both neutral and ionized, vary in antiphase with the rare-earth lines, being strongest when the field is of negative polarity. The crossover effect is prominent. Field intensity may be systematically weaker subsequent to 1953.

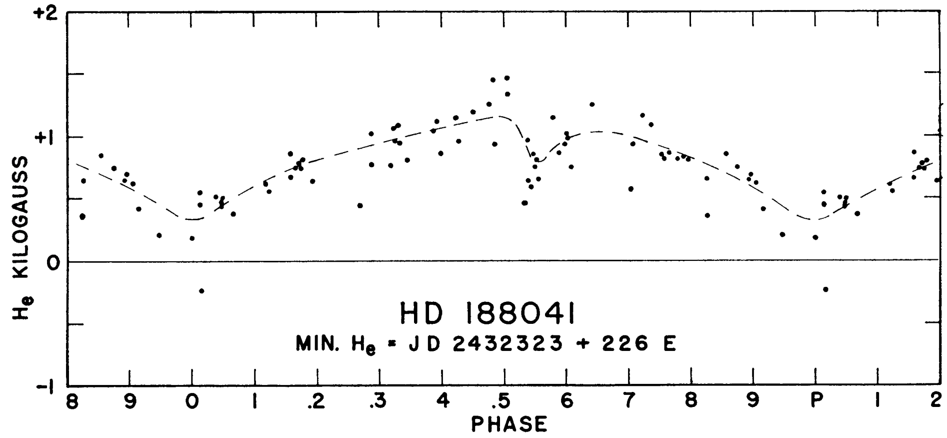

FIG 10 —Magnetic variation of the 226-day variable HD 188041 (No 72) Because the lines are ultrasharp and numerous, the probable errors are only about ±0.04 kilogauss, and the large, apparently random, dispersion of the individual observations is physically real. There are strong indications of an abrupt discontinuity in the magnetic variation between phases 0 5 and 0 6. All plates but one show positive magnetic polarity, but there is no doubt about the unique reversal Intensity of lines of Sr II and the rare earths varies in the same period as the magnetic field

Table 8 Principal features are the abrupt rise in magnetic amplitude between type B8 and A0, with the maximum amplitudes occurring among the A0 and A2 stars. These are the same classes—and, indeed, the same stars—in which the outstanding spectral peculiarities are known. Among the later A types, the magnetic amplitude tends to diminish The star β CrB is exceptional in having so strong a field for such a late spectral type and also, according to Eggen (1957), is unusual in color index.

The mean range of variation in the periodic variables of the α-group is 3530 gauss, or, excluding HD 98088, which has fundamental differences from the others, and HD 188041, which has a much longer period, the mean range is 4240 gauss. The range of the 6 irregular β-variables is 1935 gauss, while the range of the 5 irregular non-reversing γ-variables is 1140 gauss.

It is difficult to derive significant data on the mean rate of change of the magnetic fields, but, in general terms, it is fairly evident that the most rapidly changing strong fields are to be found among the subdivisions A0p and A2p. Included here are not only the outstanding periodic magnetic variables but also rapid irregular variables such as 21 Persei, HD 10783, and HD 133029. The typical variables of spectral classes A5, A7, and F0 have notably slower magnetic variations. Examples are γ Equulei (A7p), HD 188041 (A5p) with its 226-day period, and β Coronae Borealis (F0p), which may display a pseudo-cycle of length 40–60 days. Little is known as yet about the rate of change of the comparatively weak fields of the B8 and B9 stars, in which Mn II is usually the outstanding spectral peculiarity. It is possible that the fields of these stars change quite rapidly.

TABLE 8

RANGE OF MAGNETIC VARIATION

Spectral Subdivision	No of Stars	Mean Range in H_e (gauss)	Largest Range in H_e (gauss)
B8, B9	5	600	1100 (κ Cnc)
A0p	22	1600	4000 (HD 125248)
A2p	12	1660	7860 (53 Cam)
A3p	2	775	980 (HD 134793)
A4p	6	1090	2640 (HD 153882)
A5p	1	1700	1700 (HD 188041)
A7p	3	900	1600:(ω Oph)
F0p	1	1980	1980 (β CrB)

ANOMALOUS LINE INTENSITY

Nearly all the magnetic A stars of Table 1 have the designation "peculiar," indicating that anomalous line intensities have been observed in their spectra. In Table 2 of the catalog are found 33 additional peculiar A stars probably having magnetic fields, whereas in Table 3 of the catalog no peculiar A stars are found among the sharp-line stars that show no evidence of the Zeeman effect. Anomalous relative line intensities are obviously closely related to the presence of the strong magnetic field, probably through the influence of the field in altering the relative abundances of the elements in the spectroscopically effective regions, combined with the comparatively minor effect of magnetic intensification through Zeeman broadening of the lines.

It has been known for some time that, in proceeding from the hotter to the cooler stars in the range B8p–F0p, the accentuated elements, in approximate order of their appearance, are Mn, Si, λ 4201 (unidentified), and the group including Sr and Cr with

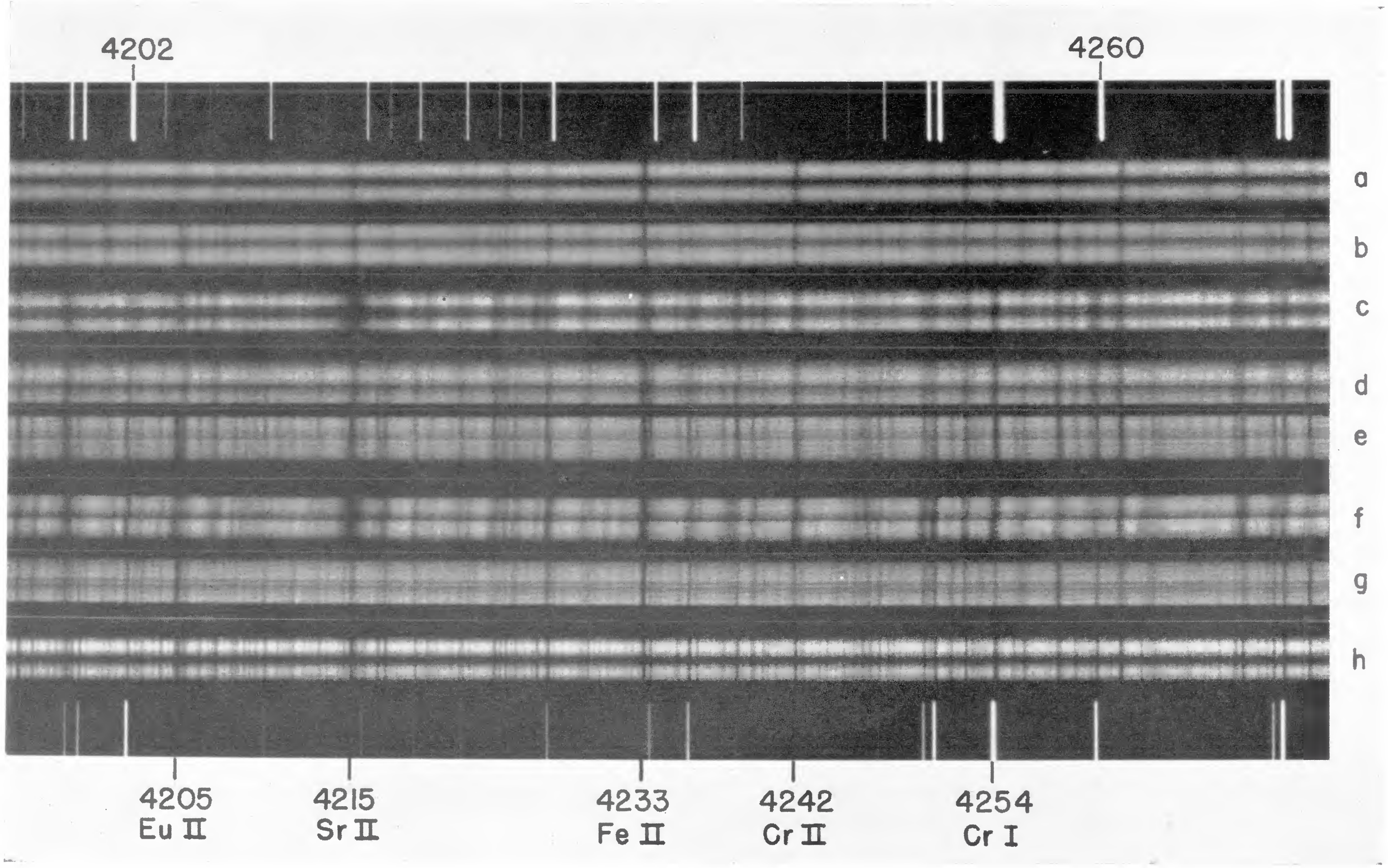

Fig. 11.—Spectrograms of the eight known α-variables, obtained with the double analyzer for rotatory polarization. Periods range from 4 to 226 days. *a*, HD 32633 (B9p, $w = 0.4$, $P = 4.0$ days); *b*, α^2 CVn (A0p, $w = 0.3v$, $P = 5.5$ days); *c*, HD 98088 (A2p, $w = 0.4$:, $P = 5.9$ days, spectroscopic binary); *d*, HD 153882 (A4p, $w = 0.4$:, $P = 6.0$ days); *e*, HD 71866 (A0p, $w = 0.26$, $P = 6.8$ days); *f*, 53 Cam (A2p, $w = 0.25$–$1v$, $P = 8.0$ days); *g*, HD 125248 (A0p, $w = 0.2v$, $P = 9.3$ days); *h*, HD 188041 (A5p, $w = 0.11$, $P = 226$ days). Zeeman displacements are seen most readily in *f* (53 Cam), while the crossover effect is seen in *e* (HD 71866).

Eu and other rare earths. This is illustrated in Table 9, which has been compiled from the data of Table 1.

Among the hotter (B8p–B9p) stars, relatively weak fields, with an unknown rate of change, characteristically result in abnormally strong Mn II and Si II; in some, Y II is also prominent. The strong and rapidly varying field of types A0p, A2p, and A3p brings out a variety of abnormally strong elements (practically all in such stars as 21 Persei and HD 173650), whereas the more slowly varying fields of the cooler subdivisions A5p, A7p, and F0p seem to accentuate only the lines of Sr, Cr, and the rare-earth elements. The most specific peculiarity is λ 4201, which seems to be limited to type A0p.

In certain peculiar stars, some elements other than Ca II are abnormally weak, relative to the others. Examples are iron, as shown by the lines on both the neutral and the ionized atom in HD 25354, and Mg II in 53 Cam.

In the spectra of the peculiar A stars, the K line of Ca II characteristically has a sharp, narrow profile and a relatively low total intensity. In many instances the sharp core shows rather broad but very shallow wings, sometimes with widths of several angstroms. (To a smaller degree, lines of Sr II show this behavior.) In a considerable number of the magnetic stars, the K line shows even greater anomalies, such as a variable or asymmetric profile, extra components, or temporary disappearance of the core (HD 49967). Such stars are listed in Table 10.

TABLE 9*

ELEMENTS SHOWING LINES OF UNUSUAL STRENGTH

Element	B8, B9	A0	A2	A3	A4	A5	A7	F0
Y II	3							
Mn II	5	6			2		.	
Si II.	8	17	4				(2)	
λ 4201		8	.		.	.		.
Sr II .		15	14	2	7	1	4	2
Eu II+Gd II		12	9	1	4	1	3	2
Cr I+Cr II	(2)	8	9	2	4	.	1	.
No of stars	8	26	17	2	7	1	4	2

* The number of stars characterized by abnormally strong lines of the elements indicated is entered for each spectral subdivision

The asymmetric K-line profile, sharper on the longward side, as observed in a few of the stars in Table 10, suggests the ejection of ionized clouds or streams such as the sun produces on a relatively insignificant scale.

The "metallic-line" stars, as compared to the peculiar A stars (Roman, Morgan, and Eggen 1948), show notably greater equivalent widths of lines of the metals and particularly of Ca II; their distinctly different color is well shown in Eggen's (1957) results. In several such stars (Table 11) the presence of magnetic fields is either observed or suspected. The number of the object in Table 1 or its listing in Table 2 of the catalog is indicated.

The spectral anomalies thus far referred to are obvious, readily visible to the eye upon comparison of the spectrograms. Quantitative measurements of equivalent width go much further. For example, G. R. and E. M. Burbidge (1955), using a curve-of-growth method, have compared line intensities and have derived abundance ratios for 23 elements in comparing α^2 CVn with the normal A0 IV star γ Gem, and in comparing HD 133029 with α^2 CVn. Such measurements support the contention that the anomalous line intensities result from abnormal abundances of the elements in the spectroscopically effective portions of the stellar atmospheres. These results indicate a general qualitative trend for typical magnetic stars, but a survey of the spectra of the stars of Table 1 shows that large individual deviations occur in the spectral peculiarities of the magnetic stars; diversity in detail is the rule, and it is rare that two or more stars can be found with spectra that are essentially identical. The unpredictable variations in line profiles and in total intensities observed in many of the magnetic stars (e.g., 21 Persei, HD 25354, 41 Tauri, HD 49976, HD 56495, 45 Leonis, 45 Herculis, HD 173650, and HD 4778) suggest that spectrophotometry of high precision may be unprofitable in certain cases until more is known of the physical processes in these stars as a result of semiquantitative investigations.

SPECTRUM VARIABLES

The magnetic A stars are "peculiar" stars, and, among the peculiar stars, those that have periodically varying magnetic fields are found to be spectrum variables, in the sense that lines of certain elements, including some but not all of those showing marked intensity anomalies, display variations in intensity. In typical spectrum variables, such as α^2 CVn and most other members of the α-group (Table 5), these variations are periodic and are synchronous with the magnetic variations. In contrast, the typical irregular magnetic variables of the β- and γ-groups (Tables 6 and 7) are not spectrum variables. We have already concluded that the spectrum peculiarities (abundanced anomalies) are closely related to the magnetic field. It further appears that spectrum variability in a

TABLE 10

MAGNETIC STARS WITH ANOMALOUS K-LINE, Ca II λ 3933

Cat No	HD Number or Name	Sp Type	Remarks on K Line
14	25354	A0p	Strong
15	41 Tau	A0p	Sometimes double
17	30466	A0p	Variable width
18	32633	B9p	Very weak; interstellar component?
22	42616	A2p	Flat-bottomed profile; longward edge sometimes sharper
24	49976	A0p	Usually sharp; once broad and shallow with no core
29	15 Cnc	A0p	Usually wide and shallow; sometimes profile is square
31	3 Hya	A2p	Variable profile?
35	30 UMa	A0p	Strong
62	153882	A4p	Square
.	168814	(A0p)	Shortward edge rounded; longward edge sharp
65	173650	A0p	Square, sharp-edged
70	184905	A0p	A weak, wide shallow component plus a sharp, variable component; the wide component is sometimes sharper on the longward side; the sharp component is missing on two plates
82	215038	A0p	Very sharp

TABLE 11

METALLIC-LINE STARS, PROBABLY WITH MAGNETIC FIELDS

No	Star	No	Star	No	Star
16	68 Tau	T 2	15 UMa	61	HD 153286
T 2	HD 16956	39	17 Com B	19	16 Ori
T 2	HD 50168	69	51 Sag	47	+46°1913
27	HD 56495	T 2	γ Cap		

star results from a higher degree of organization in the magnetic pattern of its outer layers, which occurs in periodic magnetic variables but not in irregular magnetic fluctuators.

The spectrum variables of type A were discussed by Deutsch (1947, 1956), who compiled a catalog of 20 such stars in 1947, with descriptions of their variations. In the present paper the emphasis is on the magnetic fields of the A-type stars, but some supplementary descriptive data on the spectrum variations have accrued.

Intensity variations of the largest amplitude are found for the elements Sr II (HD 49976, HD 134793) and Eu II (HD 125248). Marked variations in the chromium lines are much less common but are outstanding in α^2 CVn and HD 125248, where they vary in antiphase with the rare-earth elements. (It has been remarked before that in α^2 CVn, lines of Cr I and Cr II are at maximum intensity when the magnetic field has positive polarity, while the reverse is true of HD 125248.) Lines of Si II and the unidentified λ 4201, although frequently of abnormal strength in A0p stars, show only limited intensity variations in a few of the short-period variables (Table 13) and to an even lesser degree in α^2 CVn and a few other stars. Iron and manganese lines are rarely found to show appreciable intensity variations. Ti II lines show marked changes in 53 Cam and 73 Dra, though in few others. While Ca II is abnormally weak in nearly all the peculiar stars, it rarely undergoes marked changes of intensity. Mg II, on the other hand, is nearly normal in most stars of the group but undergoes variations in 53 Cam, while Mg I varies in HD 56495. Periodic variations in line intensity are usually attended by systematic variations in line width and in many cases, but not invariably, by small systematic differential velocity fluctuations.

TABLE 12

ERRATIC (δ) SPECTRUM VARIABLES

No	Star	H_e Range (gauss)	Remarks
14	HD 25354	−380 0:	*Eu, Cr,* Mn, λ 4201; Fe weak; variable profiles
24	HD 49976	−810 +	*Sr, Ca;* profiles diverse, vary irregularly
27	HD 56495	−? +570	*Cr, Mg* I, Sr
53	HD 134793	−530 +450	*Eu, Sr,* Cr; widths vary
65	HD 173650	−540 +700	*Sr, Eu,* Si, Mn, Cr, Gd, λ 4201; peculiar variable profiles
87	108 Aqu	+	*Sr, Ca,* λ 4123
88	HD 224801	+2300	*Eu,* Si, Sr, λ 4201

Until recently, it was believed that all spectrum variables of type A were periodic, like those of the α-group. It now appears, however, that there is a small group of magnetic stars showing irregular spectrum variations or variations that are not simply correlated with the magnetic changes. This, which we may denote as the δ-group, is constituted as in Table 12. Assignments to this group should be regarded as somewhat tentative, since some of these stars have not been studied so thoroughly as have the members of the α-, β-, and γ-groups.

With the exception of HD 224801, the erratic spectrum variables have one common characteristic—the range of magnetic-field variation is limited to about 1 kilogauss, or approximately one-fourth the range of the α-variables (Table 5).

Because of the association of peculiar spectra with magnetic fields, it is reasonable to infer that the peculiar A stars and spectrum variables with lines too wide to permit measurement of the Zeeman effect likewise possess magnetic fields. About 84 such stars are listed in the catalog (thirty-three in Table 2, for which the Zeeman effect is doubtfully

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observed, and 51 in Table 4, for which the lines are definitely too broad). Of the broader-line peculiar stars, those with spectrum variations for which periods have been determined are listed in Table 13, which has been adapted from a paper by Deutsch (1956). Variations in luminosity and color have been measured for several of these stars by Provin (1953).

The broad-line variables of Table 13 have short periods and are, with the exception of ι Cas, of type A0p or A2p, in accord with the tendency for magnetic variations to be most rapid for these spectral subdivisions (with the possible exception of types B8p and B9p).

In Table 1 there are also listed several magnetic variables having comparatively broad lines, with widths between 0.4 and 1 A. These have usually not been measured in the ordinary way, but the polarity and order of magnitude of the field intensity have been established by inspection of the double spectrograms. These stars are grouped in Table 14.

TABLE 13

BROAD-LINE SPECTRUM VARIABLES

Star	HD No	Sp	Period	Variable Elements	Remarks
HR 5313	124224	A0p	0 52	Si	
56 Ari	19832	A0p	0 73	Si ? λ 4201	
21 Com	108945	A2p	1 03	Sr	w=1:
χ Ser	140160	A0p	1 60	Sr, Cr	
ι Cas	15089	A5p	1 74	Sr, Cr (Bahner)	w=1 3:
. . .	107612	A2p	2:	Sr, Cr	w=0 8:
HR 1732	34452	A0p	2 7	Sr, λ 4201	
γ Ari (S)	11503	A0p	(2 607)	Cr, Eu, Si	

TABLE 14

FIELD PRESENT, 0 4 < w < 1

No	Star	Sp	w	No	Star	Sp	w
5.	43 Cas	A0p	0 7	82	HD 215038	A0p	0 8:
29	15 Cnc	A0p	0 7:	84	κ Psc	A2p	8v
58	ω Oph	A7p	0 6	87	108 Aqr	A0p	8:
64	HD 171586	A2p	0 8:	88	HD 224801	A0p	8:
59	45 Her	A0p	0 6±	89	HD 4778	A0p	0 5–1
70	HD 184905	A0p	1:				

Notwithstanding the breadth of the lines, efforts to estimate the upper limit of the magnetic-field intensity of the stars of Tables 13 and 14, made by examining the spectrograms with a hand lens, indicate that these fields are probably no stronger than the fields of the α-variables, and it is quite unlikely that any of them equals the 5-kilogauss field of 53 Cam. For several, if not all, of these stars there is qualitative evidence that the line profiles have diverse and variable widths.

It has been shown that anomalous line intensities occur in the spectra of both the periodic and the irregular magnetic variables and that these variables are indistinguishable on the basis of isolated spectrograms. If, as is highly probable, the anomalous line intensities result from abnormal relative abundances of the elements in the spectroscopically effective outer layers of the stars, one is led to suppose that in the irregular magnetic variables the surface layer has a sensibly uniform, though abnormal, composition and that it has been mixed through irregular hydromagnetic turbulence, while in the periodic magnetic variables the atmosphere of the star is more highly organized into distinct zones or regions, each with its identifiable peculiarities. The magnetic field associated with the respective regions may be supposed to preserve their identity, although at the same time allowing relative motion or even cyclic submergence and emergence of volumes of material associated with the magnetic field. Presumably, the processes responsible for the abundance anomalies have been going on over long intervals of time, but only a very small fraction of the material of the whole star need have been affected.

A secondary and probably minor cause of anomalous line intensity is "magnetic intensification" (Babcock 1949). Lines showing a multiplicity of components in the Zeeman pattern can, if the pattern is wide and if the number of effective atoms is sufficient to place the line on the otherwise flat, or saturated, portion of the curve of growth, be intensified in a strong field by a factor that approaches as an upper limit $n/2$, where n is the number of components in the pattern Such intensification should be particularly effective for such lines as λ 4205 Eu II ($^9S_4$–$^9P_3$), which has the pattern (**0.00,** 0.25, 0.50, 0.75) **1.25,** 1.50, 1.75, 2.00, 2.25, 2.50, 2.75. Magnetic intensification seems incapable, however, of accounting by itself for the relative intensities of peculiar lines of various elements as encountered in the magnetic stars. G. M. and E. R. Burbidge (1955*b*) showed that the apparent unimportance of magnetic intensification in α^2 CVn and HD 133029 is probably due to its masking by local turbulent velocities.

If the anomalous abundances in the atmospheres of the magnetic A stars are the result of surface nuclear reactions, as argued by Burbidge, Burbidge, Fowler, and Hoyle (1957), it is required that these reactions result from highly energetic collisions of ions accelerated in rapidly varying magnetic fields. The significant fact here in regard to models of the α-variables is that the abundance anomalies point to rapid intrinsic changes in the atmospheric magnetic fields of the α-variables, just as in the β- and γ-variables. This argues for a pole-on model of the α-variables involving periodic hydromagnetic fluctuations rather than simple oblique rotation of a magnetically rigid star carrying an oblique magnetic dipolar field. Hence one is led to suspect that the principal difference between the periodic α-variables and the irregular magnetic variables is that the atmospheric motions in the former have become co-ordinated in a large-scale hydromagnetic cycle that dominates the surface layers.

At the present time it can hardly be regarded as proved that the abundance anomalies in the magnetic stars result from surface nuclear reactions. This theory seems not to account for the great overabundance of europium, which is so characteristic of many of the magnetic stars; and there are other discrepancies. It would seem that other theories, leading to progressive segregation or sorting of chemical elements in the atmospheres of magnetic stars, deserve critical investigation. What, for example, of the differential mobilities of the constituents of a partially ionized gas in a magnetic field? What about differential leakage through the magnetic lines of force of neutral atoms as compared to ions? What of the microstructure of a stellar atmosphere? Is it possible that the gradient of the local magnetic field is sufficient to produce significant differential paramagnetic and diamagnetic forces resulting from the specific magnetic moments of ions in various stages of excitation?

SPECTROSCOPIC BINARIES

Thirteen spectroscopic binaries are listed among the 89 stars of Table 1, as shown in Table 15. Those that are believed to be newly identified as binaries are marked with asterisks. References to earlier work are given in the catalog.

The fact that some binaries with periods of a few days have strong observable magnetic fields is noteworthy in itself, for under such conditions the effect of magnetic forces on ionized material in the vicinity of the binary system cannot fail to be of importance. Consideration of these forces and processes is therefore essential in discussion of corpuscular streaming and of the evolution of binary systems. On the other hand, several of the binaries listed show magnetic variations that are unrelated to the orbital motion. It is also noteworthy that, with the exception of HD 98088 and HD 125248, none of the periodic magnetic variables (α-variables of Table 5) displays any evidence of orbital motion. The slow variations in velocity of HD 125248 suggest that the star is a member of a binary system with a period of some years, but they seem quite unrelated to the 9-day magnetic variations.

HD 98088 is an exceptional star which differs from the other variables of Table 5 in that the crossover effect is not observed in its spectrum and that it is a spectroscopic binary with a period of revolution equal to the period of magnetic variation. The magnetic and line-intensity variations can be represented formally by a model viewed at large obliquity, which rotates on its axis in the same period as the orbital revolution and which maintains one face toward the companion star. This does not exclude the possibility that the star undergoes a hydromagnetic oscillation in resonance with the tidal effects of its elliptical orbit ($e = 0.176$).

TABLE 15

SPECTROSCOPIC BINARIES WITH OBSERVED MAGNETIC FIELDS

No	Star	Period	No	Star	Period
3	HD 8441*	Weeks?	34	κ Cnc	$6^{\mathrm{d}}39316$
4	HD 9996*	?	35	30 UMa	$11^{\mathrm{d}}6$
8	HR 710*	$2^{\mathrm{d}}997814$	37	HD 98088	$5^{\mathrm{d}}905$
15	41 Tau*		46	HD 125248	Years?
32	3 Hya*	Months?	55	β CrB	10 496 years

COMMENTS ON CERTAIN MAGNETIC VARIABLES

HD 133029 (*No. 52*).—(52 Her and HD 215038 are probably similar) One of the strongest stellar fields is found in this γ-variable. Results based on seventy-four plates distributed over 8 years show that the variations are irregular, between the limits $+1150$ and $+3270$ gauss. Values near the mean are more common than near the extremes, indicating that the variations are not sinusoidal. Some of the magnetic changes are quite rapid. There are pronounced anomalies in line intensity (Burbidge and Burbidge 1955*b*), but no spectrum variations have been reported. The line width, w, is about 0.4 A. It is assumed that the dominant component of the stellar field is dipolar and that the star must have rotated many times on its axis during the years covered by the observations. The most plausible model for this star is a rapid rotator, observed nearly pole-on, in which the magnetic axis is essentially symmetric with the rotational axis. Hydromagnetic fluctuations at the stellar surface are presumed to account for the irregular variations in H_e and, in part, for Doppler broadening of the lines. It has not seemed possible to devise a model for this star in which the magnetic axis is appreciably inclined to the rotational axis.

HD 188041 (*No. 72*).—The magnetic maxima are non-uniform in amplitude, but the minima recur at regular intervals of 226 days. It is highly improbable that the period of axial rotation could be as long as this. There is evidence for an abrupt change in H_e near mid-period. Hence the cyclic variations are attributed to some intrinsic hydromagnetic process. If this is correct, it proves that a hydromagnetic cycle can result in spectrum variability, for variations in the Gd II and Eu II lines in the 226-day period are established. Longer-term variations in line intensity also occur.

RR Lyrae (*No. 68*).—Observations prove that a strong variable magnetic field can occur in a non-rigid, pulsating star. It is hardly necessary to add that the cluster-type variables like RR Lyr are far removed from the main-sequence, non-pulsating, magnetic A stars and that the hydromagnetic processes in the two types of star must be radically different.

HD 71866 (*No. 36*).—This star is a typical α-variable, with a period of 6.8 days and nearly symmetric magnetic reversals between the approximate extremes -1700 and $+2000$ gauss. It is also a spectrum variable. Several measurements of the over-all widths of typical metallic lines of moderate intensity yield the mean value $w = 0.26$ A. If the obliquity of the axis of rotation to the line of sight is 90° and if the stellar radius is 2.3 $R\odot$, we find $v_e = 18$ km/sec, leading to expected Doppler rotational broadening of 0.53 A at λ 4300. Other effects contributing to line broadening can scarcely be neglected. Thus it appears practically impossible that the obliquity, i, of the rotational axis can be greater than 30°. On the other hand, unless i is considerably greater than 30°, it is extremely difficult, if not impossible, to represent by the rigid "oblique rotator" model the nearly symmetric and complete magnetic reversals. Observations near positive and negative magnetic maximum show a longitudinal Zeeman effect that is essentially "pure" as regards polarity; there is no trace of contamination of the profiles by polarity of the opposite sign. Further, it has been shown for this star (Babcock 1956) that the crossover effect is not compatible with the rigid rotator model: (*a*) the mean matching equatorial velocity required to yield maximum visibility of the crossover effect in the presence of the observed magnetic-field intensity is only 3.5 km/sec; (*b*) the crossover effect is uniquely conspicuous for some of the lines of Fe I but far less so for lines of Fe II. The random fluctuations in velocity, within a range of about 8 km/sec, are perhaps best attributed to hydromagnetic disturbances at the surface.

HD 187474 (*No. 71*).—Five plates, distributed over a 4-month interval in 1957, give for H_e the results -1890, -1840, -1845, -1840, and -1920, respectively. The probable error for each is about ± 90 gauss, and the mean effective field is -1867 gauss. This star is unique, among all those in Table 1, in that the available evidence indicates that the field may be nearly invariant. The Palomar plates give no evidence of spectrum variability, but variations in the K line and in λ 4078 have been suspected by C. and M. Jaschek (private communication). The lines are of diverse widths between 0.1 and 0.4 A, those of Eu II being among the broadest. All elements are in good agreement in yielding nearly the same value of H_e, with the exception of Cr II lines on one plate. If the magnetic field is essentially dipolar, the inclination of the dipole axis to the line of sight must be nearly constant, because H_e is constant, and this inclination cannot be large, because the Zeeman effect is principally longitudinal. It is most probable that the rotational axis has only a small inclination to the line of sight and that the obliquity of the magnetic to the rotational axis is not large, i.e., the field is axisymmetric. Possibly the peculiar excitation is related to the uniquely invariant magnetic field. If the appearance of many unusual lines of Ti II and Fe II (especially unclassified lines of Fe II) can be taken as an indication of a constant magnetic field, this will have a bearing on the interpretation of the α-variables.

53 Camelopardalis (*No. 28*).—This star has a uniquely large magnetic amplitude, varying in an 8-day period. The longitudinal Zeeman effect at maximum appears to be essentially "pure," or uncontaminated by transverse or reversed fields. The rate of change, dH/dt, is very great near the crossover phases, and the deviations from one cycle to another are notable. The crossover effect in the line profiles is prominent but not so extreme as in the spectrum of HD 71866. On the oblique rotator model, the line widths in 53 Cam should be about 0.45 A, but the observed range of w is 0.15–1 A, so that a simple model does not suffice.

HD 32633 (*No. 18*).—The reversing magnetic field reaches a positive maximum of about +2 kilogauss in a period of 4.0 days, but in the phases of negative polarity the amplitude seems quite erratic, as is the crossover effect. This randomness of magnetic activity suggests a degree of atmospheric mixing which may account for the fact that no line-intensity variations are observed. Line widths range from 0.3 to 0.5 A; yet, on the oblique rotator model, Doppler broadening should amount to 0.9 A if i is large. King (1951) classifies the star as A2 II.

THE PERIODIC (α) MAGNETIC VARIABLES

The fact that the typical α-variables have the largest magnetic amplitudes, that their fields all show reversals of polarity with some approach to symmetry, and that their periods lie in the limited range 4.0–9.3 days indicates that a physical process of basic significance is operating. The development of a model to represent the magnetic variations in the periodic variables, with all their complex associated effects, is an outstanding problem that is far from solution. Certain conditions are imposed by theory, and many interrelated phenomena are involved—variations in the Zeeman effect, in profiles and equivalent line widths, in the crossover effect, in differential velocities, and in luminosity. In this section the approach to two basically different models will be considered in the light of available data.

The two models are (A) the hydromagnetic oscillator, based on a greatly amplified and accelerated magnetic cycle similar in kind to the 22-year magnetic cycle of the sun, and (B) the oblique rotator, a rigid star, carrying an appropriate pattern of magnetic areas distributed over its surface, which rotates about an axis oblique to the line of sight, resulting in a periodically changing effective field. The rigid model has the appeal of simplicity, while the oscillator model has the advantage of similarity to physical phenomena, complicated though they may be, that are observed on the sun.

A. *The Solar-Cycle Model*

There is no reason to suppose that the sun is unique in undergoing a magnetic cycle. It is a typical main-sequence star, which, compared to the average A-type star, has a diameter half as great and a rotational period forty times as long. Differential rotation gives the sun a period of about 25 days near the equator, 34 days near the poles. The 22-year magnetic cycle, affecting surface activity and coronal streamers, reflects the subsurface circulation of material with its associated magnetic fields according to some fundamental hydromagnetic process that must be intimately connected with the axial rotation of the sun as a whole. A solar model having a torsional oscillation as a basic feature of the magnetic cycle is suggested by both observation (Richardson and Schwarzschild 1953) and by theory (Walén 1949). In stars possessing convective zones and rotating ten to a hundred times as rapidly as the sun, it is only to be expected that a vastly enhanced hydromagnetic cycle of the same general kind will operate.

The sun possesses a poloidal or "general" magnetic field, limited to high lattitudes (Babcock and Babcock 1955). This poloidal field is known to undergo significant systematic variations in intensity and polarity that are undoubtedly related to the progress of the main 22-year magnetic cycle (H. D. Babcock and Livingston 1958). If the sun could be viewed along the direction of its axis, the contributions to the effective magnetic field in integrated light would be partly from the polar regions and partly from the toroidal fields of the lower latitudes. The transitory activity in the lower latitudes is now believed to arise through the agency of subsurface fields encircling the sun, of opposite polarity in the northern and southern hemispheres. Portions of these toroidal fields are occasionally brought to the surface, permitting the lines of force to arch into the solar atmosphere and corona; they control the formation of surface magnetic regions, faculae, spots, flares, and prominences.

It has been shown by Grotrian and Künzel (1950) and by Kienle (1950) that the integrated light of the low-latitude zone of the sun, in either hemisphere, would yield, in the mean, a symmetrically reversing effective magnetic field. This follows from the fact that div $H = 0$, so that there is conservation of toroidal flux in surface bipolar magnetic regions, and that sunspots (from which the optical contributions to the Zeeman effect are suppressed through darkening) are larger, more frequent, and of longer duration in the "preceding" as contrasted to the "following" parts of bipolar magnetic regions. Hence, in integrated light, the polarity that predominates in the lower latitudes is the polarity characteristic of the "following" parts of bipolar regions.

There occur in the sun systematic migratory motions in the latitude of the toroidal fields; apparently, the meridional motions of the associated surface magnetic regions, faculae, and prominences are more rapid. Magnetic regions associated with the toroidal field actually push far poleward at certain phases of the solar cycle, as evidenced by the solar magnetograms and by the variation in latitude of the stable prominences (see Fig. 12, adapted from Anathakrishnan 1952) that tend to mark the boundaries of such regions, especially on the poleward side (Babcock and Babcock 1955). Such effects on an amplified scale in a star having a surface field of the order of a few kilogauss, where the magnetic pressure is 10^5 dynes/cm^2, could go far toward accounting for many of the phenomena observed in the sharp-line magnetic A-type stars.

The integrated effect, as viewed along the axis of the model, would then be a combination of the "polar" and "toroidal" contributions, each of which varies systematically with the progress of the main magnetic cycle. Each is subject to appreciable short-term fluctuations, and, if the obliquity of the axis is not precisely zero, there may be intermittent modulation in the period of the axial rotation, owing to the fact that the distribution of magnetic activity in longitude is not uniform.

To develop this model a little further, two distinct magnetic regimes can be identified by the poloidal and toroidal fields. The highly conductive material associated with the respective regimes is effectively prevented, by its fields, from intermixing. Over long periods of time the abundance ratio of the elements becomes altered, either through nuclear reactions or through segregation by differential mobility. Different relative abundances may be expected for the two magnetic regimes, owing to the difference in the degree and kind of hydromagnetic activity at the stellar surface for the poloidal and toroidal fields. For example, more flare activity may be expected in the toroidal regime. In this way, one can see the basis for a model which might account for the groups of elements that alternate periodically in the spectra of some of the α-variables. Extensive transitory clouds of optically thick prominences arising out of the toroidal regime could be particularly effective in producing a variable component of the absorption spectrum, and, if such prominences were sufficiently dense in low latitudes, they could account for the emission wings sometimes observed or suspected on absorption lines in certain magnetic stars, including α^2 CVn. The meridional component of motion, varying with phase, could produce the differential velocities, which, when integrated, lead to displacements of the order of a stellar radius. The randomness of detailed magnetic activity within a hydromagnetic cycle plausibly accounts for the observed deviations in magnetic amplitude and phase and for the fluctuations in velocity. Finally, a resonant oscillation depending upon the magnetohydrodynamic properties of the star is invoked to explain the concentration of the periods of the large-amplitude magnetic variables in the range 4–9 days.

For the foregoing reasons, briefly stated, the possibility must be considered of accounting for the α-variables as pole-on stars undergoing exaggerated solar-type magnetohydrodynamic oscillations.

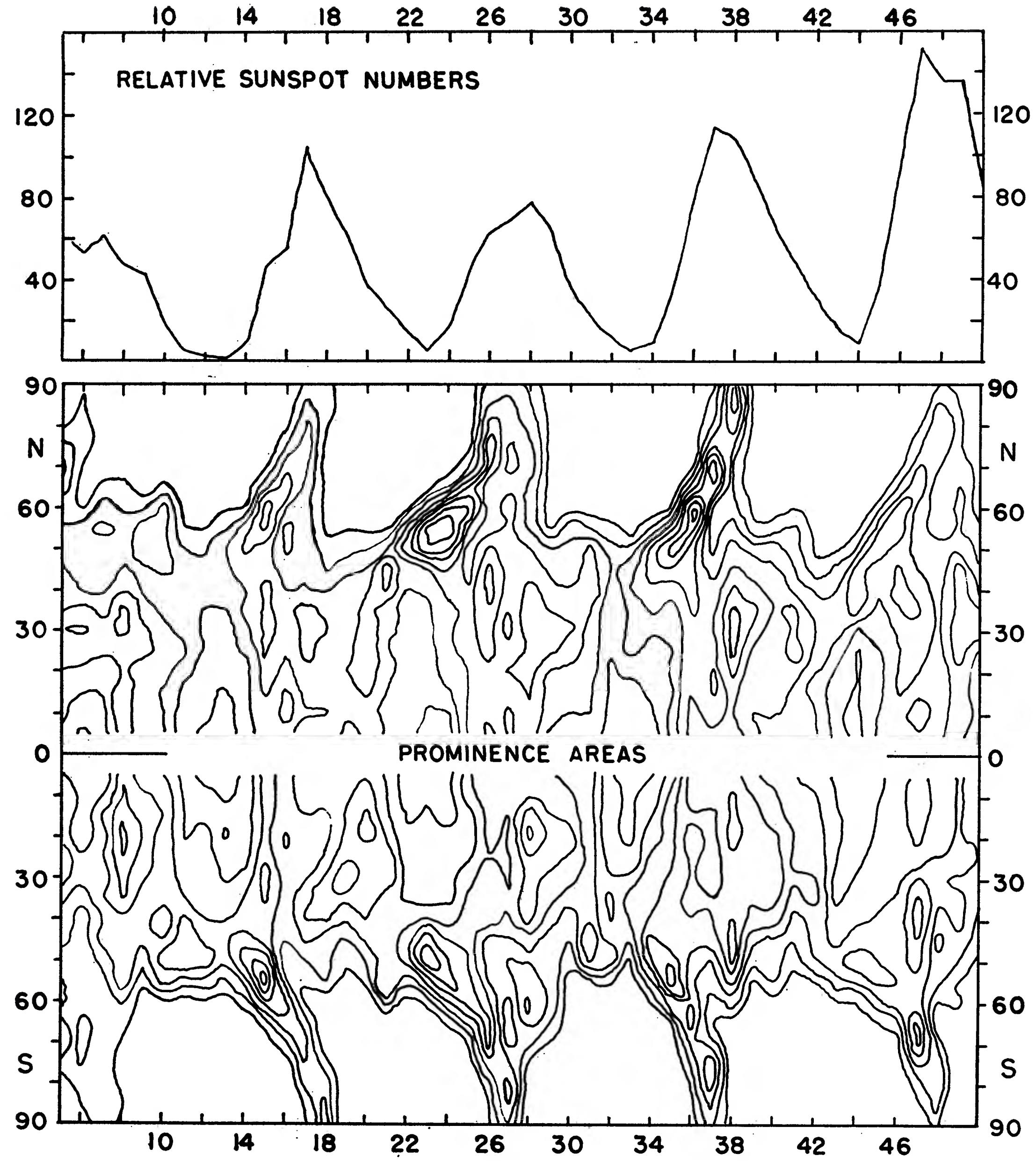

Fig. 12.—Isopleths of mean daily prominence areas on the sun for the years 1906–1950, adapted from Anathakrishnan (1952). The contour interval is 50×10^{-3} sq min of arc of prominence area. The high heliographic latitudes are free of prominences except near the phase of sunspot maximum in the 11-year cycle.

B. *The Oblique Rotator*

Initially, the oblique rotator model was considered in terms of a rigid sphere with a magnetic dipole field inclined to the axis of rotation, which, in turn, was inclined to the line of sight. Expressions for the harmonic variations of the effective field were given by Stibbs (1950). As this model was inadequate, more elaborate *ad hoc* oblique rotator models were developed, principally by Deutsch (1956, 1958).

In proposing the oblique rotator model, one must grant at the outset that differential rotation, as in the sun, does not occur; otherwise, the asymmetric pattern of magnetic areas would be rapidly destroyed by shearing. Possibly the strong field provides the internal rigidity to eliminate differential rotation, but it is difficult to maintain this view in the light of evidence for the irregular magnetic variables. Complete rigidity cannot be admitted in any event, since most of the α-variables show random deviations in amplitude or phase. Thus, on the rotator model, some degree of shifting and activity of the surface areas must be presumed.

For an A0 star, having a radius of 2.3 $R\odot$, the equatorial velocity of rotation, v_e, is about $125/P$ km/sec, where P is the period in days. Accordingly, at a wave length of 4300 A, the Doppler broadening by rotation is represented by $w_r = 3.6$ (sin $i)/P$ angstroms.

The strongest support for the oblique rotator hypothesis comes from the finding by Deutsch (1955) that the periods and line widths for many of the spectrum variables correspond fairly well to the inverse period—line-width relationship. But for the α-variables the agreement has not been so good as to be really convincing, as shown by the column headed $3.6/P$ in Table 5. Discrepancies by a factor of 2 occur between the index of line width, w, and the predicted rotational broadening, $3.6/P$, in the sense that the observed line widths are too narrow. Yet the α-variables are sharp-line stars in which sources of line broadening other than axial rotation are important. This difficulty is emphasized by comparing the line widths of the α-variables with those of such γ-variables as HD 133029, 52 Her, and 78 Vir, which also have w in the range 0.1–0.4 A, yet which are, in all probability, nearly pole-on and therefore show little rotational broadening. Further difficulties arise in connection with the irregular (δ) spectrum variables (Table 12). Even for the broader-line A stars, rotational broadening cannot be distinguished from turbulent broadening by large eddies, as shown by Struve and Huang (1952).

In an attempt to verify the oblique rotator hypothesis and to map the magnetic fields and abundance anomalies of the stellar atmosphere, Deutsch (1958) elaborated the model by developing the magnetic potential and the local equivalent widths in spherical harmonics. The Laplace coefficients of these expansions were related to the Fourier coefficients of the observed curves for HD 125248. The solution yielded a model with an axial obliquity of 30° and with various skewed, asymmetric distributions of the magnetic field and of the equivalent widths for the three groups of elements typified by Eu, Cr, and Fe. The comparison of the prediction of the model with the observations appears reasonably satisfactory with regard to the mean magnetic field, equivalent widths, and velocities. But there is little or no indication that the model is capable of accounting for the crossover effect at the phases when $H_e = 0$, or for the purity of the observed polarity in the Zeeman patterns at the phases of maximum field intensity. Further, the model for HD 125248 does not yield entirely acceptable values for the line widths. The contours of magnetic-field intensity required by the model (Deutsch's Fig 9) show values ranging from 8 to 20 kilogauss, with a mean of about 12 kilogauss in the vicinity of the locus of the subsolar point. In a field of 12-kilogauss intensity, the Zeeman broadening for typical lines ($z = 1.4$) amounts to about 0.3 A. If the widening due to axial rotation ($P = 9.3$ days, $i = 30°$), which by itself yields $w_r = 0.2$ A, is taken into account and if some allowance is made for intrinsic line width, the predicted widths are roughly 0.5 A, which is about twice the observed value.

A further difficulty with the model is that, as Deutsch points out, the distribution of equivalent widths is distinctly asymmetric about the equator; all three abundance maxima occur in the unobserved zone of the star. His calculations have shown that if this configuration were observed under an inclination of $i = 150^\circ$, instead of 30°, all three groups of lines would be about four times stronger when averaged over the cycle. The amplitudes of the curves giving H_e and v as functions of phase would be comparable to the values actually observed, but the variation in equivalent width would be less than one-third as great. No magnetic star is known that corresponds to these conditions.

It is significant that no periodic magnetic variable (with the single exception of the 226-day variable HD 188041) shows a field that varies harmonically without reversal of magnetic polarity. All the typical α-variables approach a fair degree of symmetry about the $H = 0$ axis in their reversals. Yet, if all the α-variables of Table 5 plus the broad-line spectrum variables of Table 13 are oblique rotators, we have a total of 16; and on grounds of probability it is to be expected that at least one, with a period less than 10 days, should have sufficiently small axial inclination to yield a harmonically varying effective magnetic field of limited amplitude showing always the same polarity. This evidence favors the view that, when magnetic variables show periodicity, it is the result of some intrinsic physical process, resulting necessarily in reversals of polarity and favoring periods of the order of one week.

There are a number of additional points of evidence, none of them really conclusive, that bear on the interpretation of the periodic magnetic variables. No final decision can be made at present, but it seems that two promising approaches for future work lie in the detailed analysis and explanation of the crossover effect and in the accumulation of more data on the magnetic and spectrum variables with lines somewhat wider than 0.5 A.

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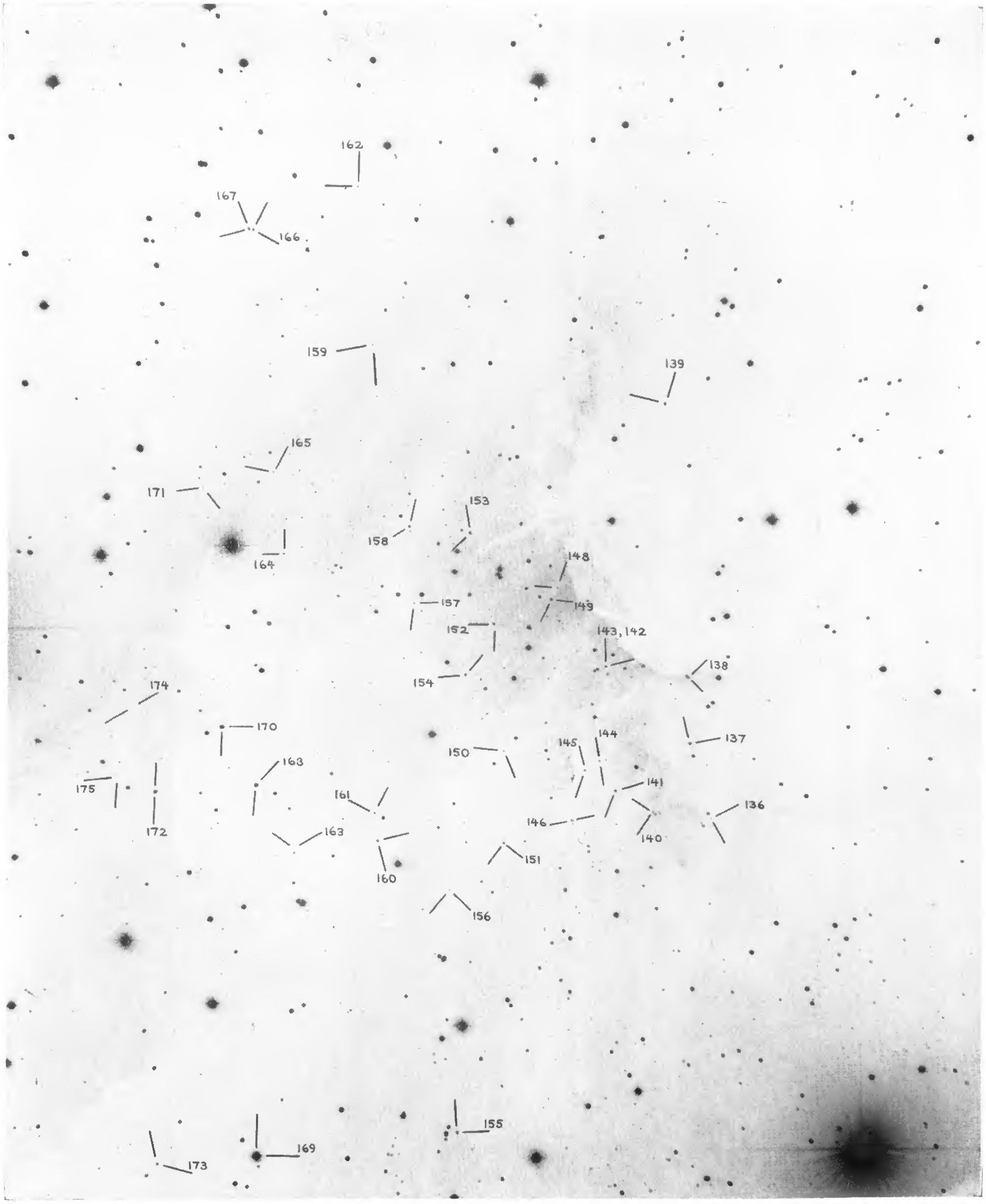

FIG. 1.—The region of IC 5070. Emission-line stars are marked with their LkHα numbers. North is at the top and east to the left. The scale is 1 mm = 58″, and the area shown is 36′ × 44′. The original negative was a 31-minute exposure on a Kodak 103a-O plate with the Crossley reflector.

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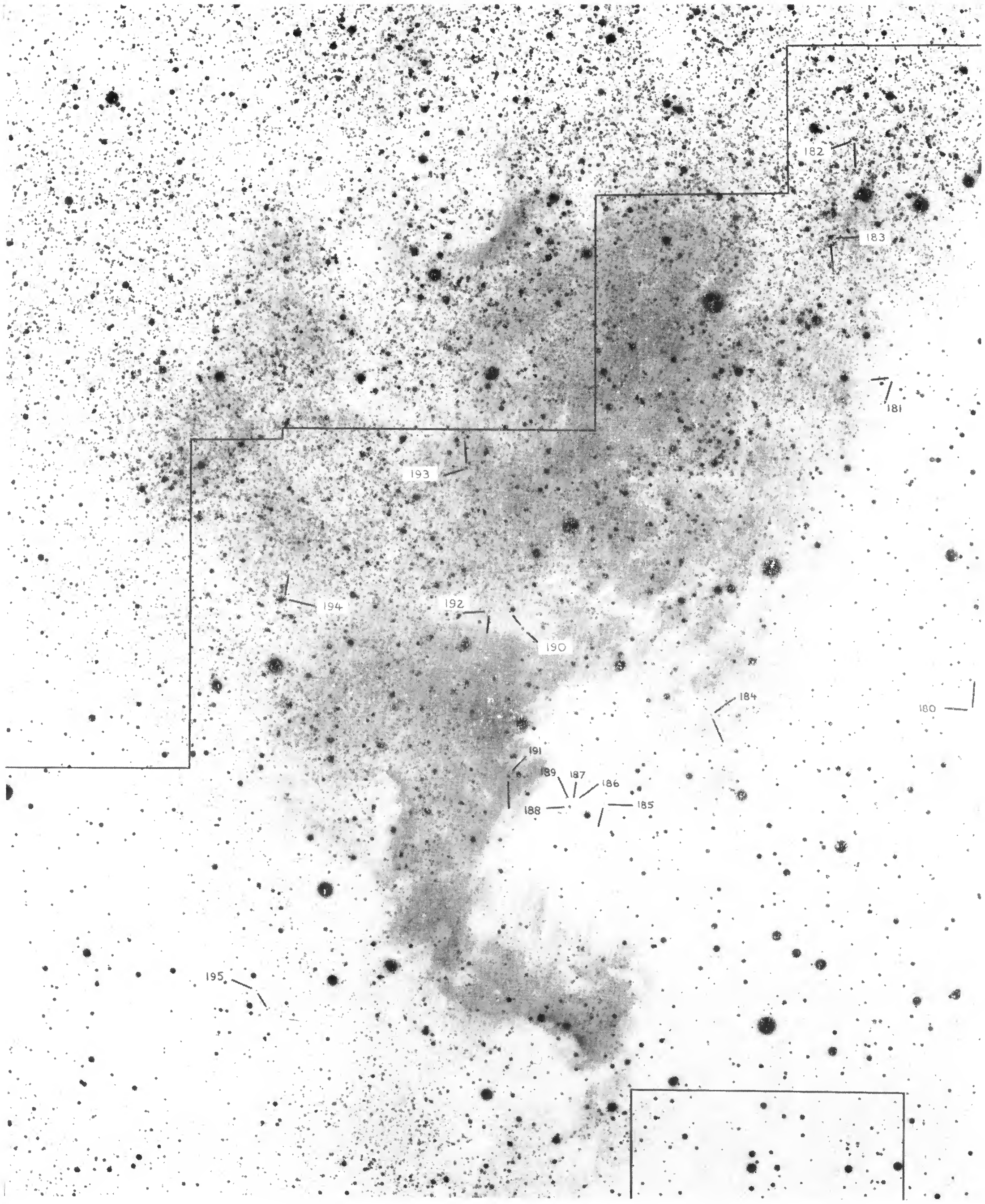

FIG. 2.—The region of NGC 7000. Emission-line stars are marked with their LkHα numbers. The solid lines inclose the area covered in the slitless survey. North is at the top and east to the left. The scale is 1 mm = 58″, and the area shown is 2°.0 × 2°.5. The western edge overlaps with Fig. 3. Both Figs. 2 and 3 are from a 4-hour exposure on a Kodak 103a-O plate taken by Mr. W. W. Shane with the 20-inch Astrograph.

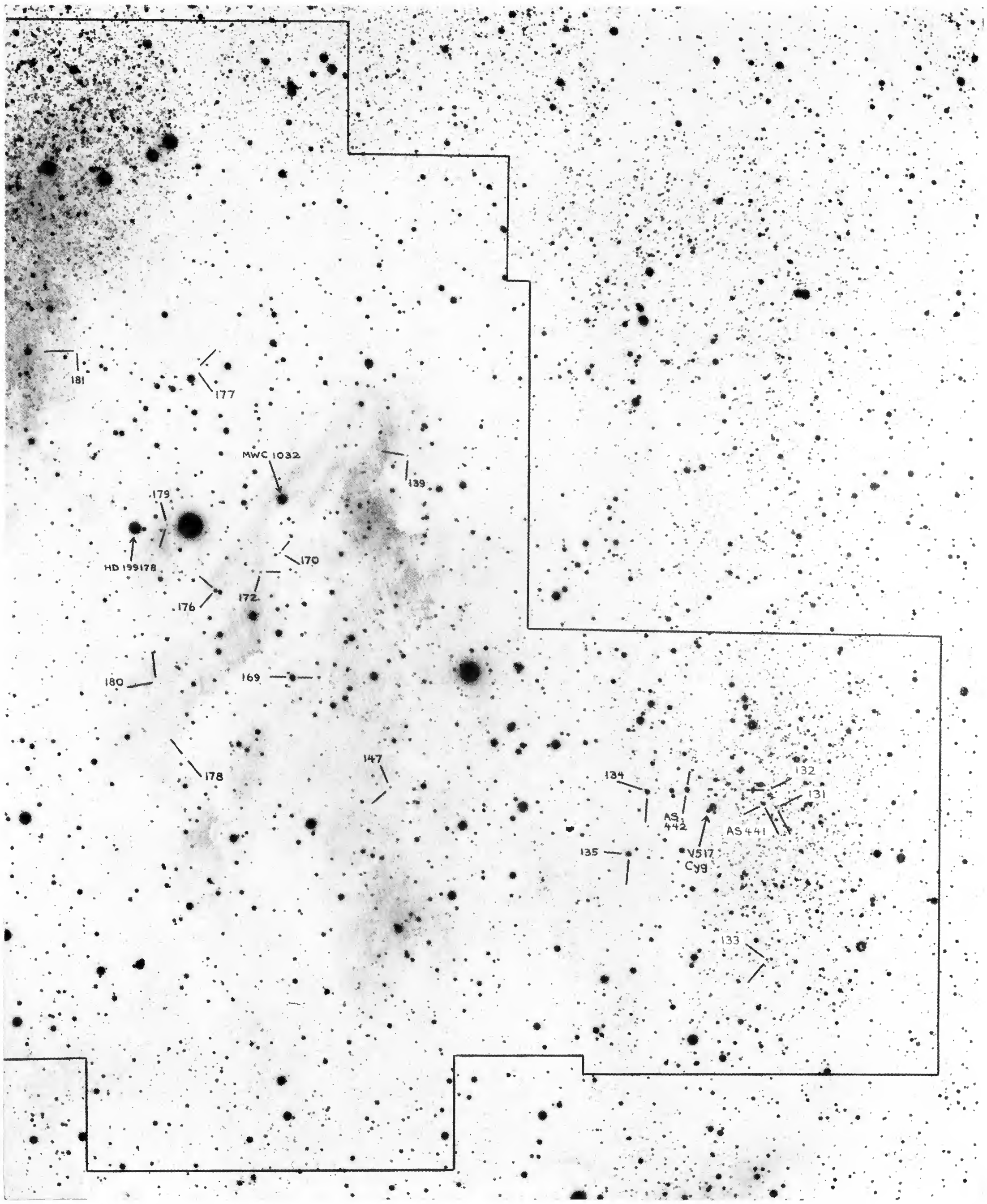

FIG. 3.—The region of IC 5070. Emission-line stars are marked with their LkHα numbers. The solid lines inclose the area covered in the slitless survey. North is at the top and east to the left. The scale is 1 mm = 58″, and the area shown is 2°0 × 2°5. The eastern edge overlaps with Fig. 2. Emission-line stars in the immediate vicinity of IC 5070 are marked in Fig. 1, which shows that area with a larger scale.