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A SEARCH FOR WEAK LONGITUDINAL MAGNETIC FIELDS ON LATE-TYPE STARS

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ABSTRACT

Accurate measurements of the mean longitudinal component of the photospheric magnetic field for 26 late-type stars have been obtained by a multiline Zeeman polarimetric technique. None except those chosen as magnetic standards exhibits clear evidence of a magnetic field, although three show marginally significant polarizations. The multiline Zeeman polarimetric technique is shown to be an extraordinarily sensitive method for the detection of magnetic fields on cool stars.

Subject headings: stars: late-type — stars: magnetic — Zeeman effect

I. INTRODUCTION

The study of stellar magnetic fields developed an early focus on the chemically peculiar A- and B-type stars which frequently exhibit mean longitudinal field strengths of the order of 1 kilogauss. Rather few magnetic observations have been made of late-type stars. Only 36 of the 330 stars in Babcock's (1958) classic catalog of photographic magnetic observations are of spectral type later than F5. Babcock reported fields, typically of a few hundred gauss, in nine of these, including RR Lyr, the Mira variable R Gem, the subdwarf HD 19445, and five M- and S-type giants, but when Preston (1967) subsequently observed several of these stars, he was unable to confirm the presence of fields in any of them. More recently, Boesgaard (1974; see also Boesgaard, Chesley, and Preston 1975) reported weak fields ($\lesssim$300 gauss) in several active, young lower-main-sequence stars, but it appears that zero-point errors in photographic Zeeman polarimetry are severe enough to make it exceedingly difficult to obtain observational standard errors of less than 100–150 gauss (Preston 1969; Landstreet 1980), so that these results must be considered marginal. Photoelectric measurements (Severny 1970; Borra and Landstreet 1973) may have smaller errors, but have so far produced only marginal results. Thus rather little is known about the frequency of occurrence or the typical strength of longitudinal magnetic fields among late-type stars except that such fields must typically be less than a few hundred gauss.

Recently Robinson, Worden, and Harvey (1980) reported line profile measurements of 70 Oph A (K0 V) and ξ Boo A (G8 V) which they interpret as indicators of localized surface fields of the order of kilogauss. Although unconfirmed, these measurements offer more convincing evidence of fields than the marginally significant longitudinal field observations previously available for these stars. However, since such measurements detect surface fields rather than longitudinal fields, they offer little information on the extent of organization of the fields detected.

In this paper we report the development of a new multiline photoelectric technique of Zeeman polarimetry which is very sensitive to weak longitudinal fields. We have equipped the coudé radial velocity spectrometer of the 5 m Hale telescope (Griffin and Gunn 1974) with a polarization modulator to allow polarimetry of some 340 lines simultaneously. This technique permits measurement of a longitudinal magnetic field in a sharp-line K star of B magnitude 5 to a standard error of less than 10 gauss in about an hour of observation. It is thus an exceedingly powerful method of searching for weak longitudinal fields in late-type stars. We have used this technique to carry out a general high-accuracy survey of some 26 late-type stars, achieving errors of less than 20 gauss in 10 of them. In the following section, we discuss the instrument used. In § III, the observation techniques required and the method of data reduction are described. The categories of stars observed and the results obtained are discussed in § IV.

II. INSTRUMENT

The Palomar radial velocity spectrometer (Griffin and Gunn 1974) employs a diaphragm mounted in the focal plane of the 3.7 m camera of the coudé spectrograph followed by a Fabry lens and a photomultiplier. The diaphragm transmits only those parts of the spectrum occupied by absorption lines in the K2 giant α Boo. If the stellar absorption spectrum and the diaphragm are shifted relative to one another, a minimum amount of light is transmitted to the photomultiplier when the two are in registration. Repetitive scanning of the spectrum

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across the diaphragm is accomplished by tilting a plane-parallel fused silica block which is mounted on a motor-driven cam just behind the spectrograph slit. The accumulation of photomultiplier pulses as a function of tilt-block position allows the observation of an average line profile for the ensemble of lines represented on the diaphragm.

Assuming negligible rotational Doppler line broadening, the fractional circular polarization varies across absorption line j according to

$$\frac{V_j(\lambda)}{I_j}=\left(\frac{e}{4\pi mc}\right)z_j\lambda^2 B_e \frac{dI_j/d\lambda}{I_j}, \qquad (1)$$

where z_j is the intensity-weighted average of the displacement of the σ components of the line relative to the "normal" Zeeman displacement, $I_j(\lambda)$ is the spectral line flux profile of line j, and B_e is the effective magnetic field, i.e., the intensity weighted mean longitudinal component. In previous photoelectric Zeeman analyzers, V/I is measured (or sampled) in a single spectral line. In the system described here, we measure the integrated polarization $\boldsymbol{V}/\boldsymbol{I}$ of the approximately 340 metal lines transmitted by the radial velocity spectrometer mask. In this case,

$$\boldsymbol{V}=\frac{e}{4\pi mc}B_e\sum_j z_j\lambda_j^2(dI_j/d\lambda)$$

$$\approx\frac{e}{4\pi mc}B_e\langle z\rangle\langle\lambda^2\rangle\frac{d}{d\lambda}\left(\sum_j I_j\right),$$

and therefore

$$\boldsymbol{V}/\boldsymbol{I}\approx\frac{e}{4\pi mc}B_e\langle z\rangle\langle\lambda^2\rangle\left(\frac{d\boldsymbol{I}/d\lambda}{\boldsymbol{I}}\right), \qquad (2)$$

where we have ignored the dispersion in z (about $\pm 30\%$) and the variation in λ^2 (no more than $\pm 10\%$) in carrying out the averages. Thus a field strength may be extracted from simultaneous measurement of polarization $\boldsymbol{V}/\boldsymbol{I}$ in many spectral lines in essentially the same fashion as in a measurement of a single line, substituting the average line profile $\boldsymbol{I}(\lambda)$ for the individual line profile $I(\lambda)$.

In the instrument described here, an average line profile is first obtained just as in a radial velocity measurement. An auxilliary motor controller then allows the tilt block to be set at any desired position so that the circular polarization may be sampled in each wing of the line profile.

The simultaneous measurement of the wings of some 340 metal lines greatly enhances the signal-to-noise ratio as compared to that obtainable from a single line coudé measurement (e.g., Severny 1970; Borra and Landstreet 1973). The advantage in sensitivity over Cassegrain Balmer-line polarimetry, however, depends upon the sharpness of the metal lines and accordingly is substantially diminished in the case of rapidly rotating stars (Landstreet 1980).

If a nonuniform field is present on a star for which Doppler broadening dominates the line profile, the polarization profile $\boldsymbol{V}(\lambda)/\boldsymbol{I}(\lambda)$ is an intensity-weighted average of the Doppler-shifted contributions from different parts of the stellar disk. Near zero crossing, the polarization profile may be complex, differing considerably from equation (1) (the "crossover" effect; Babcock 1951). In such a case, a polarization measurement which depends upon only two points in the line is seriously undersampled and is likely to yield an inaccurate field strength measurement. Although this consideration is not a serious liability in a survey program, it diminishes the accuracy of the technique for precise measurements near zero crossing.

Instrumental phase shifts and polarization which vary with hour angle are introduced by oblique reflections from the coudé flats. The magnitude of the phase shifts may be estimated from the measurements of Babcock (1962) and of Borra (1976) on the essentially identical three-mirror coudé optics of the Hale and Hooker telescopes, respectively. As these two sets of measurements agree to within 0.05 waves, we have taken their average as the basis for phase compensation and have compensated for the phase shifts using the compensator described by Babcock (1962). The five-mirror coudé system of the Hale telescope, used for declinations greater than +45°, employs three oblique reflections, rather than one, with a total phase shift of nearly 0.5 waves. For such large phase shifts the differences between Borra's (1976) and Babcock's (1962) phase shift measurements are large enough that the compensation is quite uncertain, so we have limited our observations to objects at declinations less than +45°. For declinations less than +10°, the instrumental phase shift is less than 0.05 waves and no compensation was used. Instrumental polarization cannot be compensated out, but is expected to be constant across the line profile $\boldsymbol{I}(\lambda)$. It is, however, time variable, and so we remove it by repeatedly alternating measurements between one line wing and the other.

III. OBSERVATIONS AND DATA REDUCTION

Observations were made on 1979 June 9–11 and on 1979 November 6 and 7. Circular polarization was measured in each wing of the average line profile at points selected for equal residual intensity and maximum profile slope. The effects of instrumental polarization were minimized by the regular alternation between long- and short-wavelength ("red" and "blue") line wings. In order to obtain a prompt check on the time variation of the instrumental polarization, we used the alternation pattern red-blue-blue-red, with a new integration starting about every 5 minutes. Before and after the observations of each star, the operation of the modulator system was checked by inserting an HNCP-37 circular polarizer into the beam.

Each night's observations included the measurement of a known star. The requirement that the magnetic standard stars be cool enough to have an appreciable number of strong neutral metal lines (and thus match the Arcturus mask in the spectrometer) limited the choice of magnetic stars to ones having spectral type of about A5 or later. This was a very severe constraint on possible standards. During the June observations the F0p star β CrB (Preston and Sturch 1967; Wolff and Bonsack 1972; Borra and Vaughan 1977; Borra and Landstreet 1980) was used as a standard; in November the Ap stars γ Equ (Bonsack and Pilachowski 1974; Borra and Landstreet 1980) and HD 24712 (Preston 1972; Bonsack 1979) served as standards.

Reduction of the polarization data involves two steps. The first is a correction for instrumental polarization; the second is the extraction of effective field strength from the corrected line wing polarization. The effect of a constant instrument polarization may be largely eliminated by replacing $V(\lambda)$ in equation (2) with 1/2 $(V_{\rm red} - V_{\rm blue})$. Because the instrumental polarization varied significantly during many of the observations, however, a more careful treatment of the data was required.

For the integration times used in these measurements ($\sim 50^{\rm m}$), the instrumental polarization was observed to vary approximately as a linear function of hour angle. In the case of a nonmagnetic star, all the data from both line wings are scattered about a single instrumental polarization line. The effect of a magnetic field is to displace the red and blue wing polarization data from the zero-field line by equal amounts of opposite sign. As a result, the data are best fitted by a pair of lines having the same slope but y-intercepts which differ by twice the polarization induced in either line wing.

Accordingly, all the data were reduced by a uniform procedure whereby the red and blue wing polarization measurements were separately fitted by a least-squares method to a pair of lines constrained to have the same slope. As an example, Figure 1 shows the data obtained in one measurement of the magnetic standard β CrB, together with the best-fit lines. In all cases the formal uncertainty in the separation of the least-squares lines equals the uncertainty in the difference between average line-wing polarizations $\langle V_{\rm red} \rangle - \langle V_{\rm blue} \rangle$, as expected.

For the α Boo mask used in the Palomar radial velocity spectrometer, we used $\langle \lambda^2 \rangle \approx \langle \lambda \rangle^2 = (4612\ \text{Å})^2$. The average z value of a random sample of 33 lines is $\langle z \rangle = 1.28 \pm 0.07$ with a dispersion of individual lines around this value of 0.39. With these values, equation (2) reduces to

$$B_e = 7.88 \times 10^2 \frac{(V/I)}{(dI/d\lambda)/I}, \qquad (3)$$

for B_e in gauss, line gradients in Å^{-1}, and V/I in percent polarization.

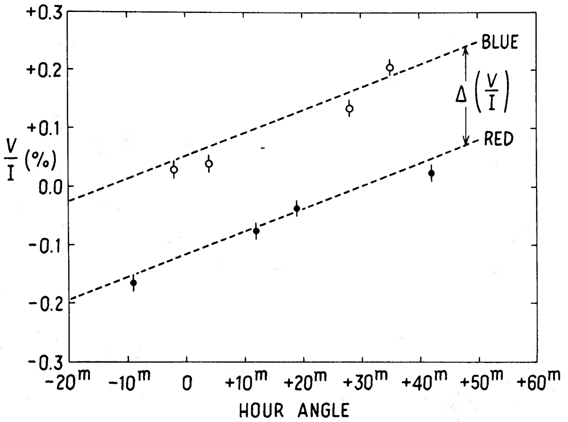

FIG. 1.—Observed line-wing circular polarization of β CrB vs. hour angle. Open circles refer to the blue wing of the average line profile, the closed circles to the red wing. The dashed lines are the best-fit instrument polarization curves.

IV. RESULTS

All observations of magnetic standard stars are given in Table 1. Successive columns list for each star observed the HD number, name, spectral type, blue magnitude m_B (in the UBV system), Julian date at the midpoint of observation, phase of the observation calculated from the best ephemeris available, integration time Δt, normalized line wing slope $(dI/d\lambda)/I$, polarization to field strength conversion factor $\gamma = B_e/(V/I)$ from equation (3), value of χ^2/ν for the pair of lines which are the best fitted to the observed polarization values, and effective magnetic field strength B_e calculated from the observed polarization with the tabulated γ value. The standard error σ given for B_e is calculated from photon statistics. If the scatter of polarization measurements about the best-fit line pair is larger than that expected from counting statistics at the 95% confidence level, a more conservative estimate of σ is given in parentheses which is larger than the first estimate of σ by $(\chi^2/\nu)^{1/2}$.

A comparison of our magnetic observations of β CrB with the photographic observations of Preston and Sturch (1967) and the Hβ observations of Borra and Landstreet (1980) is shown in Figure 2. It is clear that our data are in general agreement with previous measurements, as we find the field of β CrB to be going through positive crossover with about the right slope. A small displacement in phase between our measurements and earlier ones is probably due to the uncertainty of the present period, which renders all phases uncertain by at least ~ 0.03 cycles. Deviation of our data from the shape of magnetic curves measured previously probably reflects the fact that we are undersampling a complex

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TABLE 1

OBSERVATIONS OF KNOWN MAGNETIC STARS

HD	Name	Spectral Type	m_B	JD (244,000+)	ϕ	Δt (min)	$(dI/d\lambda)/I$ (Å^{-1})	γ (kilogauss/1%)	χ^2/ν	$B_e \pm \sigma$ (gauss)
137909	β CrB	F0 SrCrEu	3.92	33.767	0.951	52	0.363	2.17	1.43	-183 ± 11
				34.768	0.005	49	0.357	2.21	2.69	$-58 \pm 11(18)$
				35.770	0.059	42	0.342	2.31	1.30	$+255 \pm 13$
201601	γ Eqn	A5 SrCrEu	4.93	183.714	...	48	0.231	3.41	1.38	-644 ± 29
24712......	...	A5 SrCrEu	6.32	183.922	0.40 ± 0.12	51	0.180	4.38	1.07	$+96 \pm 44$

polarization profile (cf. Borra and Vaughan 1977) at precisely the phase when it is most complicated.

The variation of the field of γ Equ is very poorly understood and it may vary on an extremely long period (several decades; Bonsack and Pilachowski 1974). Our measurement of γ Equ is consistent with that found in recent Hβ observations by Borra and Landstreet (1980), who observed field strengths ranging between -210 and -660 gauss during 1976–1978. Measurement of HD 24712 was impeded by a very shallow line profile. Our result is significantly lower than the value of $+400$ gauss given by the magnetic curve found by Preston (1972) for Fe, Ti, and Cr lines (our phase is calculated from the recently improved period found by Bonsack 1979). For both stars, however, our results are of the right sign and general magnitude, and the discrepancies are no larger than those usually found between various different methods of field measurement (cf. Landstreet 1980). We conclude that our measuring technique is as sensitive to the presence of longitudinal fields as we believe, and although it is not clear that it is an extremely accurate means of *measuring* a nonzero longitudinal field (because of undersampling, etc.), it is certainly an excellent way to *detect* such a field.

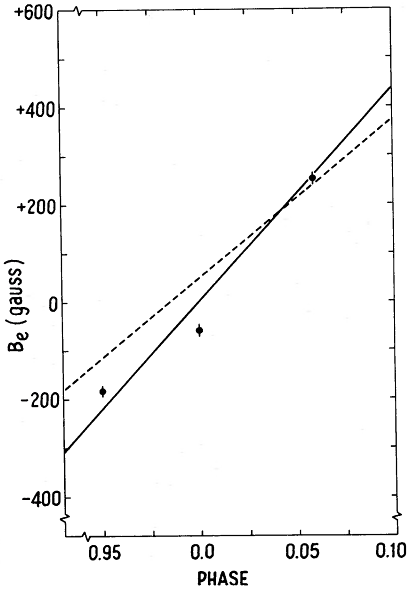

FIG. 2.—Measured magnetic field of β CrB. Solid line is the magnetic curve from Preston and Sturch (1967) derived from lines of Fe, Ti, and Cr. The dashed line shows the magnetic curve from Borra and Landstreet (1980), derived from photoelectric observations of line-wing circular polarization in Hβ. The phases of the three measurements are determined from an assumed period ($18^{\text{d}}.4881$) which is consistent with that found by Preston and Sturch ($18^{\text{d}}.487 \pm 0.002$) and matches the zero crossings of their measurements and ours.

Observations of program stars are listed in Table 2 in a format very similar to that of Table 1. Stars are grouped by classification type and within groups are listed in order of HD number or right ascension. The Table lists all stars observed by us, including five for which no integrated absorption line was detected, probably because of very rapid rotation of the star. Rotational line broadening reduced considerably the efficiency of a number of the measurements reported here: for sharp-line stars the observed value of $(dI/d\lambda)/I$ is about 0.9–1.3 Å^{-1} but in some stars the value drops as low as 0.13, which greatly increases γ and results in measurements of low accuracy.

Two cool stars reported by Babcock (1958) to be magnetic were observed. For HD 4174, 90% of Babcock's plates show fields large enough (up to 1200 gauss) to be easily detected by our technique, but our measurement is a null. For AG Peg, the field reported by Babcock is typically 300–600 gauss with kilogauss fields found on only 2 of 15 plates; our error is too large (173 gauss) to be sure of detecting such a field.

Eight stars were observed because of the presence of strong Ca^+ K line emission, indicative of an active chromosphere (Wilson 1963) or of strong He λ10830, which suggests a strong corona (Zirin 1976). Because of a good match with the Arcturus mask and sharp absorption lines, these two groups of stars contain most of our best measurements, all with standard errors of less than 20 gauss. Recently Robinson, Worden, and Harvey (1980) have observed strong surface fields of about 2500 gauss covering ~30% of ξ Boo A and of up to about 1800 gauss on 10% of 70 Oph A. We find no significant longitudinal field on ξ Boo A and only a 2 σ result for 70 Oph A; clearly the fields on these stars show a large degree of cancellation over the visible hemisphere and must be fairly complex in geometry.

There is considerable evidence (Hall 1976) that some of the photometric variations of the RS CVn binaries, their long- and short-period relatives, the dMe flare

TABLE 2

MAGNETIC OBSERVATIONS OF COOL STARS

HD	Name	Spectral Type	m_B	JD (244,000+)	Δt (min.)	$(dI/d\lambda)/I$ (Å^{-1})	γ (kilogauss/1%)	χ^2/ν	B_e (gauss)	Notes
Babcock Late-Type Magnetic Stars										
4174........	...	M2ep	8.7	4183.827	51	0.944	0.84	0.95	−44±33	...
	AG Peg	Bep+M	9	4034.910	51	0.294	2.68	0.45	−51±173	...
Dwarfs with Strong *K*-Emission										
131156......	ξ Boö A	G8V	5.32	4035.644	46	0.660	1.19	0.22	+1±12	c, e, f
131977A ...	...	K5V	6.89	4033.707	47	1.28	0.62	0.79	+5±11	c
165341......	70 Oph A	K0V	4.98	4033.823	40	0.893	0.88	0.76	−16±7	a, e, f
201091......	61 Cyg A	K5V	6.43	4035.889	38	1.03	0.77	0.42	+14±14	c, d
Giants with Strong λ10830										
173764......	β Sct	G7II	5.30	4033.867	43	1.17	0.67	1.29	+3±6	a
174974......	ν^1 Sgr	cK2	6.23	4033.909	40	1.28	0.62	0.99	−16±11	...
207089......	12 Peg	K0Iab	6.67	4184.702	43	1.05	0.75	0.54	−11±15	a
218356......	56 Peg	K0Ibp	6.06	4034.975	51	1.37	0.58	0.38	−15±10	a
RS CVn and Related Binaries										
4502........	ζ And	K1III	5.18	4183.760	52	0.257	3.07	2.05	−46±21(31)	a, b
13480A	6 Tri A	G5III	5.72	4184.755	56	0.181	4.35	1.50	+163±72(88)	b
21242.......	UX Ari	K0IV	7.3	4184.897	...	0.0	...	...	...	k, l
22468.......	V711 Tau A	dG9	6.80	4183.876	48	0.135	5.84	0.53	−58±70	k, l
62044.......	σ Gem	K1III	5.40	4184.043	51	0.361	2.18	9.41	+61±86(266)	a, b, g
114519......	RS CVn	K0	8.88	4035.688	...	0.0	...	...	...	a
133640......	44i Boö	dGI	5.41	4034.819	44	0.459	1.72	0.37	+10±23	i
163930......	Z Her	F4IV-V	7.7–8.5	4035.835	47	0.144	5.47	1.28	+52±150	a
200391......	ER Vul	G5V	7.87	4034.857	...	0.0	...	...	...	a, h
210334......	AR Lac	sgK0	7.8–8.6	4034.942	...	0.0	...	...	...	a, k
216489......	...	K1IV–IIIp	6.81	4033.967	62	0.528	1.49	1.64	−22±30(38)	g
222107......	λ And	G8III–IV	4.76	4035.978	43	1.02	0.77	1.31	+15±6	a, b, d, g
dMe Flare Stars										
118100......	EQ Vir	dK5	10.52	4034.718	48	0.905	0.87	2.62	−10±68(110)	...
197481......	Gliese 803	M0Ve	10	4035.935	35	0.489	1.61	0.36	−4±160	...
T Tau and Related Stars										
284419......	T Tau	K0IV, Ve	11.39	4183.986	50	0.318	2.48	0.58	+62±272	d
	V1515 Cyg	G0–2Ib	14	4184.644	63	0.555	1.42	5.78	−384±1220(2930)	j
	V1057 Cyg	G2–5Ib	16.7–17.7	4183.601	...	0.0	...	...	...	j
Subdwarfs										
103095......	Groombridge 1830	G5V	7.18	4034.671	31	0.484	1.63	0.49	−3±41	d
140283......	...	F5	7.73	4035.797	...	0.0	...	...	...	...
Normal Dwarfs										
131977B ...	...	M2V	8.47	4035.723	43	0.309	2.55	2.03	−4±153(218)	...

[a] Strong Ca II *K*-emission.

[b] Strong He I λ10830 absorption.

[c] Weak He I λ10830 absorption.

[d] Babcock 1958, Table 3, i.e., "little or no evidence of magnetic field."

[e] Boesgaard 1974 reports magnetic detection.

[f] Robinson *et al.* 1980 report magnetic detection.

[g] Long-period RS CVn-type.

[h] Short-period RS CVn-type.

[i] W U Ma-type.

[j] FU Ori-type.

[k] Radio source.

[l] Soft X-ray source.

stars, and the W UMa binaries result from the presence of large cool spots like sunspots on the cooler component. Recently Mullan (1979) has shown that because of the cancellation between regions of opposite polarity and darkening in the spot, even rather strong spot fields (10^4 gauss) are likely to result in longitudinal fields of at most 200–300 gauss. Our observations are the first which might have been expected to detect such fields. We have 2 σ results for 6 Tri A and λ And and nulls for the other stars observed.

Several lines of evidence (Herbig 1962; Wilson 1963; Gershberg 1977) suggest that T Tau stars and their relatives may have substantial magnetic fields. Zeeman effect measurements of V1057 Cyg in the 1720 MHz OH maser line during a recent outburst (Andersson *et al.* 1979) have been interpreted as indicating a 6 kilogauss field. Our observations of such stars were greatly constrained both by their intrinsic faintness and by poor weather.

Babcock (1958) reported a field of $B_e = 415 \pm 178$ (s.d.) on one plate of the subdwarf HD 19445. For this reason we observed two subdwarfs, only one of which had a usable integrated absorption line. No field was detected.

Three of the stars observed for which no field was detected, σ Gem, EQ Vir, and V1515 Cyg, nevertheless perhaps deserve further observation as the data were significantly overdispersive. This also occurred for our observation of β CrB nearest to crossover, and it may be that significant surface fields are present in these stars. We note that each of these stars was observed at about the same hour angle and declination as another star for which the data are not overdispersive, so we do not believe that instrumental polarization or compensation errors are involved.

V. SUMMARY

We have obtained accurate measurements of the mean longitudinal component of photospheric magnetic field for 26 late-type stars of diverse characteristics. None except those chosen as magnetic standards exhibits clear evidence of a magnetic field, although three show marginally significant polarizations. The data for three others have an overdispersive character similar to that observed on the measurement of β CrB at zero crossing, and we suggest that the overdispersiveness may be attributable to the undersampling of line profiles complicated by the crossover effect of strong, but geometrically complex, magnetic fields.

The photoelectric technique employed here appears to be free of the zero point and biasing errors which afflict the photographic measurements of weak fields. Thus, we conclude that on all the stars measured, magnetic fields are either absent, very weak, or of such complex geometry that the mean longitudinal field is very small in comparison to the surface field, as is probably the case for RS CVn stars.

The multiline Zeeman polarimetric technique described here is seen to be an extraordinarily sensitive method for measuring effective fields. Contrary to early expectations (Babcock 1962), it appears that stars of a wide variety of spectral types may be measured with a single diaphragm, so that the instrument is both a versatile and powerful probe of stellar magnetic fields.

We are pleased to acknowledge the numerous people who encouraged us to make these observations and suggested stars to be observed, especially Drs. P. Bastien, B. W. Carney, L. B. Lucy, S. M. Ruciński, and H. Zirin. Drs. R. F. Griffin, J. E. Gunn, and Ms. Barbara Zimmerman were extremely helpful to us in all matters concerning the Palomar radial velocity spectrograph system; these observations could not have been carried out without their cooperation and assistance. Dr. H. W. Babcock kindly loaned us his compensator. This research has been supported by the National Sciences and Engineering Research Council of Canada.

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