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A SEARCH FOR MAGNETIC FIELDS IN NORMAL UPPER–MAIN-SEQUENCE STARS

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ABSTRACT

A search has been carried out for magnetic fields of the order of 10^2 gauss in 31 normal O9.5–F6 upper–main-sequence stars and 5 Am stars by measuring the circular polarization of the wings of single spectral lines of hydrogen, helium, or iron with a Cassegrain filter polarimeter or with a coudé line-profile scanner polarimeter. The reduction formula used to infer longitudinal magnetic fields from such polarization measurements is discussed, and is shown in a simple analytical approximation to be essentially unaffected by a nonuniform magnetic field distribution and by instrumental broadening, although it is sensitive to rotational broadening. Simple expressions are found for estimating the time required to obtain a magnetic field measurement of specified accuracy for a particular star with a particular Zeeman analyzer, and for estimating the measurement accuracy available from a photographic magnetic measurement on a plate of given dispersion and widening. These expressions are used to select the best helium and metal lines for single-line magnetic measurements of upper–main-sequence stars. Measurements of the magnetic field of α^2 CVn, 78 Vir, and β CrB using lines of Fe^+ are shown to be in reasonable agreement with Balmer-line measurements in spite of a simplified measuring procedure and approximate reduction scheme.

No magnetic fields are detected in any of the stars surveyed. The smallest standard error reached is 7 gauss, and the median error is about 65 gauss. It is clear that the measurement methods employed are not subject to serious zero-point errors, and it appears that longitudinal fields of more than 150 gauss are not common in upper–main-sequence stars.

Subject headings: stars: early-type — stars: magnetic

I. INTRODUCTION

All the well-established magnetic fields known in upper–main-sequence stars are found in Ap (Si or Sr-Cr-Eu) or Bp (He-weak or He-rich) stars. The observed longitudinal fields range from about 2×10^4 gauss in HD 215441 (Borra and Landstreet 1978) down to about 3×10^2 gauss in ν For, τ^9 Eri, and θ Aur (Borra and Landstreet 1980). At least some Ap stars, such as ε UMa, have longitudinal fields of less than about 1×10^2 gauss, below the present limit for field detection in any but very bright stars using either photographic or single-line photoelectric detection techniques. The spectral types of stars in which fields are found range from B2 for the He-rich magnetic stars (Borra and Landstreet 1979) to F0 for cool Ap stars such as β CrB.

It is not obvious that the small fraction ($\sim 7\%$) of upper–main-sequence stars that are classified Ap or Bp differ in fundamental structure from normal upper–main-sequence stars, although they show on average considerably slower rotation, atmospheric abundance anomalies, and, in most cases, magnetic fields. It is thus of interest to investigate whether some normal upper–main-sequence stars perhaps possess fields of smaller magnitude than those found in Ap and Bp stars.

The existence of fields in some upper–main-sequence stars that are not obviously peculiar is suggested by two lines of argument. The first is based on the widespread view that most or all stars above a limiting mass, or in a range of masses, become pulsars; current birthrate statistics suggest that the observed number of pulsars could be produced, for example, from stars of main-sequence mass $M \gtrsim 7\ M_\odot$, or from stars in the range of perhaps $5\ M_\odot \lesssim M \lesssim 8\ M_\odot$ (Shipman and Green 1980) if all the stars in the chosen mass range become pulsars. Stars in this mass range are B stars when on the main sequence. For a star to become a pulsar, it needs to develop a magnetic field of $\sim 10^{12}$–10^{13} gauss when it becomes a neutron star. If such pulsar fields are fossil magnetic fields, amplified by collapse, then internal fields of $\sim 10^2$–10^3 gauss should be common in the main-sequence stars that evolve to the neutron star state. It should

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be borne in mind, however, that pulsar fields could form in some as yet unknown manner during later evolutionary stages (cf. Ruderman 1972).

The existence of magnetic fields in some nonpeculiar upper–main-sequence stars is also implied by an hypothesis for the formation of Ap stars put forward by Strittmatter and Norris (1971) on the basis of theoretical work by Mestel and others. In this hypothesis, stars are assumed to form from the interstellar medium with varying ratios of magnetic to rotational energy. If this ratio is below a critical value, it is suggested that meridian circulation currents will drag the field lines below the surface of the star, so that the star remains a rapid rotator, shows no detectable surface field, and does not develop atmospheric abundance anomalies. If the ratio is above the critical value, however, meridian circulation will not be able to bury the field, and the field will enable the star to lose angular momentum either via a wind (Mestel 1968) or by interaction with the interstellar medium (Havnes and Conti 1971). When the star has slowed sufficiently (requiring a time of $\sim 10^7$–10^9 yr), field lines will close off, probably stabilizing at least parts of the atmosphere against further mass loss and mixing. Strittmatter and Norris (1971) suggest that atmospheric abundance anomalies will develop as a result of gravitational diffusion (Michaud 1980) only in regions where mass loss or accretion has been choked off. On this hypothesis, a star that is destined to become an Ap or Bp star could exhibit a detectable magnetic field for some time before it becomes a slow rotator with surface abundance anomalies.

Magnetic observations reported in the literature shed little light on the possible existence of fields of a few hundred gauss or less in normal upper–main-sequence stars. Babcock (1958) observed photographically 14 main-sequence or subgiant stars of spectra earlier than F6. He reported a field of -390 gauss on one plate of γ Vir N (F0 V). A field is listed as probable but not certain for δ Cet (B2 IV), and the other 12 stars showed no obvious evidence of Zeeman splitting. For the one measured plate of γ Vir N, Babcock's standard error is probably at least 150–200 gauss (Preston 1969), so the reported field detection is not a strong result. The plates of the 12 nonmagnetic stars and δ Cet seem to have been examined visually but not measured; they probably set limits no smaller than 500 gauss on any fields that may be present.

More limited surveys at higher precision have been carried out. Severny (1970) used a photoelectric system similar to a solar magnetograph and reported standard errors of 12–15 gauss. He observed no fields in α Lyr (A0 V) or α CMi (F5 IV) but reported a field of up to 38 gauss in α CMa. The field of α CMa, however, was subsequently not detected by Borra, Landstreet, and Vaughan (1973) or by Borra (1975). Boesgaard (1974), using a photographic Zeeman analyser, reported a field ranging between -330 and $+436$ gauss, with a typical value of 2–300 gauss, on a series of 10 plates of γ Vir N, in agreement with Babcock's (1958) initial report of a field in this star. These results must still be regarded as being somewhat uncertain, however, as only 1 of the 10 plates shows a field significantly larger than 3 standard errors, and it is not entirely clear that the errors reported ($\sigma \sim 90$–190 gauss) may not be somewhat underestimated. Boesgaard, Chesley, and Preston (1975) find no field in four plates of ι Peg (F5 V), with $\sigma_B \sim 75$ gauss.

Observations of a number of O and B stars have been reported by several authors (Conti 1970; Kemp and Wolstencroft 1973; Borra and Landstreet 1973; Borra 1974; Rudy and Kemp 1978; Wolstencroft, Smith, and Clarke 1981), but measurement errors are typically several hundred gauss and no really definite field detections have yet emerged.

The magnetic observations reported so far thus do not offer much information beyond suggesting that fields in nonpeculiar upper–main-sequence stars are not commonly much greater than ~ 500 gauss, and in a few cases are probably less than 50 gauss. To obtain further data bearing on this problem, I have carried out a systematic magnetic survey of a sample of upper–main-sequence stars in the range O9.5 to F6. (The upper spectral type limit was set by the availability of bright stars; the lower limit was set by the appearance of deep convective envelopes which lead to a type of stellar structure substantially different from that of the upper–main-sequence.) The magnetic observations were obtained with photoelectric Zeeman analyzers. Measurements were made using iron or helium lines for sharp-lined stars, as has been done previously by Severny (1970) and Borra and Landstreet (1973), and using Hβ for more rapidly rotating stars, as discussed, for example, by Borra and Landstreet (1980). Both techniques are quite sensitive when used on bright stars, and measurement errors of typically 40–100 gauss were obtained. The most accurate observations have errors of less than 10 gauss. This paper discusses the measuring techniques and reduction procedures used, the observations obtained, and the instrumental and astrophysical conclusions that follow from the results of the survey.

II. MEASURING TECHNIQUES

In the work reported here, magnetic observations have been made using both a Balmer-line Zeeman analyzer (Borra and Landstreet 1980) and a two-channel coudé line-profile scanner, equipped with a polarization modulator in front of the spectrograph slit, operating as a high-resolution Zeeman analyzer (Borra and Landstreet 1973). In this section, we first examine the expression (eq. [2] below) generally used to derive from photoelectric circular polarization measurements in absorption-line wings the effective magnetic field responsible for the observed effect. This expression applies, at least approximately, to the local emergent specific intensity from a point on the visible disk of the star. The concern here is to examine what complications occur because the observed polarization arises from an extended, rotating stellar hemisphere with a nonuniform, longitudinal surface field, and what the effect is of the profile degradation that occurs because of observation with a (sometimes all too) finite wavelength resolution. We want, in other words, to explore how far simple expressions may be trusted for data reduction, and what their fundamental limitations are for this purpose.

The simple reduction formula will then be used to derive approximate expressions that permit estimates to be made of the standard error of measurement that may be obtained from a magnetic observation of a particular star with a specific instrument. These expressions were used to guide the choice of the spectral lines used in magnetic measurements with the high-resolution Zeeman analyzer.

Unno (1956) has obtained a solution to the four coupled equations of transfer that apply when polarized light is present, using the Milne-Eddington approximations [the source function is approximated by $S(\tau)=B_0(1+\beta\tau)$, where τ is the continuum optical depth, and B_0 and β are constants; the ratio η of line to continuous opacity is independent of depth]. For a spectral line in which the π-σ Zeeman separation, $\Delta\lambda_B = zeB\lambda^2/4\pi mc^2$, due to a magnetic field of field strength B is small compared to the intrinsic (thermal or pressure broadening) width $\Delta\lambda_i$, and the line splitting can be approximated by triplet splitting (i.e., the π and σ components of the line are split into subcomponents separated by rather less than $\Delta\lambda_B$), Unno points out that the π, σ_-, and σ_+ opacity ratios may be written approximately as $\eta_\pi=\kappa_\pi/\kappa=\eta(\lambda)$, $\eta_{\sigma-}=\eta(\lambda-\Delta\lambda_B)\approx\eta(\lambda)-\Delta\lambda_B\eta'$, and $\eta_{\sigma+}\approx\eta(\lambda)+\Delta\lambda_B\eta'$, where $\eta'=d\eta/d\lambda$. In this case, Unno's approximate solutions for the local emergent intensity $I(\lambda)$ and the circular polarization $V(\lambda)$ Stokes components are given by

$$I(\lambda,\theta)=B_0\left[1+\beta\cos\theta(1+\eta)^{-1}\right], \tag{1}$$

and

$$V(\lambda,\theta)=B_0\beta\cos\theta\Delta\lambda_B\cos\psi\eta'(1+\eta)^{-2},$$

$$=\Delta\lambda_B\cos\psi\, dI(\lambda,\theta)/d\lambda, \tag{2}$$

where ψ is the angle between the magnetic field vector and the line of sight, and θ is the angle between the local surface normal and the line of sight. When spatially unresolved light from a star is observed, equations (1) and (2) must be integrated over the visible hemisphere. In general this will involve two major complications. First, the polarization profiles $V(\lambda,\theta)$ from various parts of the disk will be Doppler shifted relative to one another by stellar rotation. Second, the angle ψ and magnitude of $\Delta\lambda_B$ will in general vary over the visible stellar disk. To obtain simple analytical expressions, we are forced to completely ignore the first of these effects, thus assuming that the velocity broadening of the line, $\lambda v/c$, is small compared to $\Delta\lambda_i$. In this case, the average Stokes intensity and circular polarization components, integrated over the star's visible hemisphere, are given by (Pecker 1965)

$$\bar{I}=\frac{1}{\pi}\int_0^{2\pi}d\phi\int_0^{\pi/2}\cos\theta\sin\theta I(\lambda,\theta)\,d\theta, \tag{3}$$

and

$$\bar{V}=\frac{1}{\pi}\int_0^{2\pi}d\phi\int_0^{\pi/2}\cos\theta\sin\theta\Delta\lambda_B\cos\psi(\theta,\phi)[dI(\lambda,\theta)/d\lambda]\,d\theta, \tag{4}$$

where the integrals are taken over spherical polar coordinates ϕ (azimuth measured around an axis parallel to the line of sight that passes through the center of the visible disk) and θ (colatitude measured from the same axis, hence the same θ that appears in eqs. [1] and [2]). From equations (1) and (3), we see that in the Unno approximation

$$d\bar{I}/d\lambda=\tfrac{2}{3}\left[-B_0\beta\eta'(1+\eta)^{-2}\right].$$

Then, from equation (4),

$$\bar{V}=\left(\frac{ze\lambda^2}{4\pi mc^2}\right)\frac{1}{\pi}\int_0^{2\pi}d\phi\int_0^{\pi/2}\cos\theta\sin\theta\,(B\cos\psi)\left[-B_0\beta\cos\theta\,\eta'(1+\eta)^{-2}\right]d\theta,$$

$$=\left\{\frac{2}{3}\left[-B_0\beta\eta'(1+\eta)^{-2}\right]\right\}\left[\frac{ze\lambda^2}{4\pi mc^2}\frac{3}{2\pi}\int_0^{2\pi}d\phi\int_0^{\pi/2}\cos\theta\sin\theta\,(B\cos\psi\cos\theta)\,d\theta\right],$$

$$=(ze\lambda^2B_l/4\pi mc^2)(d\bar{I}/d\lambda),$$

$$=\Delta\lambda_l(d\bar{I}/d\lambda). \qquad (5)$$

Here we have defined a line-strength weighted effective field,

$$B_l=\frac{1}{\pi}\int_0^{2\pi}d\phi\int_0^{\pi/2}\cos\theta\sin\theta\left(\frac{3}{2}\cos\theta\,B\cos\psi\right)d\theta,$$

which is more strongly weighted toward the center of the stellar disk than the usual (limb-darkening weighted) effective field,

$$B_e=\frac{1}{\pi}\int_0^{2\pi}d\phi\int_0^{\pi/2}\frac{\cos\theta\sin\theta(1+\beta\cos\theta)(B\cos\psi)}{1+2\beta/3}d\theta;$$

in fact, B_l is the limit of B_e as β becomes arbitrarily large. This unfamiliar weighting reflects the fact that a longitudinal field measured by the Zeeman effect in a spectral line will sample the field much more strongly at the disk center, where the line is strong, than at the limb, where the line vanishes. Equation (5) is thus identical in form to equation (2) except that the $\Delta\lambda_B\cos\psi$ factor is replaced by a Zeeman splitting factor $\Delta\lambda_l$ that is evaluated with the aid of an appropriately weighted effective (longitudinal) magnetic field B_l.

Note that if equations (3) and (5) are valid for the integrated line profile emitted toward the observer by the star, they are also valid for the line profile as observed through an instrumental broadening function $F(\lambda-\lambda')$. The observed quantities $\bar{I}_0$ and $\bar{V}_0$ are given by

$$\bar{I}_0=\int F(\lambda-\lambda')\bar{I}(\lambda')\,d\lambda',$$

and

$$\bar{V}_0=\Delta\lambda_l\int F(\lambda-\lambda')[dI(\lambda')/d\lambda']\,d\lambda',$$

so that

$$d\bar{I}_0(\lambda)/d\lambda=\int[dF(\lambda-\lambda')/d\lambda]\bar{I}(\lambda')\,d\lambda',$$

$$=-\int[dF(\lambda-\lambda')/d\lambda']\bar{I}(\lambda')\,d\lambda',$$

$$=\int F(\lambda-\lambda')[d\bar{I}(\lambda')/d\lambda']\,d\lambda',$$

and

$$\bar{V}_0(\lambda)/\bar{I}_0=\Delta\lambda_l(d\bar{I}_0/d\lambda)/\bar{I}_0, \qquad (6)$$

where we have done an integration by parts and used the fact that $F(\lambda-\lambda')$ goes to zero for large values of $|\lambda-\lambda'|$.

Thus we find that equation (6), which has generally been used to interpret photoelectric Zeeman polarization measurements (e.g., Borra and Landstreet 1973, 1980), is approximately valid even in the presence of a nonuniform magnetic field and instrumental line broadening, but with three important restrictions. (1) The Zeeman splitting $\Delta\lambda_B$ must be small compared to the *local* intrinsic line width $\Delta\lambda_i$ (not the rotational velocity broadened line width), since once $\Delta\lambda_B > \Delta\lambda_i$ occurs locally, the polarization produced in a line wing at a single point on the stellar surface increases less rapidly than $\Delta\lambda_B$, and the original Taylor expansion used to derive equation (2) is not correct. For a typical metal line at a temperature of 10^4 K, thermal broadening is of the order of 0.03 Å, so equation (6) is expected to be accurate only up to $B \sim 1\times10^3/z$ gauss. For lighter helium atoms the expression should be valid up to $B \sim 4\times10^3/z$ gauss. These results are in agreement with numerical experiments carried out by Borra (1972). (2) The rotational velocity broadening $\lambda v/c$ must be less than the intrinsic line width. This may easily be seen from an example: if a longitudinal field is present on the approaching half of the visible hemisphere of a star of $v \sin i \sim 30$ km s^{-1}, while on the receding half the field is basically transverse, the characteristic S wave variation of polarization will be contained within the short-wavelength line wing, while the long-wavelength wing will be practically unpolarized. Thus, when $\lambda v/c \gtrsim \Delta\lambda_i$, $\bar{V}_0(\lambda)$ is *not* expected to be simply related to $\bar{I}_0(\lambda)$ and $d\bar{I}_0(\lambda)/d\lambda$ by equation (6). (3) The Zeeman splitting $\Delta\lambda_B$ inferred from the observed polarization profile $\bar{V}_0(\lambda)$ yields a measurement of an appropriate line-strength weighted effective field B_l rather than the usual B_e, weighted only by limb darkening.

For the interpretation of Balmer-line Zeeman analyzer measurements, where the local intrinsic line profile is several angstroms wide, the conditions above are generally fulfilled except in the line cores and in the most rapidly rotating O and B stars. On the other hand, for interpretation of metal or helium line measurements, the stellar rotation is, in general, not negligible. This does introduce substantial changes in the relationship between $\bar{V}_0$ and $\bar{I}_0$ and reduces equation (6) to a useful order-of-magnitude estimate, which may be rather inaccurate when the longitudinal field strength is strongly inhomogeneous across the stellar disk, as at crossover. However, the alternative to using equation (6) is the construction of quite elaborate models (e.g., Borra 1980), and, in the common case that the polarization line profile $\bar{V}_0(\lambda)/\bar{I}_0(\lambda)$ is sampled at only two points, there is not much justification for such complexity. Furthermore, it is found empirically (see § III) that the field inferred from narrow-line polarization measurements with the aid of equation (6) is roughly the same as that obtained by other measurement techniques, even when the observed star has rapid enough rotation to lead to $\lambda v/c > \Delta\lambda_i$. Thus, we shall adopt equation (6) to interpret the measurements reported in this paper, even though it is only a crude first approximation for the high-resolution observations.

Next, we use equation (6) to derive an expression with which the integration time for a magnetic measurement of a star with a particular choice of spectral line and instrument may be estimated. If we suppose that the main source of measurement error is photon counting statistics (the usual situation for photoelectric polarization measurements), the standard error of the polarization measurement will be given by $\sigma = (N)^{-1/2}$, where N is the total number of recorded counts. This error is a fractional polarization, which may be converted to an equivalent magnetic field standard error through equation (6). A useful estimate of the situation may be obtained by approximating a line of fractional observed line depth d and observed half-width (FWHM) $\Delta\lambda_0$ by an equivalent triangular line having the same parameters. If the line is not too deep (say, $d < 0.5$), then the standard error of a measurement of line-weighted effective field B_l is approximately

$$\sigma_B = (4\pi mc^2/ze\lambda^2)\sigma\left[(d\bar{I}_0/d\lambda)/\bar{I}_0\right]^{-1}$$

$$\approx \frac{8.59\times10^4\,\Delta\lambda_0(\text{Å})}{z\left[\lambda(\text{Å})/5000\right]^2 N^{1/2} d}\ \text{gauss.} \quad (7)$$

Now, suppose we measure the polarization in the steepest part of the wing of a specific line of wavelength λ of a given star through a particular photoelectric spectrographic instrument (e.g., a photoelectric line-profile scanner with a polarization modulator) through which the star produces a count rate of $n(\lambda)$ counts s^{-1} Å^{-1} with the slit fully opened. Suppose that the spectrograph is used with an instrumental resolution $\Delta\lambda_s$, and that the width of the monochromatic star image at the spectrograph camera focal plane is S (in the same units as $\Delta\lambda_s$). (For the Mount Wilson Observatory line-profile scanner used for most of the observations reported below, S[Å] = 0.24 β[″], where β is the diameter of the seeing disk in arcseconds.) After an integration time t, the total number of observed counts will be approximately $N_{sp} = n(\lambda)\Delta\lambda_s(\Delta\lambda_s/S)t$, where the $(\Delta\lambda_s/S)$ factor is an estimate of light loss on the spectrograph slit due to a finite (or worse) seeing disk. If the instrument has no slit losses (this is usually the situation in the sort of interference filter polarimeter used for Balmer-line magnetic observations, and can also apply for a coudé spectrograph if a very broad line [$\Delta\lambda_0 \gtrsim 0.5$ Å] is observed, if an effective image slicer is available, or if high resolution is obtained using a Fabry-Perot etalon), then the total of observed counts is given by $N_f = n(\lambda)\Delta\lambda_s t$. [It is convenient to express count rates using the open-slit $n(\lambda)$, as it is a relatively constant characteristic of a spectrograph, while the seeing disk size S may change drastically from night to night.] Now the observed half-width of the line $\Delta\lambda_0$ is partly due to the intrinsic width $\Delta\lambda_i$ of the line (as observed at very high resolution) and partly due to the finite spectrograph resolution $\Delta\lambda_s$. Approximating both profiles by Gaussians, we estimate $\Delta\lambda_0^2 \approx \Delta\lambda_i^2 + \Delta\lambda_s^2$. Combining the expressions above with equation (7) and solving for t, we find that the integration time t required to obtain a measurement of field strength with standard error σ_B is

$$t \approx \frac{7.38\times 10^9\, S\Delta\lambda_0^2}{n(\lambda)(\lambda/5000)^4 z^2 d^2 \sigma_B^2 \Delta\lambda_s^2}, \qquad (S > \Delta\lambda_s), \tag{8}$$

or

$$t \approx \frac{7.38\times 10^9\, \Delta\lambda_0^2}{n(\lambda)(\lambda/5000)^4 z^2 d^2 \sigma_B^2 \Delta\lambda_s}, \qquad (S < \Delta\lambda_s), \tag{9}$$

where S, $\Delta\lambda_0$, $\Delta\lambda_s$, and λ are in angstroms, and σ_B is in gauss. In practice, the changeover between the two cases typically occurs at $\Delta\lambda_s \sim 0.5$–1 Å.

These equations simplify if a definite value of $\Delta\lambda_s$, related to $\Delta\lambda_i$, is chosen. The optimum choice of $\Delta\lambda_s$ is the choice which minimizes the time required to obtain a given σ_B. Differentiating equations (8) and (9) with respect to $\Delta\lambda_s$, and recalling that, with increased bandpass $\Delta\lambda_s$, d will vary roughly as $\Delta\lambda_0^{-1}$ (i.e., $W_\lambda \sim \Delta\lambda_0 d$ is constant), we find that for $S > \Delta\lambda_s$ the optimum choice is $\Delta\lambda_s = \Delta\lambda_i$, so $\Delta\lambda_0 = \sqrt{2}\,\Delta\lambda_s$, while for $S < \Delta\lambda_s$ the optimum choice is $\Delta\lambda_s = \Delta\lambda_i/\sqrt{3}$, so $\Delta\lambda_0 = 2\Delta\lambda_s$. Substituting we obtain

$$t = \frac{1.48\times 10^{10}\, S}{n(\lambda)(\lambda/5000)^4 z^2 d^2 \sigma_B^2}, \qquad (S > \Delta\lambda_s), \tag{10}$$

and

$$t = \frac{1.48\times 10^{10}\, \Delta\lambda_0}{n(\lambda)(\lambda/5000)^4 z^2 d^2 \sigma_B^2}, \qquad (S < \Delta\lambda_s). \tag{11}$$

Comparing the two expressions, it would appear that high-resolution observations (for which $S \sim 0.5$ Å would be typical) should lead to much shorter integration times (or smaller values of σ_B for a given integration time) than measurements using Balmer lines with $\Delta\lambda_0 \sim 5$–10 Å, especially as a helium or metal line may be chosen to have $z \sim 1.5$–2, while for all the Balmer lines $z \approx 1.0$. These two factors, however, are offset by the far greater throughput obtained with a Cassegrain filter instrument (with an overall quantum efficiency of $\sim 2\%$) than with a typical coudé line scanner, for which the throughput may be a factor of ~ 10 smaller. In addition, even a small amount of rotation (say, $v \sin i \sim 30$ km s^{-1}) can noticeably reduce d for a narrow metal line, while the Balmer lines in B through F stars have $d \sim 0.2$–0.6, even with a 5 Å bandpass. In other words, in practice the quantity (S/nz^2d^2) for a helium or metal line observed with a coudé polarimeter is typically of the same order of magnitude for an early-type sharp-line ($\Delta\lambda_0 \lesssim 0.5$ Å) star as the quantity $(\Delta\lambda_0/nz^2d^2)$ for a Balmer-line observation of the same star using a telescope of the same aperture.

From equations (10) and (11) it is clear that the best line to observe, if one must make magnetic measurements with a single-line instrument, is one for which the product $n(\lambda)\lambda^4 z^2 d^2$ is a maximum. For the Mount Wilson coudé line-profile scanner with the choice of gratings and photomultiplier used for most of the metal-line observations reported here, the function $n(\lambda)\lambda^4$ reaches a broad maximum at about 4750 Å, and drops to half the maximum value at about 4200 Å and 5500 Å for an A0 V star. [The maximum value of $n(\lambda)$ occurs at about 4500 Å, where $n(\lambda) \approx 125{,}000$ counts s^{-1} Å^{-1} for an A0 V star of $V = 0$, equivalent to an overall detective quantum efficiency of about 0.3%.]

To obtain large values of d, most of the stars for which helium or metal lines were observed are quite sharp-lined, with $v \sin i \lesssim 30$ km s^{-1}. To optimize the value of z^2d^2, an extensive search of stellar line lists was made to pick out lines in the range 4000–5500 Å that combine strength (i.e., large d) over a reasonably wide range of spectral types (within the B0 V–F6 V range under study here) with advantageously large values of z. From an examination of line

TABLE 1

SPECTRAL LINES SUITABLE FOR ZEEMAN POLARIZATION MEASUREMENTS

Ion Multiplet	λ(Å) Transition	z Structure	Useful Range	Notes (equivalent widths, blends)
Mn 2	4034.49 $^6S_{5/2}-^6P_{3/2}$	1.70 (triplet)	A5–F5	A3: 50 mÅ; A7.5: 130 mÅ; F4: 190 mÅ.
Fe 152	4222.22 $^7D_3-^7D_3$	1.75 triplet	F0–F5	A7.5: 90 mÅ; F4: 110 mÅ.
Fe 318	4919.99 $^7F_3-^7D_3$	1.62 (triplet)	A7–F5	A7.5: 100 mÅ; F4: 200 mÅ.
Fe^+ 42	4923.92 $^6S_{5/2}-^6P_{3/2}$	1.70 (triplet)	B9–F5	A0: 120 mÅ; A7.5: 220 mÅ; F4: 300 mÅ. Present in α^2 CVn.
Fe^+ 42	5018.43 $^6S_{5/2}-^6P_{5/2}$	1.94 (triplet)	B9–F0:	A0: 160 mÅ; A7.5: 300 mÅ; F4: 300 mÅ. Blended with Ni (162) λ5018.29 in Sun.
Mg 2	5167.31 $^3P_0-^3S_1$	2.00 triplet	B9–F0:	A0: 130 mÅ; A7.5: 250 mÅ. Blended with Fe (37) λ5167.51 in Sun. Not in α^2 CVn.
Mg 2	5172.68 $^3P_1-^3S_1$	1.75 (triplet)	B9–F5	A0: 130 mÅ; A7.5: 250 mÅ; F4: 500 mÅ. Not in α^2 CVn.
Fe 553	5324.19 $^5D_4-^5D_4$	1.50 triplet	F0:–F5	A3: 60 mÅ; F4: 160 mÅ.

lists for early B-type stars given by Peters and Aller (1970), Hardorp and Scholz (1970), and Norris (1971), it quickly became apparent that the only really suitable sharp lines available in early B stars are those of helium, as almost all the lines of heavier elements have $W_\lambda \lesssim 100$ mÅ, which leads to difficulties in line identification on a single-channel instrument and poor efficiency (small d in eq. [10]). Of the available helium lines in the range 4000–5500 Å, only the lines λ4121 and λ4713 have unusually large z-values ($z=1.5$ in both cases); all the other lines have intensity-weighted z-values of 1.00–1.05. Because the λ4713 line lies very close to the maximum of $n\lambda^4$ for the Mount Wilson line-profile scanner, this line was used for virtually all observations of stars in the range B0–B5.

For the spectral range B9–F6, far more reasonably strong lines are available. After some experimentation, the procedure for choosing lines that was adopted was to search the very extensive list of lines for Hyades stars given by Conti, Wallerstein, and Wing (1965) for lines with $\lambda \gtrsim 3850$ Å having $W_\lambda \gtrsim 100$ mÅ over a substantial part of the range A0–F5. The z-values of the roughly 175 lines in the resulting list were then looked up in Becker's (1969) *Table of Zeeman Multiplets*, and a short list of about 30 lines having $z \gtrsim 1.40$ was examined more closely for variations of observed equivalent width with spectral type, blends, etc. A final list of particularly suitable lines for Zeeman observations in the wavelength range 4000–5500 Å for spectral types from B9 to F5 is given in Table 1. In this table, most of the columns are self-explanatory. In the column labeled "Structure," "triplet" denotes an exact Zeeman triplet structure, while "(triplet)" denotes a line in which the separation of π and σ components is large enough compared to splitting within either π or σ components separately that the line may be regarded to a good approximation as an exact triplet.

Of the lines in Table 1, I finally chose Fe^+ λ4923.92 for Zeeman observations of A and F stars, primarily because it is the only line in Table 1 that may be used over the full spectral range of B9–F5 that is also present in the magnetic Ap star α^2 CVn, the primary magnetic standard used in this work.

Although this paper does not discuss any photographic Zeeman observations, it is worth noting in passing that the reasoning above may be used to derive an approximate expression useful for estimating the magnetic field standard error that may in principle be obtained from a photographic Zeeman observation, ignoring systematic errors such as those discussed by Preston (1969). We may regard the grains of a photographic plate as a matrix of binary storage elements which have the value "1" if they blacken and "0" otherwise. The grains thus resemble the photons detected by a photoelectric system in their signal-to-noise characteristics. If we consider a single line observed on a plate at reciprocal dispersion F (in Å mm^{-1}) and widening w (in mm) and assume the plate has n darkened grains per mm^2, then the number of bits available for magnetic measurement in a line of full width $\Delta\lambda_0$(Å) will be given by $N \approx w\Delta\lambda_0 n/F$, which leads to a polarization standard error of $\sigma \approx (F/nw\Delta\lambda_0)^{1/2}$. This may be inserted into equation (7) above, taking $n = 3\times10^4$ mm^{-2} as typical for a correctly exposed 103a-O plate, to obtain

$$\sigma_1 \approx \frac{5\times10^2}{zd(\lambda/5000)^2}\left(\frac{F\Delta\lambda_0}{w}\right)^{1/2} \text{ gauss} \qquad (12)$$

for a measurement with one line. Combining results from m similar lines gives a standard error of $\sigma_B \approx \sigma_1/\sqrt{m}$, so that (apart from systematic errors), measurement errors of somewhat less than 100 gauss should be possible photographically in favorable cases where many ($\gtrsim 100$) narrow ($\Delta\lambda \lesssim 0.3$ Å) lines are available and a Zeeman-analyzed spectrogram of high dispersion and widening is available. The time required to obtain this standard error, of course, is simply the exposure time to obtain the plate through the polarization analyzer.

III. OBSERVATIONS

The survey discussed here consists of magnetic field measurements of a sample of 36 bright upper–main-sequence stars, which range in spectral type from O9.5 to F6 and are of luminosity class IV or V. Most are normal stars, although the sample does include five Am stars. All the stars in the sample are brighter than $V = 5$, so count rates were high and relatively accurate measurements were possible.

Magnetic field measurements of 13 of the stars were obtained using the University of Western Ontario two-channel photoelectric Pockels cell polarimeter as a Balmer-line Zeeman analyzer, as discussed by Borra and Landstreet (1977, 1980). The instrument was used on the 1.5 m telescopes of Palomar Observatory and Mount Wilson Observatory and on the 1.2 m telescope of the University of Western Ontario. In this system, a star is observed with the polarimeter through a 5 Å HPBW interference filter with a central wavelength near Hα or Hβ. By tilting the filter through a few degrees, its central wavelength may be moved 20 or 30 Å toward a shorter wavelength and set to appropriate points through the line profile. The Balmer-line profile as seen through the interference filter [the $\bar{I}_0(\lambda)$ of equation (6)] may be measured with an accuracy of a few percent by holding the interference filter of one of the two channels constant while setting the other to a series of wavelengths through the line. The ratio of count rates as a function of λ gives $\bar{I}_0(\lambda)$. For stars of low $v \sin i$ ($\lesssim 160$ km s^{-1}) and spectral types in the range A0–A3, the profile was usually not measured but was assumed to closely resemble profiles of numerous similar stars observed on other occasions. For stars outside this spectral range or having large $v \sin i$ values, the profiles were usually observed.

Polarization measurements were then obtained at two wavelengths in the line profile, symmetrically placed on either side of the line center. These points were chosen to be close to the positions of maximum line slope as observed through the filters, in order to obtain the smallest σ_B possible in a given integration time. For slowly rotating A stars, the points were usually chosen to be about 4.5 Å from the line center.

If instrumental polarization is present, it adds a spurious signal to the measured polarization that could lead to an error in the inferred effective field, or to the detection of a signal when no field is present. In fact, when the polarimeter is used with the Palomar and Western Ontario telescopes, with their direct Cassegrain foci, no detectable instrumental polarization ($V_{\rm inst} < 0.003\%$) is present. However, the Mount Wilson telescope has a bent Cassegrain focus which is fed with the aid of a folding flat on which light from the secondary falls with an angle of incidence of about 49°. This flat has the effect of introducing both a phase shift and some linear polarization. The phase shift is about 0.05 waves at Hβ, which has only a small effect on the amplitude of a circular polarization present in the incoming beam, reducing it to about 95% of its original amplitude. This is such a small effect that no compensating wave plate was used.

The linear polarization introduced is more serious, as a Pockels cell polarimeter generally exhibits some sensitivity to the two Stokes polarization components not being measured, giving an output signal typically of the order of a few percent of the amplitude of the largest unwanted Stokes component ("linear to circular conversion") which is added to the Stokes component being measured. In the present case, a linear polarization of a few percent introduced by the folding flat may lead to a spurious circular polarization signal of the order of 0.1%, larger than the effects usually measured. To minimize the polarimeter's sensitivity to this effect, it was mounted on the telescope with the Pockels cell eigenaxes parallel to the principal axes of the folding flat. To eliminate any residual effects (including those due to any other error source that introduces a polarization signal that is independent of the filter setting), use was made of the fact that equation (6) predicts that for the Balmer lines the circular polarization signal $\bar{V}_0(\lambda)$ should have the same shape but reversed sign on the two line wings. Circular polarization measurements at the two chosen wavelengths symmetrically placed on either side of the line center, V_r and V_b, were combined to give a mean polarization, $\langle V \rangle = (V_r - V_b)/2$, that was converted to an effective field measurement via equation (6). The mean $\langle V \rangle$ has any constant offset from zero of both V_r and V_b removed.

Extensive magnetic field measurements of magnetic Ap and Bp stars have been carried out by Borra and Landstreet (e.g., 1977, 1978, 1979, 1980) using the Balmer-line Zeeman analyzer technique, and the sensitivity and repeatability of this measurement method are well established. Most of the Balmer-line measurements reported here were carried out on observing runs during which the observations of magnetic Ap stars discussed by Borra and Landstreet (1980) were obtained, so it is reasonable to regard the present data as securely tied into a standard measuring system.

Helium- and iron-line magnetic measurements were obtained using the coudé two-channel photoelectric line-profile scanners of the 2.5 m Hooker telescope of the Mount Wilson Observatory (Wilson 1968) and of the 1.2 m telescope of the University of Western Ontario (Gray 1971). These line-profile scanners were converted to polarimeters by the addition of a Babinet-Soleil compensator and a Pockels cell polarization modulator, as discussed by Borra and Landstreet (1973). A total of 24 stars was observed in this manner.

Because of the large variation in line profile from one star to another, each magnetic measurement at coudé started with a line scan, typically at a resolution of 0.2 Å, covering perhaps 2 Å. (Selection of the correct line was ensured by nightly calibration of the profile channel of the scanner against emission-line sources, together with the calculation of expected radial velocity shifts of the observed stars due to terrestrial and intrinsic motion.) After the initial scan, the spectrograph resolution would be set to about 70% or 80% of the intrinsic line half-width (FWHM), and a second scan would be made to obtain the observed profile $\bar{I}_0(\lambda)$.

The line-profile scanner was then converted to a polarimeter. As with the Balmer-line observations, circular polarization was sampled at only two points through the line, symmetrically placed on either side of the line center where the slope was largest. This is not as satisfactory a procedure for sharp helium or iron lines as for the Balmer lines for any star where the observed line profile is significantly rotationally broadened, because, as discussed above, equation (6) relating $\bar{V}_0(\lambda)$ and $[d\bar{I}_0(\lambda)/d\lambda]/\bar{I}_0(\lambda)$ is not expected to hold when significant rotational broadening is present. [Some indication of the variety of $\bar{V}_0(\lambda)$ profiles that may be observed is found in the work of Borra and Vaughan (1977, 1978) and Borra (1980).] However, sampling several points through the line with a two-channel scanner would have been very time consuming and would have led to considerably reduced accuracy in individual polarization measurements at each point, because of the narrower entrance and exit slits required (cf. eq. [8]). The choice of sampling polarization at only two points in the line was made in order to make it possible to sample the fields of as many stars as possible with the highest possible accuracy.

For coudé polarization observations, phase shifts and linear instrumental polarization due to the folding flat(s) leading the beam to the coudé are a serious problem, the more so because the telescope rotates with respect to the spectrograph (and polarization modulator) during the course of an observation, which leads to time variation of the effects. The phase shift is compensated when necessary by the introduction of a rotatable Babinet-Soleil compensator into the beam ahead of the polarization modulator (cf. Borra 1976), but cross talk from the linear polarization produced by the flat can again easily produce a variable instrumental polarization of the order of 0.1%. This was dealt with by alternating measurements on the short- and long-wavelength wing of the line (in the order short-long-long-short or long-short-short-long), with individual integrations lasting typically 15 minutes. The data were then reduced by forming a final mean polarization $\langle V\rangle = (V_r - V_b)/2$, as was done with Balmer-line observations. This was found to essentially eliminate the problem of instrumental polarization.

To evaluate the usefulness of simple two-point sampling of helium- or iron-line polarization as a means of detecting and measuring magnetic fields, as well as to establish sign conventions, several observations of the known magnetic Ap stars α^2 CVn (HD 112413, A0p, $V = 2.90$, $v \sin i = 24$ km s^{-1}), 78 Vir (HD 118022, A1p, $V = 4.93$, $v \sin i = 9$), and β CrB (HD 137909, F0p, $V = 3.66$, $v \sin i \lesssim 3$) were obtained with the coudé polarimeters discussed here and reduced in the same manner as all other observations. All measurements were obtained using the λ4923 line except for the first measurement of α^2 CVn, for which the λ4233.19 line of Fe^+ was used. These measurements are listed in Table 2, which gives the Julian Date at the midpoint of observation, the phase according to standard ephemerides (references are given in Borra and Landstreet 1980), the conversion factor from circular polarization to magnetic field from equation (6) in units of gauss per percent circular polarization, the integration time for the measurement, the inferred longitudinal field B_l and its standard error, and, for comparison, the expected field based on mean magnetic curves derived from Balmer-line observations obtained by Borra and Landstreet (1980). The data for α^2 CVn are also shown in Figure 1, again compared to the mean Hβ magnetic curve.

TABLE 2

COUDÉ OBSERVATIONS OF KNOWN MAGNETIC STARS

Star	JD (2,440,000+)	Phase	$B_l/(100\ \bar{V}_0/\bar{I}_0)$ (gauss/%)	Integ. Time (hr)	$B_l \pm \sigma_B$ (gauss)	B_l(Hβ) (gauss)
α^2 CVn ...	1788.76	0.58	1290	4.5	+520±170	+660
	2178.69	0.88	690	0.8	−830±49	−1200
	2179.67	0.06	800	0.7	−650±56	−1180
	2180.82	0.27	640	1.0	−175±65	+150
	2445.90	0.73	600	1.5	−530±55	−310
	2947.67	0.47	480	1.2	+920±125	+930
78 Vir	2446.05	0.74	200	0.4	−370±105	−550
β CrB	2445.99	0.10	360	1.3	+230±65	+280

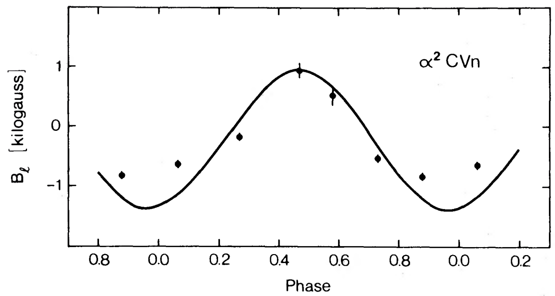

FIG. 1.—Comparison of coudé line-profile scanner magnetic field measurements of the magnetic Ap star α^2 CVn with the best sine wave fit to the Balmer-line measurements of Borra and Landstreet (1977, 1980). Error bars indicate ± 1 standard error.

It is clear from the table and Figure 1 that the coudé measurements are about as sensitive to the presence of magnetic fields as expected. In fact, in spite of the two-point polarization sampling, the coudé measurements give a surprisingly accurate indication of field strength as compared to the Hβ results. The problems that arise in interpreting the polarization data because of the Doppler shift due to stellar rotation are clearly present; the measured polarizations in the two line wings individually (after subtraction of instrumental polarization) are quite different from one another. It is not really clear exactly what these data measure, but they do give a clear indication of the amplitude of B_l.

The results of the survey are presented in Table 3. The table gives the Henry Draper number, the star name, the spectral type, V magnitude, and the projected rotational velocity from the catalogs of Bernacca and Perinotto (1970) or Uesugi and Fukuda (1970) for each star observed. Further columns list the Julian Date at the midpoint of each observation, the conversion factor from polarization to effective field strength, the integration time, and the measured effective field and standard error. All observations for which the polarization to field strength conversion factor exceeds 10,000 were obtained using the Balmer-line magnetograph at Hβ (except for the first observation of σ Ori AB, for which Hα was used). All other observations were obtained with λ4712.2 of He for stars of spectral type B5 or earlier (except for the first measurement of γ Peg, which was experimentally done with λ5015.68 of He), while measurements of later spectral types were made using λ4923.92 of Fe^+. Balmer-line observations obtained between JD 2,442,849.0 and JD 2,442,856.0 were made on the Mount Wilson 1.2 m telescope, those obtained between JD 2,443,117.0 and JD 2,443,128.0 were made on the Palomar 1.5 m telescope, and the rest were obtained with the 1.2 m telescope of the University of Western Ontario. All helium- and iron-line observations obtained between JD 2,442,172.0 and JD 2,442,447.0 were made with the Mount Wilson 2.5 m telescope, while the rest were obtained at the University of Western Ontario.

IV. DISCUSSION

A number of conclusions may be drawn from Table 3. We observe that all the results in the table are essentially nulls. Only two results (one each for α CMi and τ Sco) differ from zero by more than 2 standard deviations; from counting statistics alone we expect about 5% (2 or 3 measurements out of 51) of the table entries to exceed 2 σ, as observed. In both cases where a 2 σ result was observed, reobservation on another night produced a clear null measurement. There is thus no evidence in the table for detectable fields in any of the program stars.

It seems reasonable to conclude from this result that both the Hβ Zeeman analyzer and the coudé Zeeman analyzer show no tendency to produce spurious nonzero results. There are no obvious systematic or random zero-point errors in null measurements to the highest accuracy achieved here: $\sigma = 50$ gauss with Hβ (corresponding to $\sigma \sim 0.004\%$), and $\sigma_B = 7$ gauss ($\sigma \sim 0.04\%$) for the coudé system. This is in contrast to measurements of magnetic curves in stars that show detectable longitudinal fields, where Hβ measurements often have noticeable excess scatter around mean curves, usually in the range of 1–2 times that expected from counting statistics (Borra and Landstreet 1980).

These results also give some indication of the measurement errors available with single-line field measuring techniques at present. We may use the data of Table 3 to calculate for each star the integration time $t_{\rm std}$ that would have been required under identical seeing conditions, with the same spectrograph settings, etc. [i.e., changing only $n(\lambda)$ in eqs. (10) and (11)] if the star had an apparent magnitude of $V = 0.0$, and were observed with a telescope of 2.5 m aperture to a standard error of 10 gauss (or, equivalently, had $V = 5.0$ and observed to $\sigma_B = 100$ gauss). For Hβ Zeeman measurements, $t_{\rm std}$ is usually in the range 1.5–4 hr under reasonably good conditions of transparency and mirror cleanliness and does not vary greatly from late-B to late-A spectral types. (Some much larger values of $t_{\rm std}$ that may be inferred from Table 3 for Balmer-line measurements at Mount Wilson Observatory were made when one channel of the two-channel polarimeter was not functioning. The value of $t_{\rm std} \sim 1.5$–4 hr for Hβ applies to the large body of Ap star data reported by Borra and Landstreet [1980].)

TABLE 3

MAGNETIC OBSERVATIONS OF UPPER-MAIN-SEQUENCE STARS

HD	Name	Sp	V	$v \sin i$ (km s^{-1})	JD (2,440,000+)	$B_l/(100\ \bar{V}_0/\bar{I}_0)$ (gauss/%)	Integ. Time (hr)	$B_l \pm \sigma_B$ (gauss)
886	γ Peg	B2 IV	2.83 v	10	1558.92	1040	0.9	−190±400
					1559.89	760	1.0	−130±120
					2355.68	1290	2.0	+72±45
3360	ζ Cas	B2 V	3.72	20	1560.83	1000	1.4	+70±310
16582	δ Cet	B2 IV	4.05 v	20	2355.81	1120	2.8	+56±57
27962	68 Tau	A3 Vm	4.30	15	2356.92	210	2.5	+40±36
29140	88 Tau	A5m:	4.26	<25?	2357.84	2400	2.7	+46±167
36512	ν Ori	B0 V	4.59	15	2355.99	2500	3.8	+93±105
37468	σ Ori AB	O9.5 V	3.75	94	4202.78	22600	0.4	−40±490
					4237.77	24400	2.6	−140±260
40183	β Aur	A2 V	1.86	36	2445.68	3200	1.6	−72±80
47105	γ Gem	A0 IV	1.93	37	2849.72	13000	2.6	−165±120
60178	α Gem B	A5m	2.95	15	2445.80	1900	1.3	+130±84
60179	α Gem A	A1 V	1.97	<25	3126.91	13000	2.7	+80±55
61421	α CMi	F5 IV	0.34	3	2357.04	190	1.3	−17±7
					2358.00	190	2.8	+7±7
76644	ι UMa	A7 V	3.12	140	2853.65	13000	1.5	+80±140
82328	θ UMa A	F6 IV	3.12	<10	2854.67	16000	2.8	+250±160
87901	α Leo	B7 V	1.36	353	2849.83	16200	2.1	−15±65
95418	β UMa	A1 V	2.37	35	3118.04	13000	2.3	0±65
95608	60 Leo	A1m:	4.41	28	2174.73	470	2.8	+5±55
97603	δ Leo	A4 V	2.57	175	3117.03	15000	2.7	−75±65
97633	θ Leo	A2 V	3.34	5?	2172.75	740	3.0	−67±67
					2180.71	1200	3.2	−49±55
					2855.74	13000	2.0	−80±105
102647	β Leo	A3 V	2.14	115	3127.01	13000		−80±65
103287	γ UMa	A0 V	2.44	155	3123.00	13000	2.9	+25±50
110379	γ Vir N	F0 V	3.52	22	2175.72	1150	2.8	+84±53
					2176.72	1210	3.2	−15±43
114330	θ Vir	A1 V	4.38	<20	2177.77	190	2.7	−9±30
120315	η UMa	B3 V	1.87	226	4228.95	15900	1.9	−5±65
128167	σ Boo	F2 V	4.46	<10	2173.86	190	4.2	−11±23
					2179.77	240	2.2	−8±45
137052	ε Lib	F5 V	4.93	<20	2178.80	300	2.4	−74±60
141795	ε Ser	A2m	3.71	35	2172.94	1410	3.4	−60±48
147394	τ Her	B5 IV	3.91	20	1787.77	1900	6.2	+230±190
149438	τ Sco	B0 V	2.85	<20	2174.92	1350	3.8	−61±30
					2175.89	1050	3.6	−16±23
160762	ι Her	B3 V	3.80	<40	1560.72	750	1.6	+460±285
					1843.77	890	3.0	+40±100
					2176.91	900	3.8	+13±38
					2179.92	1080	3.6	−63±46
166182	102 Her	B2 V	4.35	<40	1845.78	1730	3.8	+280±170
					2177.93	2300	2.7	−97±88
172167	α Lyr	A0 V	0.04	23	2356.63	780	0.9	−9±19
180163	η Lyr	B2 IV	4.46	10	2178.94	1900	2.2	−65±106
					2180.95	2100	2.2	+230±125
187642	α Aql	A7 IV	0.77	245	2919.79	15000	1.2	−65±60
					2920.85	15000	1.3	+9±50
206826	μ^2 Cyg	F6 V	4.73	<15	2357.68	390	3.2	0±90
210027	ι Peg	F5 V	3.76	7	2356.73	250	2.7	−33±40

For the coudé measurements, t_{std} varies by rather more, from about 0.4 hr under the most favorable conditions of line depth and seeing (σ Boo, θ Vir, α CMi) to values of more than 20 hr for some observations made under very poor seeing conditions at Western Ontario. Typically, however, the value is again around 2 or 3 hr, so in practice Balmer-line and single helium- or metal-line field measurements are roughly comparable in sensitivity for upper-main-sequence stars.

Radical reduction of σ_B may be expected only with greatly improved coudé throughput (supercoated mirrors, image slicers, highly efficient gratings, etc.) or through the use of multiline measurement techniques. The power of the latter may be seen by comparison of the present data with multiline measurements of G, K, and M stars recently reported by Brown and Landstreet (1981), for which values of t_{std} as low as 0.007–0.01 hr are found for the stars having the most favorable spectra. This high efficiency is also found in multiline measurements of F supergiants reported by Borra, Fletcher, and Poeckert (1981), whose observations have values of t_{std} as low as 0.007 hr. On the other hand, B stars have few suitable lines for magnetic measurements, and for these hot stars substantial improvements in σ_B will be much harder to achieve.

We find from these data that the longitudinal magnetic fields of upper–main-sequence stars taken as a group are small. Because of the large variation in σ_B values in Table 3, it is not easy to give precise meaning to this conclusion. However, we may note that of the nulls in Table 1, 1 star has $\sigma_B \leq 10$ gauss, 1 more has $\sigma_B \leq 20$ gauss, 7 more have $\sigma_B \leq 40$ gauss, and a further 15 have $\sigma_B \leq 80$ gauss. Taking 2 σ_B as the limit for likely detection, it appears that longitudinal fields of more than ~ 80 gauss are not universal on the normal upper–main sequence, and fields as large as ~ 150 gauss must be distinctly uncommon.

We thus find in the present data no evidence for fields in pre-Ap stars, as proposed by Strittmatter and Norris (1971), although the sample is probably too small to provide a really stringent test of their hypothesis, especially as the sample probably contains few really young late-B or A stars. Nor do we find any evidence for the $\sim 10^2$ gauss fields widely suggested as leading to pulsar fields after stellar collapse, although here the errors are too large to offer a really severe embarrassment to the hypothesis. We find no fields outside of the already known range of magnetic Ap and Bp stars, which lie between B2 and F0, even though the present survey extends somewhat beyond these limits in both directions.

A few stars in the survey merit individual mention. The five Am stars show no significant fields, in agreement with results obtained by Conti (1969) and Borra and Landstreet (1980), and in contrast to Babcock's (1958) report of a field of 400 gauss on one plate of 68 Tau. The star γ Vir N has been reported by Boesgaard (1974) to have a variable field ranging from -330 to $+440$ gauss, but neither of my measurements give a field of as large as 100 gauss. My measurements of Procyon and Vega agree with those of Severny (1970), who found no definite field in either. The null result for ι Peg is in agreement with the observations of Boesgaard, Chesley, and Preston (1975). Wolstencroft, Smith, and Clarke (1981) have observed α Aql with an accuracy of $\sigma_B \sim 100$–130 gauss and find no field, in agreement with the result here, but they do find an S-wave of circular polarization in one wing of the Hβ line of α Leo, suggesting the presence of a field that I did not detect. Rudy and Kemp (1978) report the possible detection of a field in γ Peg that appears to exceed 1 kilogauss at times, but none of the three measurements in Table 1 shows any trace of a field.

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REFERENCES

Babcock, H. W. 1958, *Ap. J. Suppl.*, **3**, 141.
Beckers, J. M. 1969, *A Table of Zeeman Multiplets* (Bedford, Mass: Air Force Cambridge Research Laboratories, Publication AFCRL-69-0115).
Bernacca, P. L., and Perinotto, M. 1970, *Contr. Oss. Astr. Univ. Padova Asiago*, No. 239.
Boesgaard, A. M. 1974, *Ap. J.*, **188**, 567.
Boesgaard, A. M., Chesley, D., and Preston, G. W. 1975, *Pub. A.S.P.*, **87**, 353.
Borra, E. F. 1972, Ph.D. thesis, University of Western Ontario.
______. 1974, *Ap. J. (Letters)*, **196**, L109.
______. 1975, *Ap. J.*, **202**, 741.
______. 1976, *Pub. A.S.P.*, **88**, 548.
______. 1980, *Ap. J.*, **235**, 911.
Borra, E. F., Fletcher, M., and Poeckert, R. 1981, *Ap. J.*, **247**, 569.
Borra, E. F., and Landstreet, J. D. 1973, *Ap. J. (Letters)*, **185**, L139.
______. 1977, *Ap. J.*, **212**, 141.
______. 1978, *Ap. J.*, **222**, 226.
______. 1979, *Ap. J.*, **228**, 809.
______. 1980, *Ap. J. Suppl.*, **42**, 421.
Borra, E. F., Landstreet, J. D., and Vaughan, A. H. 1973, *Ap. J. (Letters)*, **185**, L145.
Borra, E. F., and Vaughan, A. H. 1977, *Ap. J.*, **216**, 462.
______. 1978, *Ap. J.*, **220**, 924.
Brown, D. N., and Landstreet, J. D. 1981, *Ap. J.*, **246**, 899.
Conti, P. S. 1969, *Ap. J.*, **156**, 661.
Conti, P. S. 1970, *Ap. J.*, **159**, 723.
Conti, P. S., Wallerstein, G., and Wing, R. F. 1965, *Ap. J.*, **142**, 999.
Gray, D. F. 1971, *Bull. AAS*, **3**, 387.
Hardorp, J., and Scholz, M. 1970, *Ap. J. Suppl.*, **19**, 193.
Havnes, O., and Conti, P. S. 1971, *Astr. Ap.*, **14**, 1.
Kemp, J. C., and Wolstencroft, R. D. 1973, *Ap. J. (Letters)*, **182**, L43.
Mestel, L. 1968, *M.N.R.A.S.*, **138**, 359.
Michaud, G. 1980, *A.J.*, **85**, 589.
Norris, J. 1971, *Ap. J. Suppl.*, **23**, 193.
Pecker, J.-C. 1965, *Ann. Rev. Astr. Ap.*, **3**, 140.
Peters, G. J., and Aller, L. H. 1970, *Ap. J.*, **159**, 525.
Preston, G. W. 1969, *Ap. J.*, **158**, 243.
Ruderman, M. 1972, *Ann. Rev. Astr. Ap.*, **10**, 427.
Rudy, R. J., and Kemp, J. C. 1978, *M.N.R.A.S.*, **183**, 595.
Severny, A. 1970, *Ap. J. (Letters)*, **159**, L73.
Shipman, H. L., and Green, R. F. 1980, *Ap. J. (Letters)*, **239**, L111.
Strittmatter, P. A., and Norris, J. 1971, *Astr. Ap.*, **15**, 239.
Uesugi, A., and Fukuda, I. 1970, *Contr. Inst. Ap. Kwasan Obs. Univ. Kyoto*, No. 189.
Unno, W. 1956, *Pub. Astr. Soc. Japan*, **8**, 108.
Wilson, O. C. 1968, *Ap. J.*, **153**, 221.
Wolstencroft, R. D., Smith, R. J., and Clarke, D. 1981, *M.N.R.A.S.*, **195**, 39P.

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