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DISCOVERY OF MAGNETIC FIELDS IN THREE SHORT-PERIOD Ap STARS

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ABSTRACT

Magnetic fields of the order of several hundred gauss have been detected in the short-period Ap stars θ Aur ($P = 1^d37$), CU Vir ($P = 0^d52$), and ϕ Dra ($P = 1^d72$) using an Hβ magnetograph technique. In each case the fields are variable with the periods previously determined from photometry or spectroscopy. The observed magnetic curves are compatible with dipole field geometries on the oblique rotator model. The inferred poloidal fields are of the right order of magnitude to suppress thermal circulation currents. In CU Vir, the region of helium deficiency and silicon excess seems to lie near the magnetic equator, a geometry which Strittmatter and Norris predicted would arise during the magnetic braking of an Ap star by a centrifugal wind.

Subject headings: stars: magnetic — stars: peculiar A

I. INTRODUCTION

Magnetic fields of a few hundred gauss or more have been detected in most of the bright sharp-lined ($v \sin i \lesssim 30$ km s^{-1}) peculiar A stars of the Si and Sr-Cr-Eu types which have been observed for magnetism, and it is widely believed that these fields are intimately connected with the occurrence of the atmospheric abundance anomalies and nonuniform distribution of elements which characterize the Ap stars. However, a search for magnetic fields in broad-line Ap stars ($v \sin i \gtrsim 30$ km s^{-1}) by Landstreet *et al.* (1975) led to no strong evidence for fields in any short-period ($P \lesssim 2^d5$) Ap stars. Although their errors were typically 300–700 gauss, Landstreet *et al.* were able to show that fields in the short-period Ap stars are statistically smaller than those in long-period Ap stars and may be entirely absent. This result is theoretically somewhat puzzling and requires further observational clarification, so a search for fields of a few hundred gauss is being carried out in some of the brighter short-period Ap stars. In this *Letter* we report the first results of this search.

II. OBSERVATIONS

The observations reported here have been obtained by a Balmer-line magnetograph technique, using a Pockels cell polarimeter similar to that described by Angel and Landstreet (1970) on the 1.5 m telescopes at Mount Palomar and Mount Wilson and the 1.2 m telescope of the University of Western Ontario. Essentially, we measure the circular polarization in the wings of Hβ (in passbands isolated by tilted interference filters of 5 Å HPBW) which arises because of the longitudinal Zeeman effect when a field is present. This method of field measurement, and our reduction procedure, are discussed by Landstreet *et al.* (1975) and Borra and Landstreet (1975, 1977).

Using this system, we have detected magnetic fields in the short-period Ap stars θ Aur (HD 40312, Sp = B9 Si, $v \sin i = 45$ km s^{-1}), CU Vir (HD 124224, B8 Si, 135 km s^{-1}) and ϕ Dra (HD 170000, B9 Si, 93 km s^{-1}). (Balmer line spectral types and peculiarity types are from Osawa 1965, and projected rotational velocities are from Abt, Chaffee, and Suffolk 1972.) Our magnetograph observations of these stars are given in Table 1, where the Julian date of observation (less 2,440,000), the measured longitudinal field H_e and its standard error σ_H, and the phase (computed as described below) are tabulated.

A useful test of our data is to compare the periods of variation that are consistent with our observations with periods obtained from photometry or spectroscopy. We have calculated the power spectra of our observations of each of the three stars discussed here, for all independent periods between 4 times the time interval between first and last observation, and 1 day (θ Aur, ϕ Dra) or 0.5 day (CU Vir). For θ Aur, Winzer (1974) obtained the ephemeris

$$\text{JD (light max)} = 2,441,238.88 + 1.3717\ \text{E} \quad (1)$$

from two observing runs spaced almost exactly 1 year apart. From the data in Winzer's thesis, neither the resonance period near 3^d7 nor the sidelobe period 1^d3665 or 1^d3770 can be completely excluded. A power spectrum of our data gives the periods $1^d34 \pm 0^d05$ and $3^d8 \pm 0^d4$ as the only significant peaks. Thus, the variation found by Winzer is confirmed, although we cannot refine his period.

The period of CU Vir has been studied by Deutsch (1952), Hardie (1958), Peterson (1966), Blanco and Catalano (1971), and Winzer (1974). It appears that a period of $0^d520675 \pm 0^d000005$ is consistent with all the observations. Using Winzer's observations we adopt

TABLE 1

MAGNETIC OBSERVATIONS

JD (2,440,000+)	$H_e \pm \sigma_H$ (gauss)	ϕ
	θ Aurigae	
2764.94......	−260±40	0.53
2765.95......	+330±55	0.27
2766.95......	+260±70	0.00
2767.92......	−120±55	0.71
2768.87......	−130±45	0.40
2769.88......	+270±55	0.13
2770.87......	+170±50	0.86
	CU Virginis	
2593.67*.....	+400±270	0.57
2850.86......	+490±195	0.53
2852.84......	+560±165	0.33
2858.82......	+390±190	0.82
2941.73......	−420±175	0.05
2944.72......	+330±150	0.80
2946.73......	+640±140	0.65
2947.72......	+780±150	0.55
	ϕ Draconis	
2632.77......	+ 60±160	0.02
2636.71......	−300±140	0.32
2850.02......	+720±175	0.60
2852.98......	−130±130	0.32
2921.83......	− 40±130	0.44
2941.93......	+ 60± 95	0.14
2942.91......	+490± 95	0.72
2943.90......	−135±110	0.29
2944.88......	+430±100	0.86
2944.95......	+450±120	0.90
2945.95......	+210±100	0.49
2946.93......	+ 40±100	0.06
2947.93......	+430± 90	0.64
3001.77......	+ 35±100	0.01
3003.83......	−150±120	0.21

* Measured in Hα.

the ephemeris

$$\text{JD (light max)} = 2{,}441{,}455.696 + 0.520675\ \text{E}\ . \quad (2)$$

We find the periods $0^d_.5212 \pm 0^d_.0005$, $0^d_.921 \pm 0^d_.001$, $1^d_.090 \pm 0^d_.001$, and $11^d_.95 \pm 0^d_.08$ to give the best representations of our data, again consistent with the photometric and spectroscopic period.

For ϕ Dra, Winzer (1974) gives the ephemeris

$$\text{JD (light max)} = 2{,}441{,}444.98 + 1.7164\ \text{E} \quad (3)$$

from two photometric runs approximately 1 year apart. The resonance period near $2^d_.4$ can probably be excluded by the large value of $v \sin i$ (see below), but again some uncertainty as to the correct extension period may remain. Our data have the largest power at the periods $1^d_.688 \pm 0^d_.002$, $1^d_.716 \pm 0^d_.002$, and $2^d_.457 \pm 0^d_.004$. Of the possible periods less than 2 days, only $1^d_.7164 \pm 0^d_.001$ is consistent with both our data and Winzer's, so that we may regard his period as confirmed.

Thus in each case our magnetic observations are consistent with previously determined periods. We have therefore displayed the magnetic data in Figures 1–3 using phases calculated from equations (1)–(3).

III. DISCUSSION

As these are the first magnetic fields detected in short-period peculiar A stars, there are several points to be examined in the light of the new data. (i) We shall model the magnetic field geometries as far as possible with the limited information available, to determine whether the fields seem consistent with the oblique dipole rotator model (cf. Preston 1971). We then attempt to deduce the relationship between the inferred field geometry and the abundance distributions suggested by the spectroscopic and photometric observations. (ii) Angular momentum may be lost from a rotating magnetic star either by a centrifugal wind (Mestel 1968) or by accretion from the interstellar

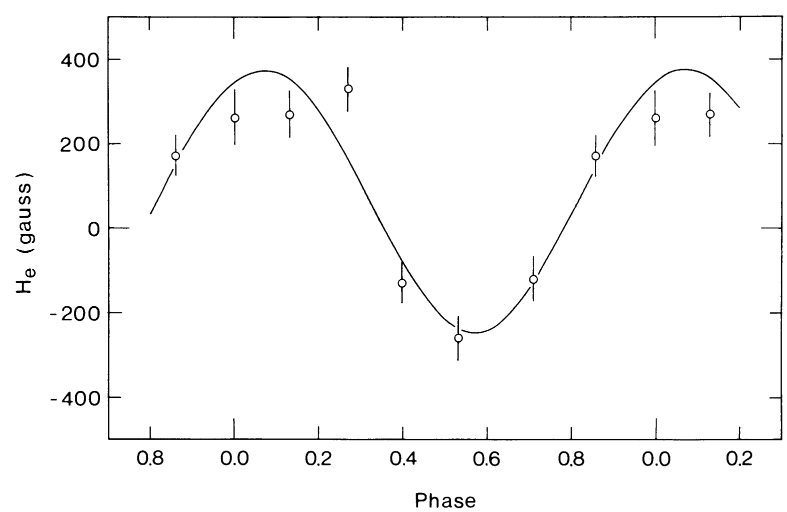

FIG. 1.—Hβ magnetograph observations of θ Aur plotted against phase. The smooth curve is the least-squares best-fit sine wave through the data.

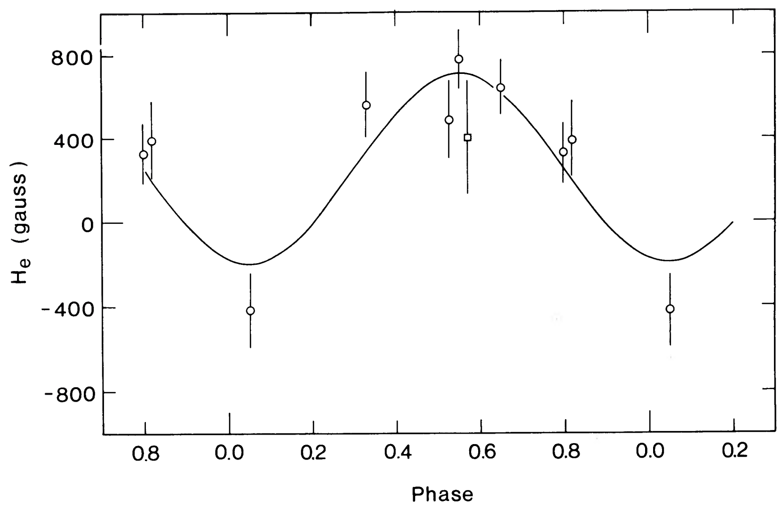

FIG. 2.—Hβ (*circles*) and Hα (*square*) magnetograph observations of CU Vir

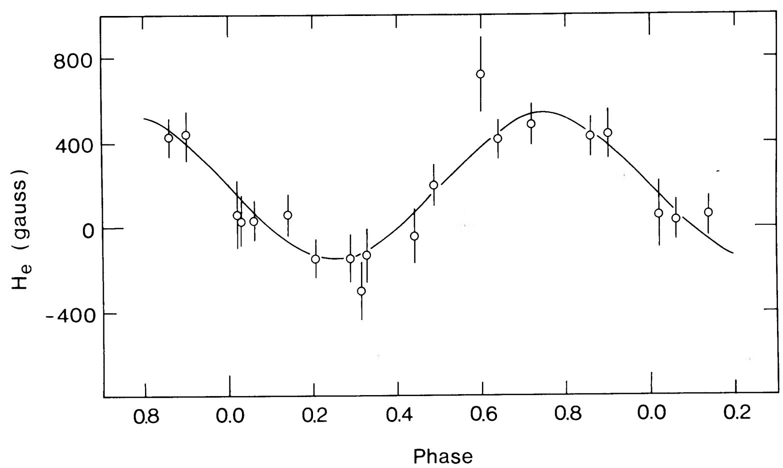

FIG. 3.—Hβ magnetograph observations of ϕ Dra

medium (Havnes and Conti 1971). Strittmatter and Norris (1971) have suggested that a magnetic star which is being slowed by a centrifugal wind will at first lose material from essentially the entire surface, and will not appear to be spectroscopically peculiar. As it slows, field lines near the magnetic equator should close first, producing a stable zone within which gravitational diffusion (Michaud 1970) will quickly produce abundance anomalies. Gradually as the star slows further, the stable zone in which abundance anomalies can arise grows. Thus among the most rapidly rotating Ap stars, if angular momentum loss occurs by mass loss rather than by accretion we might expect to find some stars which peculiarities are confined to the region of the magnetic equator. It is of interest to consider whether this picture applies to any of the present sample of rapidly rotating Ap stars. (iii) It has been suggested by Mestel (1971) that a star can maintain an observable photospheric magnetic field only if the ratio of magnetic to rotational energy is sufficiently large. Strittmatter and Norris (1971) have proposed as a criterion

$$H \gtrsim H_c = 1.2 \times 10^4 \lambda^{1/2} \text{ gauss} , \qquad (4)$$

where H is the typical photospheric field, and $\lambda^{1/2} = v_r/v_e$ is the ratio of rotational velocity to escape velocity for the star. The stars discussed in this *Letter* combine relatively rapid rotation with comparatively small magnetic fields, and it is of interest to see whether the observed poloidal field component alone can satisfy the criterion of equation (4), or whether substantial toroidal fields may be required to suppress thermal circulation currents.

We first calculate the value of i, the angle of inclination between the rotation axis and the line of sight, for each of the three stars considered here. For each star we take the values of $v \sin i$ and P from § II, and assume that the stellar radius R lies between R_z and $2R_z$, where R_z is the zero-age main-sequence radius of a normal star of the same (hydrogen) spectral type. From $\sin i = (Pv \sin i)/(50.6R)$ we then find a range of possible i values. We next fit a sine wave to the magnetic data by least squares. These best fit sine waves are shown as smooth curves in Figures 1–3.

From the fitted curves we read off the extreme positive and negative values of H_e, H_e^+, and H_e^-. We use the relation $\tan \beta = \cot i \ (1 - r)/(1 + r)$, where $r = H_e^-/H_e^+$ (Preston 1967), to determine the allowed range of β, the angle between the magnetic axis and the rotation axis, for a centered dipole magnetic field distribution. We also calculate the allowed range in field strength H_p at the magnetic pole, again assuming a centered dipole field distribution. Finally, we calculate the possible range of H_c from equation (4). The resulting allowable ranges of i, β, H_p, and H_c are tabulated for each star in Table 2.

We have performed similar calculations for each star on the assumption that the field is actually a modestly decentered dipole with $a = 0.2$ (cf. Landstreet 1970; Preston 1970). In each case the allowed values of β change by only a few degrees, although the field H_p at the strong pole may increase by a factor of $\sim$2.

From Table 2 we see that in θ Aur and CU Vir the magnetic and rotation axes are approximately orthogonal, while in ϕ Dra they seem to be roughly aligned. In ϕ Dra, $i \gtrsim 80°$ even for $R = 2R_z$, and we are probably looking at the star nearly equator-on. If the period were actually $\sim 2^d.4$ (cf. § II), we would require $R > 2R_z$, so that ϕ Dra would have to be entering the evolutionary stage of rapid evolution toward the giant branch, or else be larger than indicated by its hydrogen spectral type.

Comparing H_p and H_c in Table 2, we see that the observed poloidal fields are of the right order of magnitude to suppress thermal circulation currents without requiring toroidal field components much larger than the poloidal ones.

Because of the limited accuracy of the periods of θ Aur and ϕ Dra, the relative phases of photometric and magnetic variations are uncertain by at least ± 0.25 cycle, and no conclusions may be drawn about the relationships between the abundance anomalies, which presumably cause the photometric variations, and the magnetic field distributions. Refinement of the photometric periods and study of possible spectrum variations in θ Aur and ϕ Dra would certainly be of value.

For CU Vir, with its well-known period, the relative phases of the photometric spectroscopic and magnetic variations are determined to within $\sim \pm 0.05$ cycle. Passage over the positive magnetic pole ($\phi = 0.5$) coincides with minimum light and silicon line strength, and maximum helium line strength. Passage near the negative magnetic pole ($\phi = 0.0$) occurs at maximum light. Peterson's (1966) measurements of He I and Si II line strengths appear to show a double wave structure near this phase, so that the negative field extremum coincides with a weak secondary maximum of He and a secondary minimum of Si. Helium is weakest and silicon strongest at approximately the two phases when the line of sight crosses the magnetic equator. If, as is normal in Ap stars, helium is deficient and silicon is overabundant in the regions of anomalous abundance, it appears that the region of helium underabundance and silicon overabundance is restricted to the magnetic equator. This is precisely the situation suggested by Strittmatter and Norris (1971) for a magnetic star decelerating by a centrifugal wind, and is the opposite of what would be expected on the accretion model of Havnes and Conti (1971), where abundance anomalies would be expected to be strongest at the magnetic poles.

The light curves do not show a double wave structure, in spite of the large amplitudes of variation, but the maxima at $\phi = 0.0$ are significantly broader than the minima at $\phi = 0.5$. It is not clear whether this is to be interpreted in the same fashion as the spectrum variations, or whether the source of the light variations is actually concentrated at one of the two magnetic poles.

TABLE 2

STELLAR MAGNETIC MODEL PARAMETERS

Star	i (°)	β (°)	H_p (gauss)	H_c (gauss)
θ Aur........	20–50	75–85	1400–2600	700–2300
CU Vir.......	20–55	55–75	2200–3800	2200–6500
ϕ Dra........	$\gtrsim$80	$\lesssim$20	$\gtrsim$3000	3800

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