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A SEARCH FOR MAGNETIC FIELDS IN Be STARS

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ABSTRACT

No mean longitudinal magnetic fields have been detected in a sample of 15 Be and related stars, with $\sigma \approx 70$–250 gauss. These objects are thus magnetically indistinguishable from normal upper main-sequence stars. However, large surface fields could escape detection, depending upon field geometry and orientation. Models for Be envelopes which require predominantly toroidal fields are not seriously constrained by these observed limits on effective field strength. Circumstantial evidence suggests that many Be stars may indeed be magnetic; accordingly, future more rigorous searches for fields are desirable.

Subject headings: stars: Be — stars: magnetic

I. INTRODUCTION

Interest in the effects of a global magnetic field upon a rotating stellar wind is burgeoning. Mihalas and Conti (1980) proposed that magnetic fields might influence line radiation driven wind geometry to modify Of star line profiles; Nerney (1980) suggested that low mass-loss rate winds (from OB supergiants and rapidly rotating Be stars) could be driven entirely by magnetically enforced corotation; and Underhill (1980) argued that the release of magnetodynamic energy above the photosphere may be responsible for the generation of superionized species in magnetic winds. Underhill (1983) has also interpreted the scatter in terminal velocities seen in luminous early-type stars as possible evidence for the partial driving of stellar winds by Alfvén waves. Friend and MacGregor (1984) have constructed models of line radiation–driven winds from hot magnetic stars, and investigated the possible consequences for braking times due to angular momentum loss by the wind.

For classical Be stars (the group of near main sequence rapidly rotating B type stars whose spectra show Balmer emission lines) it is widely believed that the optical emission arises from a relatively cool envelope, concentrated toward the equatorial plane, within which the expansion velocity v_r is $\lesssim 100$ km s^{-1}. On the other hand, the resonance doublets of superionized species such as N V, C IV, and Si IV, in the UV spectra of Be stars, often show the archetypal indicators of high velocity (~ 1000 km s^{-1}) mass loss via a stellar wind. A central theme of current Be star research is the desire to understand the physical mechanisms responsible for the production and maintenance of this apparent two-component structure. One also wishes to understand the physical relationships, if any, between the stellar wind and the emission envelope, as well as the forces which drive the variability seen in both wind and envelope (Barker, Marlborough, and Landstreet 1984). The observations reported in this paper were carried out in the hope of determining the role of any global magnetic field in generating the structure of Be star winds and envelopes.

II. OBSERVATIONS

Magnetic field measurements on stars are usually measurements of the mean longitudinal (or effective) field, obtained by observing circular polarization in the wings of one or many spectral lines (cf. Landstreet 1980, 1982). Field measurements such as this are made difficult by the early spectral types and large projected rotational velocities (Slettebak 1982) of Be stars. Because of the high photospheric temperatures, the metallic lines in the visible spectra of Be stars are weak, and the large values of $v \sin i$ broaden these lines to the point that they are useless for magnetic measurements. Thus, it is necessary to use either helium or hydrogen lines. The helium lines are also greatly broadened by rotation, but the strongest ones could be used for measurements. The photospheric Balmer lines are intrinsically very broad so that their profiles, though broadened considerably by rotation, remain deep and thus suitable for Zeeman measurements. However, in Be stars, the lower members of the Balmer series are often in emission. This emission comes from an extended region around the star in which the mean longitudinal field, if any, is expected to be much lower than that present in the photosphere, since the field probably falls off above the photosphere at least as $(r/R_*)^{-3}$. The emission-line radiation thus acts simply to dilute any polarization that may be present, which results in a larger measurement error than would be obtained with emission absent. Field measurements using Balmer lines are thus most sensitive if obtained in the higher lines of the series, where emission is generally very weak, or if obtained in the lower lines of the series at times when the (often strongly variable) emission is weak.

All the observations discussed here were obtained with a Balmer line Zeeman analyzer, as described by Borra and Landstreet (1977, 1979, 1980). In The University of Western Ontario photoelectric Pockels cells polarimeter, Balmer lines are isolated by appropriate interference filters, which, by tilt scanning, typically cover a range extending 10–20 Å to either side of the line. Filters are presently available for Hα, Hβ, and Hδ. The Hα filters were ruled out because this is the line in which emission, when present, is strongest. The Hδ filters were not used because they have very low peak transmission (16% compared to 40% for Hβ and 65% for Hα). Measurements were therefore made at Hβ.

The stars observed are listed in Table 1. The table lists in successive columns, for each star, the common name, HD number, spectral classification and peculiarities, and $v \sin i$. The remaining columns give the Julian date at the midpoint of each observation, the telescope used (indicated by C100 and C40, respectively, for the 2.6 m and 1.0 m telescopes at Las

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TABLE 1

OBSERVATIONS OF MEAN LONGITUDINAL MAGNETIC FIELDS

Star	HD	Spectral Type[a]	Peculiarities	$v \sin i$[a] (km s^{-1})	JD 2,440,000+	Telescope	(gauss per %)	$B_l \pm \sigma$ (gauss)
λ Eri	33328	B2 IIIp	E, β Cep	220	4327.53	C100	32,150	-26 ± 247
ν Gem	45542	B6 IV	E	170	3124.01	P60	23,500	-16 ± 165
19 Mon	52918	B1.5 III	E, β Cep	270	4333.58	C100	25,480	$+97 \pm 162$
β CMi	58715	B8 V	E	245	2852.64	MW60	20,000	-240 ± 240
					2858.64	MW60	20,000[b]	$+260 \pm 180$
					3119.95	P60	24,500	-100 ± 170
κ Dra	109387	B5 III	E	200	2858.72	MW60	20,000[b]	-70 ± 200
					3561.91	P60	20,000[b]	-150 ± 140
ι Lup	125238	B2.5 IV[c]	...	235[d]	4326.54	C100	18,100	$+92 \pm 98$
			E		4338.85	C100	19,170	-5 ± 98
η Cen	127972	B2 IV		350	4348.79	C40	27,370	$+66 \pm 76$
γ Lup	138690	B2 IV[c]	...	320[e]	4345.76	C40	24,920	$+45 \pm 74$
θ CrB	138749	B6 III	E	320	3264.78	P60	21,600	$+100 \pm 190$
σ Sco	147165	B2 III + O9.5 V[c]	β Cep	55[d]	4346.70	C40	17,280	-47 ± 76
ζ Oph	149757	O9.5 V	E, β Cep	320	4344.50	C40	27,670	$+11 \pm 77$
θ Oph	156056	B2 IV	β Cep	≤ 40	4326.84	C100	16,470	$+7 \pm 71$
λ Sco	158926	B2 IV + B[c]	β Cep	145[d]	4346.83	C40	19,000	-2 ± 70
λ Cyg	198183	B5 V	E	120	3443.64	P60	18,300	-290 ± 170
o And	217675	B6 III	E	260	3442.75	P60	18,600	-10 ± 120

NOTE.—E = emission.

[a] Slettebak 1982.

[b] Assumed.

[c] Hoffleit and Jaschek 1982.

[d] Uesugi and Fukuda 1982

[e] Wolff, Edwards, and Preston 1982.

Campanas Observatory, and by MW60 and P60 for the 1.5 m telescopes at Mount Wilson and Palomar Observatories), the conversion factor (in gauss percent polarization) from measured polarization to inferred field strength (usually determined from a line profile scan obtained on the same night as the magnetic observation), and finally the measured longitudinal field strength. Integration times ranged from 0.5 to 4.9 hour, depending on the telescope used and star brightness.

All of the stars listed in Table 1, except κ Dra, were observed at times when no emission was detectable in the Hβ line profiles, as observed through the 5 Å filters used. For the stars with no emission, reduction of circular polarization observations to measured field strength was carried out in the normal way (Borra and Landstreet 1980). For κ Dra, the profile showed clear evidence of weak Hβ emission both nights it was observed; the polarization measurement was reduced to a field measurement by using the observed Hβ absorption line profiles of the other Be stars to estimate that in κ Dra the intensity I_l in line emission was about 10% of the stellar photospheric intensity I_p at the two points in the Hβ line wings at which observations were obtained. The observed values of polarization, $V_0 \pm \sigma_0$, were then reduced to inferred photospheric polarizations $(V_p \pm \sigma_p) = (V_0 \pm \sigma_0)(I_l + I_p)/I_p$, which were converted to field strength using an assumed $\gamma = 20{,}000$ gauss per percent, typical of the other stars observed at this spectral type.

This reduction procedure clearly illustrates the effect of unpolarized line radiation in diluting the photospheric field measurement. If the observed flux at a line, $I_l + I_p$, is a factor f larger than the photospheric flux would be without emission present (I_p), the measured polarization has a standard error which is smaller by $f^{1/2}$ than it would be without emission (because of the added photons), but the inferred photospheric polarization error σ_0, and hence the inferred field strength error, is a factor f larger than without emission. Thus the overall effect of emission of strength f is to increase the measured field error by $f^{1/2}$. For stars with weak emission, this is not a major source of signal degradation, but the dilution would be unacceptable for stars with strong line emission.

It should be noted that all the Hβ profiles of Be stars observed in this program are somewhat broader and shallower than those seen in Ap and Bp and normal, but slowly rotating B stars of the same temperature, so that γ is typically 50% larger for the Be stars. This is probably primarily due to the large average projected rotation velocities of the Be stars. However, it is possible that most or all of the stars observed actually had a small amount of emission at Hβ which did not appear clearly enough at 5 Å resolution to be recognized. This would probably be no more than perhaps 10% of the observed flux. If this were the case, the reduction procedure adopted here (assuming no emission) is in fact the most conservative one, in the sense that it results in the largest calculated field errors. If weak emission were actually present, the true value of γ would be smaller than that inferred from the profile, probably by about 20%–40%, while the true photospheric polarization would only be ~10% more than that measured. The field strength and its error inferred from the correct γ and corrected polarization would therefore be smaller than that resulting from the adopted reduction procedure.

III. DISCUSSION

a) Peculiarity Types

Clearly, no magnetic fields have been detected. The standard errors of individual measurements in Table 1 range from 70 to 250 gauss, and in every case the amplitude of the measured mean longitudinal field is less than 2 σ.

The peculiarities column of Table 1 indicates that the observed stars may be divided into four major groups, although for any individual object, membership in one specific group is not necessarily unambiguously defined (and is liable to change as further observations are pursued).

First are the Be stars whose only apparent peculiarity is that of showing Balmer emission lines: ν Gem, β CMi, κ Dra, η Cen, θ CrB, λ Cyg, and o And. All except η Cen are of late spectral type; η Cen, θ CrB, and o And are well known to display shell spectral at various times. Second are the emission line β Cepheids: λ Eri (Bolton 1982), 19 Mon (Balona and Engelbrecht 1979), and ζ Oph (Vogt and Penrod 1983). All are of early spectra type and all have relatively weak Hα emission which is not always present. It is possible that η Cen and o And are in transition (in the literature) from the first to the second group: Baade (1983) found weak Hβ emission microvariability in η Cen which may be analogous to β Cep behavior; Harmanec (1984) has suggested that short-period light variations in o And may be due to rotating spokes of density enhancement along magnetic lines of force. This latter model was also considered, but rejected, by Vogt and Penrod (1983) as a possible explanation of short period line profile variations seen in ζ Oph. Third are the non–emission-line β Cepheids σ Sco, θ Oph, and λ Sco, all with relatively low values of $v \sin i$. Notice that the single measurement of σ Sco in Table 1 places a much more stringent upper limit on any mean longitudinal magnetic field than the observations of Rudy and Kemp (1978). Finally, Table 1 includes two normal B stars, ι Lup and γ Lup, with high values of $v \sin i$ and early spectral type, which might be possible candidates for showing future emission. For the emission-line stars, historical descriptions of their spectra are given by Hubert-Delplace and Hubert (1979), Andrillat and Fehrenbach (1982), and Slettebak (1982); recent Hα behavior is summarized by Barker (1984).

The relevant point to be emphasized here is that there is no evidence for the presence of an effective field in any of the stars in Table 1, regardless of spectral type or apparent peculiarities, with errors on the order of 100 gauss. Further, from the point of view of magnetic observations, no distinction can be made between any of the stars in Table 1 and the normal upper main-sequence stars studied by Landstreet (1982).

b) Be *Star Models*

Several models have been presented in the literature which invoke the presence of magnetic fields in Be stars. Models for the equatorial Balmer emission envelopes have been constructed by Limber (1974) and Saito (1974). These are steady state magnetohydrodynamic extensions to Be stars of the model developed by Weber and Davis (1967) for the solar wind. This approach was further extended by Barker (1979) to include the Castor, Abbott, and Klein (1975) line radiation pressure force. Analyses of the relation between the radial and azimuthal velocity distributions in a rotating magnetic wind have been presented by Barker (1982) and by Barker and Marlborough (1982).

It has also been suggested that the time scales for variation of emission and/or shell spectra may result from MHD interactions in the envelope; this work has been primarily directed toward explaining the long-term shell episodes of Pleione. Crampin and Hoyle (1960) postulated that a magnetic field, and its subsequent amplification due to the rotation of the circumstellar envelope, was ultimately responsible for the dissipation of the dense envelope around Pleione at the end of the shell episode between 1938 and 1951. This idea was later developed in more detail by Henriksen (1969). Hazlehurst (1967) and Limber and Marlborough (1968) also proposed the existence of a weak magnetic field to transfer angular momentum to material in the envelope.

A common feature of the quantitative models of Limber (1974), Saito (1974), and Barker (1979, 1982) is that they result in tightly wound field lines around the star, with the azimuthal components of the magnetic field greatly exceeding the radial components at the photosphere (this may be most easily seen in Table 1 of Limber). Thus, if any of these models are correct, a Be star's photospheric magnetic field could be mainly toroidal in geometry, rather than poloidal. Furthermore, stability of the internal field appears to require at least some internal toroidal component, although this may well vanish at the surface (Mestel and Moss 1983). The standard technique for detection of magnetic fields in nondegenerate stars, adopted in this work, is designed to measure only the mean longitudinal field, and cannot detect any toroidal fields (Landstreet 1980, 1982). Therefore the present observations place no constraints upon any azimuthal field components, which for the models cited above typically lie in the range 100–1000 gauss. Even though Table 1 suggests that any longitudinal fields in the Be stars surveyed are probably less than ~ 100 gauss, it should be noted that the measured longitudinal field is merely the average weighted by $\cos \theta$ (where θ is the angle between the local surface normal and the line of sight [Landstreet 1982]) over the visible hemisphere, of the signed field component along the line of sight, and thus B_l places limits only on the integrated poloidal field components. Many of the above models require photospheric radial fields on the order of 10–100 gauss; the rapid stellar rotation wraps up the field lines to give the high azimuthal model field components. These models are hence essentially unconstrained by the observed limits on B_l.

Notice that this discussion applies equally to the work of Clayton and Marlborough (1980), who found an upper limit of ~ 300 gauss for any mean longitudinal fields in eight A type shell stars; it was argued that their results did not support the models of Limber (1974) and Saito (1974), and thence, by association, these models were probably also inapplicable to the Be stars. Because Clayton and Marlborough failed to distinguish between the azimuthal fields of the models and the mean longitudinal fields observed, their conclusions were not justified.

In general, as emphasized by Barker *et al.* (1981), even large local surface magnetic fields may exist undetected if the combination of field geometry and stellar orientation is unfavorable to the observer. In particular, Barker and Marlborough (1985) pointed out that the asymmetric shifted narrow absorption components seen at C IV $\lambda\lambda$1548, 1550 in several Be stars, indicate that material may be released or superionized at discrete locations within the high-velocity stellar wind. This might be consistent with a scenario proposed for the luminous OB stars by Underhill and Fahey (1984) in which abrupt energy release occurs in local regions in the wind where closed magnetic loops are disrupted. Unfortunately, once again, the present observations provide no constraints on any such locally strong but globally complex and disordered magnetic fields.

c) *Prospects For Field Detection*

Evidently, a thorough direct search for any magnetic fields in Be stars is of considerable importance in evaluating and restricting the range of possible models which may be applicable. How plausible is it that any fields may in fact be present, awaiting detection? The circumstantial evidence is substantial and encouraging.

First, strongly magnetic main sequence early B stars certainly exist: the helium strong stars typically have predominantly dipolar fields with surface strengths $\sim 10^3$–10^4 gauss, and frequently possess stellar winds whose structure is unmistakably modified by the field (Barker *et al.* 1982). Further, the rapid rotators among these objects often show weak Hα emission (Walborn 1974) which displays V/R variations on a period identifiable as the stellar rotation period; i.e., at least some magnetic Be stars are observed to occur, but by historical accident, they are known preferentially as helium strong stars.

Wolstencroft, Smith, and Clarke (1981) have reported the possible detection of a strongly magnetic patch on the surface of the bright B star α Leo; interestingly, Hα emission has also been claimed for this star (Singh 1982), but that report has never been confirmed. There is also some evidence for a strongly decentered dipole field in the O4ef star ζ Pup (Moffat and Michaud 1981) in which periodic minor fluctuations in Hα emission are observed, apparently on the stellar rotation period. However, Barker *et al.* (1981) did not find any mean longitudinal field in three observations with $\sigma \approx 100$ gauss.

The best available models of Be envelopes (Poeckert and Marlborough 1978) are not able to reproduce simultaneously the emission profiles of all the hydrogen lines (Lowe *et al.* 1985); this problem might be corrected with suitable modification of the circumstellar azimuthal velocity distribution, possibly a result of angular momentum transfer within a magnetic envelope.

Finally, additional positive circumstantial evidence is provided by Barker *et al.* (1981), who argued that if an expanding circumstellar envelope is forced into solid body rotation by a global stellar magnetic field, then the resultant line profiles are expected to be of P Cygni type VI—i.e., more or less symmetric centrally placed emission, with a pronounced central reversal—exactly like the typical emission profile seen at Hα in many Be stars.

On the negative side, Strittmatter and Norris (1971) suggested that a global magnetic field must be large enough to suppress merdional circulation or it will be dragged below the surface. This requires a field strength $B \gtrsim 10^4 \lambda^{1/2}$ gauss, where λ is the ratio of centrifugal force to gravity. The notion that in rapidly rotating B stars, any surface field must either exceed ~ 10 kilogauss, or be zero, could fit very well an apparent dichotomy between strongly magnetic helium strong stars and nonmagnetic classical Be stars. In addition, Moss (1980) suggested that (if upper main-sequence stars contain fields generated by a contemporary core dynamo) the dynamo may be oscillatory in the most rapid rotators, and as a result, the amplitude of the field which diffuses to the surface to be observed, may be negligible.

How might the present search for Be star magnetic fields be improved? Perhaps the greatest single problem is that one does not know in advance if any specific field geometry exists preferentially among the classical Be stars. In any case, the emission line stars may not form a homogeneous group: several diverse types of objects (such as interacting binaries, β Cepheids, helium strong stars, rapid rotators evolving off the main sequence, stars with strong equatorial winds, etc.) may be generically classified as Be stars, yet only some subgroups may be magnetic.

Toroidal fields can be detected in rapid rotators by appropriate observational techniques (cf. Fig. 2 in Barker *et al.* 1981), but a rather higher resolution than that employed here would be necessary to permit efficient detection, and consequently substantial allocations of large-aperture telescope time would be required. A search of this nature is planned for the future.

The present work may, in hindsight, suffer from serious selection effects. The Be stars in Table 1 cannot be considered to form a representative sample: stars with strong Hα emission are completely lacking, and the distribution in both spectral type and $v \sin i$ is inadequate. The poor sample in $v \sin i$ is potentially disastrous if, for example, Be stars tend to have a dipolar field aligned with the rotation axis. On the other hand, if Be stars commonly have strongly decentered fields (in effect, a single strongly magnetic spot, as suspected for α Leo and ζ Pup) then it will be necessary in future work to observe each candidate star throughout a rotation cycle in order to ensure detection. As a corollary, each individual observation ought to be completed within a time which is short compared to the rotational period, to avoid smearing of any polarization signature.

Finally, there does not seem to be any practical direct method of detection for disordered fields such as those proposed by Underhill and Fahey (1984), although indirect inferences based on, for example, the presence of gyroresonance radiation (Underhill 1984) might be worthwhile in the future.

IV. SUMMARY

In a search for magnetic fields in Be stars, no mean longitudinal fields have been detected in observations with standard errors of 70–250 gauss. With regard to their lack of strong effective fields, the Be stars are thus indistinguishable from normal upper main-sequence stars; this is true regardless of the spectral peculiarities displayed by individual objects in the sample. However, the present observing techniques are not designed to detect efficiently fields of various plausible geometries, and therefore even large surface fields could exist but escape detection. In particular, models for Be envelopes which require predominantly toroidal fields are essentially unconstrained by the observed limits on effective fields. Considerable circumstantial evidence suggests that many Be stars (other than the helium strong stars) may in fact possess significant magnetic fields, and the directions that may be taken in future searches have been outlined.

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