MAGNETIC FIELDS IN Be STARS?

(Review Paper)

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Abstract. No mean longitudinal or toroidal magnetic fields have yet been detected on any classical Be star. Models of stellar winds and circumstellar envelopes around magnetic Be stars are not appreciably constrained by present observed upper limits on field strength. A few magnetic Be stars do exist among the helium strong stars, but these objects show spectral phenomenology which is unmistakably distinct from that shown by every other object known as a Be star.

INTRODUCTION

Despite the fact that no magnetic fields have yet been detected in any Be stars (nor in any OB stars in general, apart from a few helium peculiar variables) it is nevertheless important to consider the observed upper limits on field strength, and the constraints thereby placed upon the various models which invoke the presence of magnetic fields in Be stars.

It has been suggested that the time scales for variation of emission or shell spectra may result from magnetohydrodynamic interactions in the circumstellar envelope; this work has been primarily directed toward explaining the long-term shell episodes of Pleione. Crampin & Hoyle (1960) postulated that a magnetic field, and its subsequent amplification due to rotation, 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 & Marlborough (1968) also proposed the existence of a weak magnetic field to transfer angular momentum to material in the envelope. Models for equatorial Balmer emission envelopes have been constructed by Limber (1974) and Saito (1974). These are steady state extensions to Be stars of the model developed by Weber & Davis (1967) for the solar wind. None of these early models included the effects of line radiation pressure.

More recently, Mihalas & Conti (1980) proposed that magnetic fields might influence line radiation driven wind geometry to modify Of star

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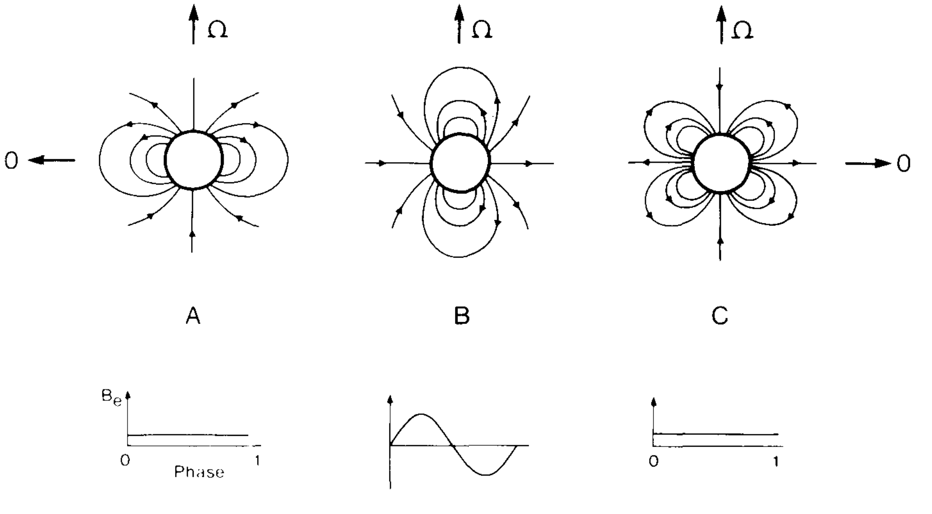
line profiles, while Nerney (1980) suggested that low mass-loss rate winds (from OB supergiants and rapidly rotating Be stars) could be driven entirely by magnetically enforced corotation. Additional circumstantial evidence that magnetic fields might influence the behavior of Be stars was provided by 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.

A detailed time dependent magnetohydrodynamic model has been developed for Pleione by Saito & Saito (1984). An expansion velocity variation of 17 year period, with amplitude 1-2 km/s at the photosphere, is amplified into an 80 km/s expansion velocity variation at 1000 R_*. These features of the model compare favorably with the observed shell episodes.

Poe & Friend (1986) constructed the first Weber & Davis based model to correctly incorporate the effects of line radiation forces. For Be star models, even photospheric radial fields as low as 100 gauss can significantly increase the angular velocity of the wind, making it more nearly approach solid body rotation.

Figure 1. Three possible magnetic field geometries for a star with angular velocity Ω, and the mean longitudinal field B_e measured during a rotation period by an observer whose line of sight lies nearly in the equatorial plane OO. Case A: Centered dipole with rotation and magnetic axes parallel. Case B: Centered dipole with rotation and magnetic axes orthogonal. Case C: Linear quadrupole with an axisymmetric purely radial field in the equatorial plane.



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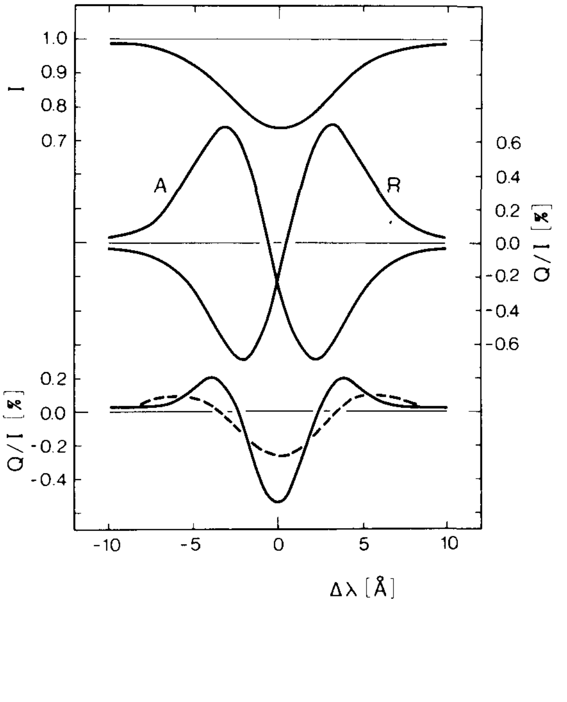
Finally, Underhill & Fahey (1984) have proposed that parcels of material might be released locally into the stellar wind when closed magnetic loops (forming a globally complex disordered field) are disrupted. The released material might produce the discrete UV absorption components observed in numerous OB and Be stars.

The consensus of the models, then, is that photospheric magnetic fields as low as 10-100 gauss may greatly influence, if not dominate, the dynamical behavior of stellar winds and circumstellar envelopes. Accordingly, one wishes to know what observational constraints may be placed upon any of these magnetic models.

It should be pointed out, however, that there are theoretical objections to the idea that any OB stars may have detectable global fields. First, 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.

Figure 2. Non-zero circular polarization arising from a rotating star with a purely toroidal magnetic field. Top: Model Hβ profile for effective temperature 50,000 K and projected rotational velocity 210 km/s. Middle: Zeeman polarization profiles from the approaching (A) and receding (R) half-hemispheres for a toroidal field of strength 10,000 gauss at the equator. Bottom: Net observable polarization profile resulting from the Doppler shift of profiles A and R above. Any azimuthal field is best detected by observing at line center, and not at the steepest portions of the Hβ profile (contrary to the case for longitudinal fields).



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Second, Strittmatter & Norris (1971) suggested that a global field must be large enough to suppress meridional circulation or it will be dragged below the surface. This requires a field strength $B > 10^4 \lambda^{0.5}$ 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 $\sim$ 10 kilogauss, or be zero, could fit very well an apparent dichotomy between strongly magnetic helium strong stars and non-magnetic classical Be stars.

MAGNETIC OBSERVATIONS

Detection Techniques

The processes affecting the profile observed when a spectral line is formed in the presence of a magnetic field have been reviewed by Landstreet (1980, 1982). Usually the existence of a global stellar magnetic field which has a line of sight component (a mean longitudinal field B_ℓ) is inferred from the presence of a characteristic "S-wave" circular polarization profile across the spectral line. The mean stellar surface field can be measured only for a very few sharp-lined stars with strong fields; it is important to realize that the ratio of surface to longitudinal field, and even the very detection of a longitudinal field, depend extremely strongly upon the field geometry and its orientation relative to the line of sight at the time of observation. This is illustrated in Figure 1 for three plausible magnetic field geometries. Field detection becomes progressively more difficult for successively higher order multipole components, and present techniques cannot detect any locally strong but globally complex magnetic fields. The photon counting problem is severe for present optical techniques: a 100 gauss longitudinal field typically produces a peak circular polarization of only 0.005%.

Table 1

New Magnetic Observations of Be Stars

Star	B_ℓ (gauss)	B_ϕ
66 Oph	30 ± 90	0 ± 140
48 Lib	175 ± 195	0 ± 310
θ CrB		0 ± 140
ζ Oph		0 ± 250
χ Oph	10 ± 50	

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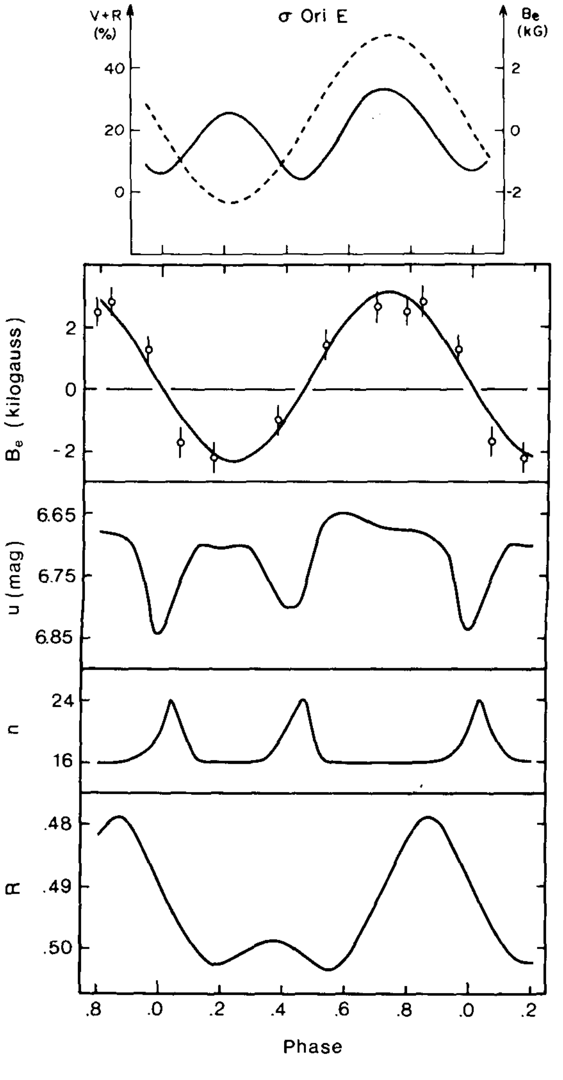
Figure 3. The best studied helium strong star HD 37479 (rotation period 1.19 day). The bottom panel (from Landstreet & Borra 1978) shows the variations in mean longitudinal magnetic field, photometric helium line strength index R, Strömgren u magnitude, and number n of the highest visible Balmer shell line. In the top panel (from Nakajima 1981) the solid line shows the corresponding variation of the Hα emission strength V+R (the sum of the red and violet emission peak intensities) expressed as a percentage of the local continuum level. The dashed line indicates the mean longitudinal magnetic field.



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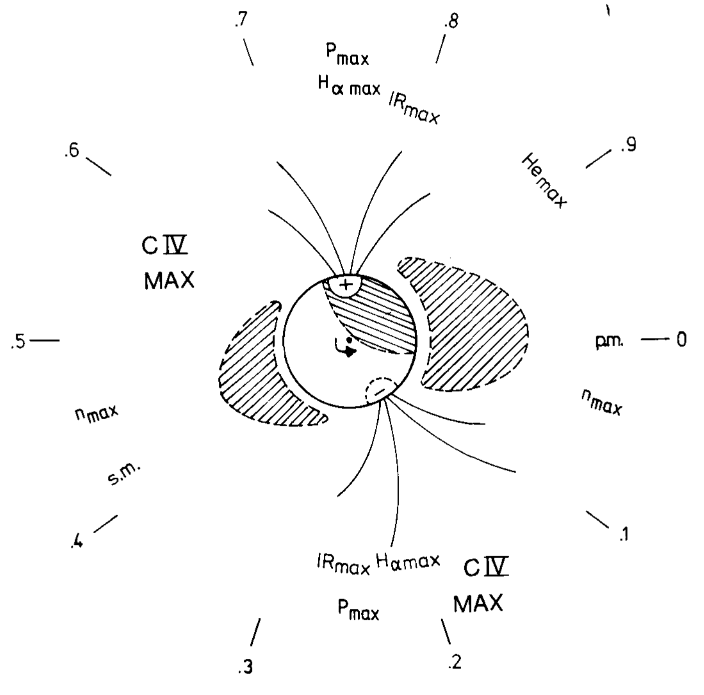
Observational Results

Among the OB stars in general, magnetic fields have been detected only in the helium spectrum variables (Borra & Landstreet 1979). Severny (1970) claimed a 6σ detection of a 130 gauss longitudinal field in Rigel, but curiously the observation has never been repeated. Several searches with null results, with errors of ∿ 500 gauss, are reviewed by Borra, Landstreet, & Mestel (1982). More recent observations of ζ Pup (Barker et al. 1981), twelve normal main sequence O9.5 - B7 stars (Landstreet 1982), and five normal B stars (Barker et al. 1985)--all with greatly reduced errors of ∿ 100 gauss--also failed to detect any fields.

Figure 4. A perfect example of international non-collaboration. This model for σ Ori E (Groote & Hunger 1982) shows (viewed rotationally pole-on) the phases of maxima in Hα emission, IR emission, helium line strength, shell absorption, and linear polarization. The primary and secondary light curve minima are marked by p.m. and s.m. respectively. The projected orientation of the magnetic polar regions is also shown. The shaded region on the star marks the location of the helium strong spot, while the shaded circumstellar regions show the Hα emission clouds. Superposed on this diagram are the phases of maximum C IV absorption, obtained independently by Barker et al. 1987. These phases coincide with the times of helium minima, and do not correspond to the magnetic field phasing (see Figure 3).



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Barker et al. (1985) also observed ten Be stars (λ Eri, ν Gem, 19 Mon, β CMi, κ Dra, η Cen, θ CrB, ζ Oph, λ Cyg, and o And) and again no longitudinal fields were found with errors of 75 - 250 gauss. However, as shown by Figure 1, even kilogauss surface fields could exist and easily escape detection, depending on the field geometry and orientation at the time of observation.

Observations for longitudinal fields may not be the most appropriate for Be stars. A common feature of quantitative models such as those of Limber (1974) and Saito (1974) 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 (although this is not always true when line radiation forces are

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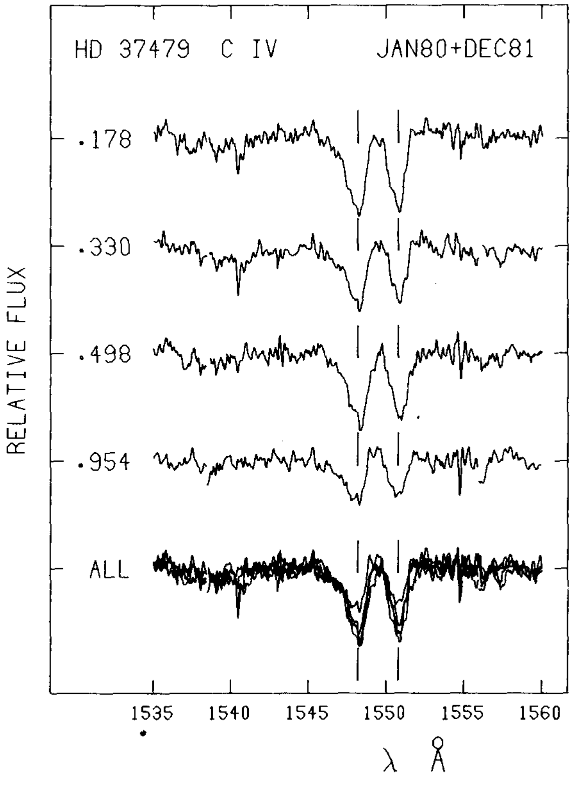
Figure 5. The asymmetric C IV resonance doublet in σ Ori E, indicating the existence of a stellar wind. The vertical dashed lines mark the component rest wavelengths; the persistent shortward absorption extends to -600 km/s. Only a few representative profiles are shown, with the rotational phases (see Figure 3) marked; the four displayed phases are shown superposed at the bottom. The vertical spacing between horizontal tick marks for adjacent spectra equals the local continuum level. From Barker et al. 1987.



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included). Thus, if any of these models are correct, a Be star's photospheric 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 & Moss 1983).

Normally an azimuthally symmetric toroid produces zero net contribution to the mean longitudinal field of a star, but such a field is detectable in a rotating star, because rapid rotation has the effect of breaking the cancellation of Zeeman polarization profiles which arise from opposite (approaching and receding) portions of the visible stellar disk. The effect is illustrated in Figure 2. The standard observational technique adopted in prior work is not designed to detect toroidal fields.

Table 1 presents the preliminary results of new observations made at the 3.6 m Canada-France-Hawaii telescope (Barker, Brown, & Marlborough 1987) which explicitly included searches for any toroidal field component B_ϕ. None has been found: in every case the measured circular polarization at line center is less than the photon counting error.

Table 1 also gives three new longitudinal field observations. Barker et al. (1985) did not observe any Be stars with strong Hα emission, and stars with low v sin i were largely excluded. The longitudinal field measurements of 66 Oph and χ Oph correct this deficiency, but still no fields were detected. Many of the models for magnetic Be stars were constructed specifically for Pleione; this star is far too faint to be observed magnetically, so instead, the most similar bright shell star 48 Lib was observed--again no detection.

HELIUM STRONG STARS

The helium strong stars (extremely scarce objects, with only a dozen or so known) have predominantly dipolar kilogauss fields, and show helium abundance anomalies dependent on the magnetic geometry. Thus these stars (and the cooler but similar helium weak stars) are hot analogs of the classical Ap stars. Only one star, HD 37776, has been found to have a strongly quadrupolar field (Thompson & Landstreet 1985). The fact that even one star does exist with a higher order magnetic field structure than dipolar, could be taken as encouraging evidence for the existence of globally complex disordered fields.

Ultraviolet observations (Barker et al. 1982) show that many of the helium strong stars possess stellar winds whose structure is controlled by the global magnetic field: C IV emission varies in a strictly periodic fashion, on the stellar rotation period. The most rapidly rotating of these objects also show weak Hα emission which displays V/R variations on the rotation period, and thus these are magnetic Be stars. Interestingly, among the helium spectrum variables, there is no evidence for the presence of discrete absorption components in UV resonance doublets, nor for the presence of non-radial pulsation.

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The magnetic field and stellar wind behavior of this group of stars is reviewed by Barker (1987); the typical characteristics are summarized in Figures 3, 4, and 5 for the prototype σ Ori E. The point is that although these few magnetic Be stars certainly do exist, all aspects of their spectral phenomenology are quite markedly different from the behavior shown by every other object known as a Be star.

THE FUTURE

Two different approaches to magnetic field detection might become useful in the future. First, Gnedin & Silant'ev (1984) showed that the Faraday rotation effect for magnetic stars could produce linear polarization with the magnitude and wavelength dependence typically observed in Be stars. If one assumes all the polarization arises from this effect, it is possible to place limits on the field strength--but this requires prior knowledge of the circumstellar envelope physical parameters, and furthermore since electron scattering in a flattened equatorial disk can also reproduce the observed linear polarization, there is not yet any reason to adopt an alternate explanation based on Faraday rotation. Similarly, if any locally strong but globally complex and disordered fields (not detectable by present techniques) should exist, indirect inferences based on the presence of gyroresonance radiation (Underhill 1984) might become practical--but again prior knowledge of envelope parameters appears to be necessary in order to derive quantitative results.

Obviously the present observational situation is unsatisfactory. Further, the quantity of large-aperture telescope time already allocated in searches for magnetic Be stars--all with null results--makes it unlikely that any additional observations will be forthcoming in the foreseeable future. The most promising route to pursue for the moment appears to be the detailed calculations in progress (Barker, Brown, & Marlborough 1987) with a line profile and polarization profile code, to evaluate more precisely the range of field strength and geometry which might exist without having been revealed by present detection methods. This will at least provide unambiguous constraints for the models.

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DISCUSSION FOLLOWING BARKER

Henrichs:

Isn't it true that if a study of an increasing sample of Be stars would always give essentially zero results, the chance of hiding a few kilogauss field would be increasingly more unlikely?

Barker:

Yes, that is now becoming more probable, especially with the new results for the strong Hα emission stars, which were not previously observed.

Harmanec:

I suggest a very systematic monitoring of o And (a very bright B6e star), for which I have found a stable 1.57-day photometric period. Analysis of the past three years of collaborative UBV and polarimetric observations of the star from several European and American observatories on the assumption that it is a spotted star (by K. Olah) indicated a possibility of understanding the observed variations as produced by a flattened envelope around the star, the plane of which is tilted with respect to the equatorial plane of the star. There seem to be also slight polarimetric variations associated with 1.57-day period. There is thus a good case to consider the presence of a magnetic field in this object.

Barker:

I agree. The star is bright enough that I may be able to attempt the magnetic observations even with the 1.2-m telescope at Western Ontario.

Buscombe:

Stoeckley and Buscombe (1983, submitted) have evidence from model simulations that 5 out of 10 well-resolved sets of line profiles for bright B stars indicate polar acceleration.