# 2. MAGNETIC FIELDS

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# OBSERVATIONS OF MAGNETIC FIELDS IN B STARS

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**Abstract.** Globally ordered magnetic fields are known to exist in non-degenerate stars with spectral types between approximately F0 and B2. Among the B stars, and in order of increasing effective temperature, these include the Bp Si stars, helium-weak stars, and the helium-strong stars. These rather remarkable objects present us with an excellent opportunity to quantitatively examine the possible effects of magnetic fields on the photospheres, winds, and circumstellar environments of hot stars. In this paper we review some of the observations of the magnetic fields and field geometries of magnetic B stars, and also briefly discuss the success of attempts to measure magnetic fields in hotter OB and Be stars. We point out some of the interesting observational similarities of the helium-weak and helium-strong stars to Be and other hot stars, including their spectroscopic and photometric variability, variable winds as demonstrated by the UV resonance lines of C IV and Si IV, and their non-thermal radio emission. Continuing work also suggests that a considerable fraction of the rapidly rotating magnetic helium-peculiar stars are in fact variable Be and Be shell stars.

## 1. Introduction

Magnetic fields in stars other than the sun have been known to exist since Babcock's (1947) discovery of a strong field in the peculiar A star 78 Vir. Today several peculiarity classes are recognized among the upper main sequence magnetic stars and in order of increasing temperature these include the SrEuCr Ap stars, the Si Ap stars and the helium-peculiar stars.

The magnetic fields of these peculiar magnetic stars have a much different nature than fields in the sun and solar-type stars (Saar 1990). Rather than being locally complex, the magnetic fields appear to be globally ordered and have much simpler magnetic geometries. The observed magnetic fields are also generally variable in early-type stars and such variations are interpreted in terms of the Oblique Rotator Model (OBM) in which a usually predominantly dipolar magnetic field has its magnetic axis inclined to the star's rotation axis by some angle, $\beta$. As the star rotates, the orientation of the magnetic field to the observer changes and results in a variation of the observed field strength.

Since this review is concerned with magnetic fields in B stars we will limit our discussion for the most part to the helium-peculiar stars, although the hottest Si Ap stars are actually late B-type objects. The former group includes the B3–late B helium-weak stars with abnormally weak helium lines (Borra *et al.* 1983) and the B2–B3 helium-strong stars which have neutral helium lines too strong for their colours (Bohlender *et al.* 1987).



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## 2. Measuring Magnetic Fields in B Stars

Several excellent reviews in the literature discuss in some detail the various techniques for measuring magnetic fields of early type peculiar stars (Landstreet 1980, 1992; Mathys 1989). Unfortunately, not all techniques used for cooler Ap stars are applicable to magnetic B stars. For example, magnetic B stars tend to rotate more rapidly than cooler Ap stars so that it is generally not possible to estimate surface magnetic field strengths by searching for Zeeman broadening of line profiles, a technique frequently employed for late type stars (e.g. Gray 1988). Even if a B star has a low $v \sin i$, the small number of useful spectral lines in these hot stars makes such an approach difficult. A few techniques that have been used successfully to measure magnetic fields in B stars are discussed below.

### 2.1. The Effective or Longitudinal Magnetic Field

Babcock's pioneering magnetic field measurements consisted of a high resolution spectrograph coupled with a Zeeman analyser that produced two simultaneous spectra of a star in right and left circularly polarized light (Babcock 1951). The shift between the two profiles is proportional to a weighted line-of-sight component of the magnetic field (the *effective* or *longitudinal* magnetic field) as well as the Zeeman sensitivity of the spectral line. This classical "photographic" technique consists of measuring these small shifts for many lines, but the technique is now employed with CCDs instead of photographic plates. Mathys (1988) has published some beautiful polarized line profiles for the helium-weak star HD 175362 and has used these to obtain a magnetic curve for this strongly magnetic star, as well as other helium-weak and helium-strong stars (Mathys 1991). Clearly, this technique requires very high signal-to-noise ratio data as well as moderately high spectral resolution to be successful. It is also only useful for slowly rotating stars, of which there are a limited number among B stars. In addition, since peculiar stars often have metal abundances that vary by as much as a factor of 100 over the surface, the magnetic field may not be sampled uniformly over the observed disk of the star which can make interpretation of the magnetic field structure problematical.

A less restrictive instrument for measuring longitudinal magnetic fields in hot stars is the Balmer line polarimeter, first developed for stellar applications by Angel & Landstreet (1970). A typical 2-channel photoelectric polarimeter uses narrow band ($\approx 5$ Å) filters to measure the polarization in the red and blue wings of various Balmer lines (usually H$\beta$) or more recently He I $\lambda$5876 (Bohlender *et al.* 1987). Mathys (1989) has demonstrated that the longitudinal magnetic field strength is proportional to the differential polarization measured between the two wings. Since pressure broadening dominates these line profiles, magnetic field measurements with a Balmer

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line polarimeter have the advantage that they can be performed even for rapidly rotating stars and since hydrogen and helium are generally much more evenly distributed over the surfaces of magnetic stars than are heavier elements the magnetic field is sampled much more uniformly over the surface of the star.

## 2.2. The Surface Magnetic Field

Surface magnetic fields have been measured in only a few B stars. Babcock's star (HD 215441), a Bp Si star, presents an ideal case: this object has a very large magnetic field and rotates very slowly as far as B stars are concerned ($P_{rot} = 9^{d}.4871$). With a sophisticated line synthesis program that includes the effects of a magnetic field and non-uniform surface abundances on the line profiles of a star Landstreet *et al.* (1989) modelled the resolved Zeeman splitting observed in spectra of the Si III multiplet 2 lines to measure dipolar, quadrupolar and octupolar polar field strengths of 67, 55, and 30 kG respectively. (This multiplet is perhaps the best suited as a surface magnetic field diagnostic in the visible spectral region of B stars since the three lines have a range of Zeeman sensitivities and Zeeman splitting patterns.) The $\lambda$4574 profile also demonstrates the remarkable uniformity of the surface field of the star: the intensity between the resolved Zeeman components of the line, a simple triplet, approaches the continuum very closely which can only occur if the range in surface magnetic field strength is very small.

The majority of magnetic B stars rotate too rapidly to have resolved Zeeman components or even enhanced broadening of magnetically sensitive lines. However, a related technique that has had some success in measuring surface fields in moderately rotating magnetic B stars is the observation of differential magnetic intensification of spectral lines in a multiplet. The principle behind this technique has been discussed by Babcock (1949) and is illustrated in Fig. 1 for the Si III multiplet 2 lines. Each line in the multiplet is located on the flat portion of the curve of growth. As the magnetic field strength increases, each line splits into its multiple Zeeman components (whose relative strengths and splittings are illustrated) and as the field continues to increase the separations between individual $\sigma$ and $\pi$ components eventually exceeds the thermal broadening of the line. The result is a desaturation of the line and an increase in the equivalent width—an effect very similar to that caused by microturbulence. The important difference is that the degree of intensification depends on the Zeeman structure of the line profile as well as the magnetic field strength so that the line strengthening is different for each line in the multiplet. If the quality of the data is high enough so that the continuum can be located with high precision and blended lines eliminated from the analysis then this technique, in principle, can be carried out for any star regardless of $v \sin i$ if the magnetic field is large enough. Surface magnetic field strengths have been derived in this manner

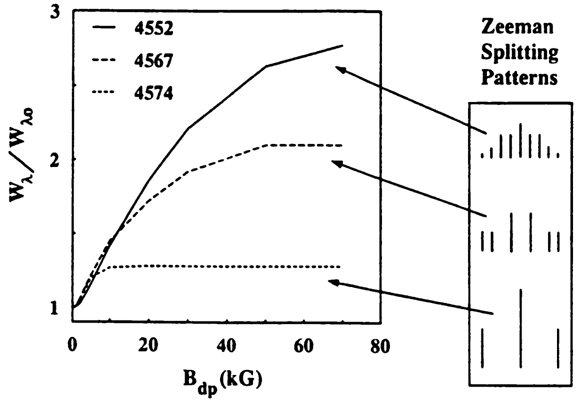


Fig. 1. Differential magnetic intensification of the Si III multiplet 2 lines. Calculated equivalent widths of each line in the multiplet relative to the equivalent width with no magnetic field present are plotted as a function of the polar field strength of a dipolar magnetic field. The equivalent width of the λ4574 line reaches a maximum for a relatively small field while the other two lines continue to intensify.

for only a few magnetic B stars (Bohlender 1989) but additional data is currently being analysed (Bohlender & Landstreet 1994).

## 3. Magnetic Field Observations

Typical effective magnetic field curves for two of the hottest known magnetic helium-strong stars are shown in Fig. 2. Each star has a field that varies sinusoidally with time but, as these examples show, in some cases the field strength variations are approximately symmetric about a mean value of zero, while in other cases the sign of the field does not change. In the ORM scenario the sinusoidal curves suggest field geometries dominated by a dipolar component and a non-reversing magnetic field is indicative of a small inclination of the field axis to the rotation axis.

Not all magnetic B stars have sinusoidal magnetic field curves. A few have apparently constant fields (Bohlender *et al.* 1987) almost certainly caused by an $i$ or $\beta$ near zero, but of more interest are stars with variable, non-sinusoidal field curves. The most notable of this small group of objects is the helium-strong star HD 37776 and its magnetic field curve based on data obtained by Thompson & Landstreet (1985) is plotted on their derived ephemeris for the positive extremum of the field in Fig. 3. As part of a detailed study of this star, Bohlender & Landstreet (1994) have attempted several model fits to the observed field curve and the fit for one of these is illustrated as the solid line in the figure and described by the accompanying magnetic parameters. HD 37776 is the first known case of a star whose magnetic field geometry is dominated by a quadrupolar component.

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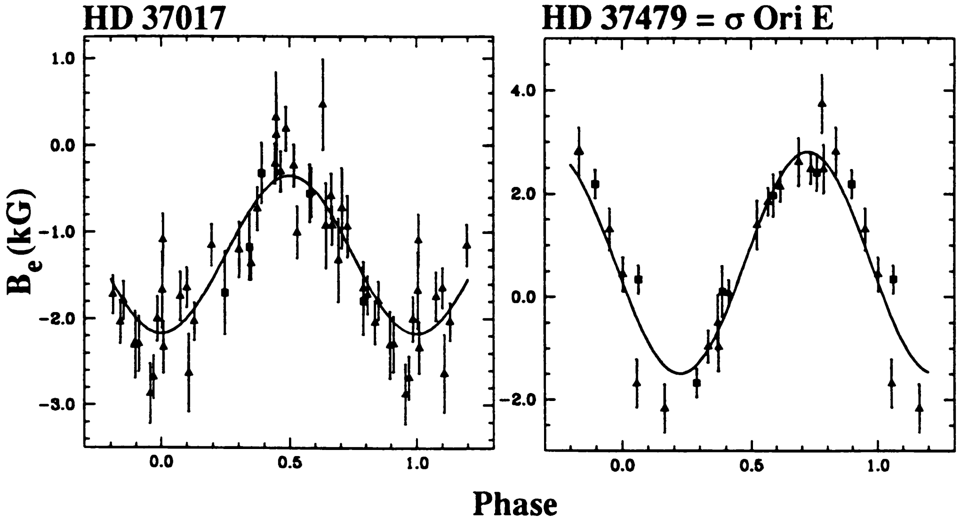


Fig. 2. Typical effective magnetic field curves for two helium-strong stars. The sinusoidal field variations imply magnetic geometries dominated by a dipolar field component.

## 4. Magnetic Fields and Stellar Winds

Besides having large (> 1 kG) effective magnetic fields, the helium-weak and helium-strong stars are spectroscopic and photometric variables, have magnetically controlled stellar winds as demonstrated by variable UV resonance lines of C IV and Si IV (Shore & Brown 1990) and variable H$\alpha$ emission (Walborn 1982; Bolton *et al.* 1986) and are also non-thermal radio sources (Linsky *et al.* 1992). The helium-peculiar stars, therefore, display many of the same phenomena seen in OB stars and present us with an excellent opportunity to quantitatively examine the effects of magnetic fields on the atmospheres and winds of hot stars.

Gravitational and radiative diffusion processes interact with the magnetic field and the stellar wind and give rise to peculiar, non-uniform abundances, usually approximately axisymmetric with the magnetic axis. Helium abundances can vary by more than a factor of 5 over the surface of a star while metal abundance anomalies can be even more pronounced. Fig. 4 shows an example of helium and silicon line profile variations in HD 37776. These large abundance variations create structural changes in the atmosphere of magnetic stars which in turn lead to photometric variations of typically several hundredths of magnitudes. (e.g. Bohlender 1988, Bohlender & Landstreet 1990a, 1994; Landstreet *et al.* 1989).

Shore & Brown (1990) have produced a phenomenological model for the winds and magnetospheres of the helium-peculiar stars based on observa-

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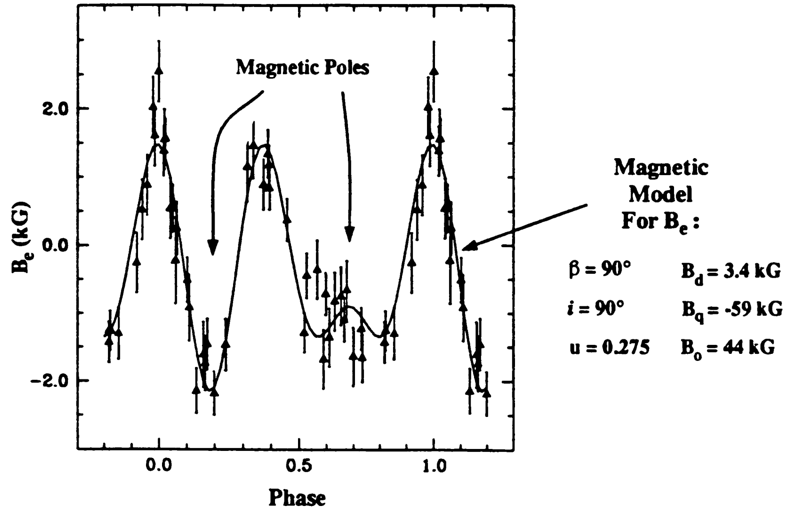


**Fig. 3. The peculiar magnetic field curve of the helium-strong star HD 37776. The model fit given by the solid curve through the data points is given by the parameters to the right of the figure. The magnetic axis for the model crosses the line of sight at the two phases indicated.**

tions of the UV line profile variations. They suggest that these stars have mass outflows restricted to the magnetic pole regions and hot circumstellar plasma trapped in the equatorial regions of the magnetic field. The variety of UV resonance profiles observed and the nature of the variability of the profiles are then a consequence of various oblique rotator geometries, and inclinations of the rotation axis to the line of sight. Linsky *et al.* (1992) have extended this picture somewhat to explain the radio emission from the magnetic peculiar stars in general.

Bolton and his collaborators have obtained extensive H$\alpha$ observations of several helium-peculiar stars to investigate cooler regions of their magnetospheres. Early results for the prototypical helium-strong star $\sigma$ Ori E were discussed by Bolton *et al.* (1986) and more detailed modelling has been presented by Short & Bolton (these Proceedings). In Fig. 5 we show an extensive collection of H$\alpha$ spectra and their residuals for the helium-strong star $\delta$ Ori C. This is obviously another case of a magnetic Be star and we believe the emission is produced by wind material trapped near the magnetic equator. If we assume that the star's magnetic field forces the emitting material into corotation with the photosphere then the peak emission occurs at about 3.4 $R_*$ above the photosphere and extends to about 5.2 $R_*$.

A similar, but less extensive data sample is shown for the helium-weak star 36 Lyn in Fig. 6. Also illustrated is our complete set of magnetic measurements for this star which permit a very precise period determination

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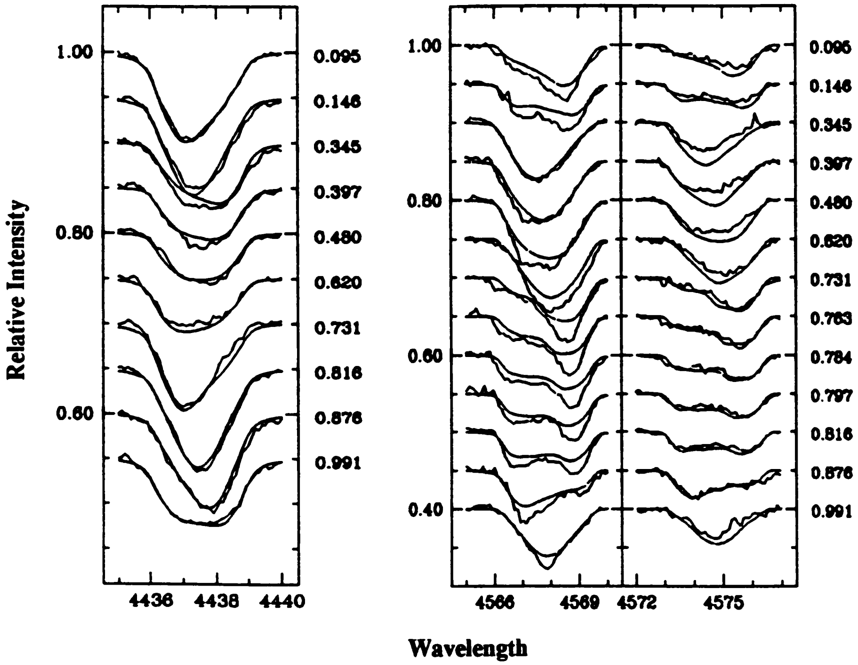


Fig. 4. Observed and modelled helium λ4437 and silicon λλ4567 and 4574 line profile variations in the helium-strong star HD 37776. For the model fits, generated without regard to the effects of the strong surface field predicted by the model in Fig. 3, the helium and silicon abundances vary by more than a factor of 5 and 70 respectively. Evidence of differential magnetic intensification in the silicon lines is apparent despite the high $v \sin i$ of 95 km $s^{-1}$.

of 3.83483 d. Additional H$\alpha$ observations are being obtained for this interesting star, but it is already clear that it undergoes two brief shell phases precisely when the magnetic equator crosses the line of sight to the observer and when the C IV and Si IV line profiles increase markedly in strength (Shore *et al.* 1990). Together, these observations again suggest that we are seeing cool and hot material trapped in the magnetosphere of this object. As of this writing, 36 Lyn is the coolest star for which we have evidence of magnetically confined circumstellar material.

## 5. Other Magnetic Field Observations

Could magnetic fields in other OB stars contribute to the extensive variability we observe in these objects? Several unsuccessful attempts have been made to measure magnetic fields in Be and Oe stars (Barker 1986). In no case, however, were more than two or three observations obtained for a single program star. We decided to pursue the question of magnetic fields in

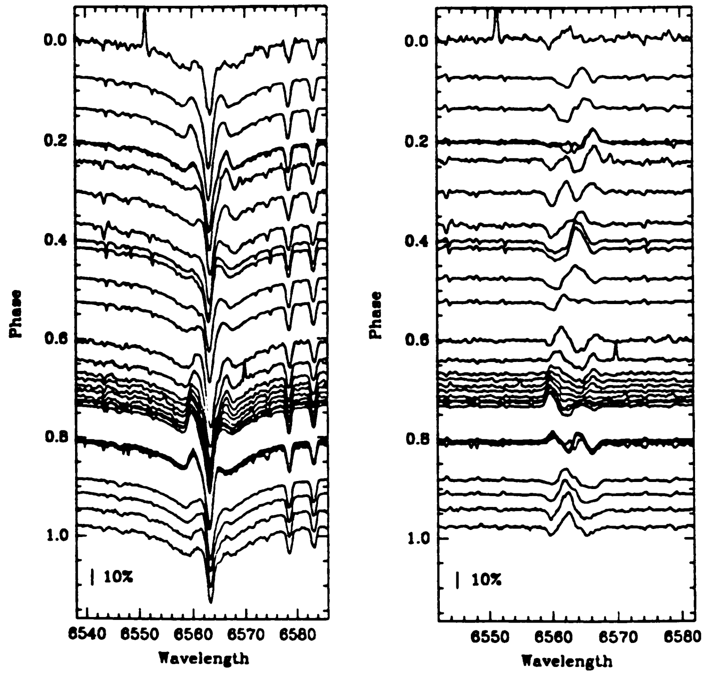


**Fig. 5.** Hα emission variability of the helium-strong star δ Ori C. The right panel displays the residual profiles after the mean of the profiles on the left has been subtracted from each observation. A rotation period of 1.4778 d has been derived from these data.

Be stars with more rigour for several objects that Harmanec (1984) has suggested might be related to the helium-strong stars because of their well defined light curves and stable periods. One of these objects was *o* And and the result of several seasons of Hβ polarization measurements is shown in Fig 7. No field was positively detected for this object or any of the other program targets. Fig. 7 also shows the magnetic curve for the bright Ap star ϵ UMa. This object has the weakest magnetic field detected so far among the magnetic Ap stars and has an amplitude of only 96 G (Bohlender & Landstreet 1990b). It is possible that a field of this magnitude could be lost in the noise of the measurements of *o* And but a considerable investment of 4-m telescope time will be needed to establish this.

We are also carrying out a long-term survey of magnetic field measurements in O stars. To date observations of more than 50 OB stars with spectral types earlier than B2 have not yielded a single positive detection of a magnetic field at the 300 G level. This survey does, however, suffer from a selection effect: we have so far avoided strong emission-line objects since emission effectively dilutes the photospheric polarization signal and makes

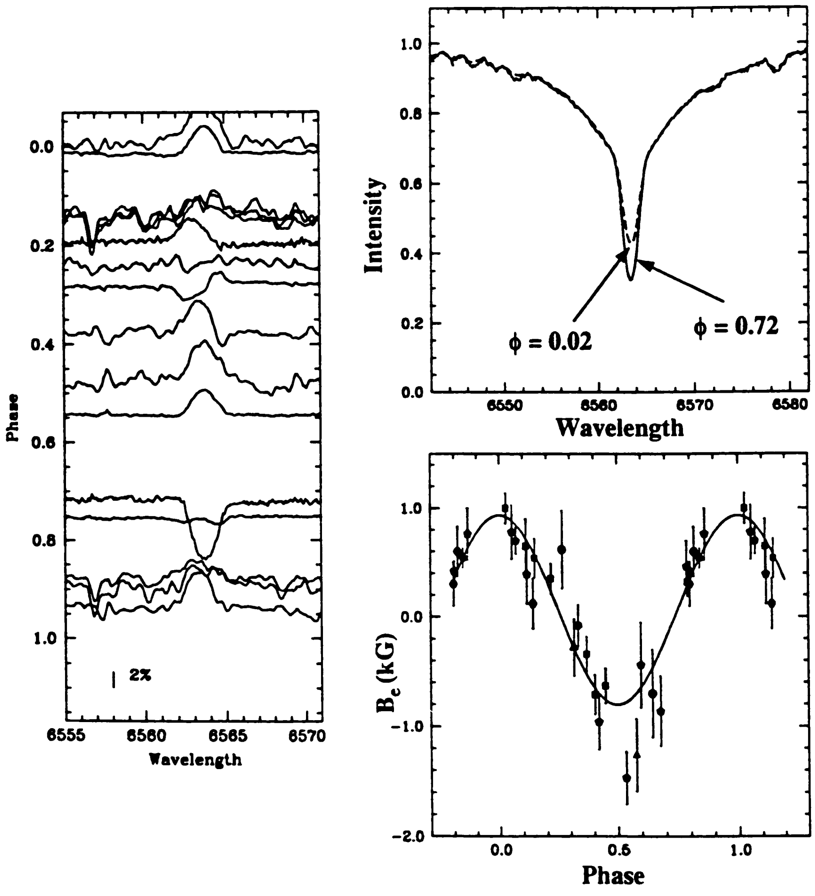


Fig. 6. Top right: the Hα shell phase of the helium-weak star 36 Lyn. Bottom right: magnetic field observations phased on a period of 3.83483 d. Left: residual Hα profile variations after the mean of all spectra has been subtracted from each observation. Two shell episodes occur precisely when the magnetic equator crosses the observers line-of-sight.

magnetic field measurements even more difficult. However, we have already seen that the hottest known magnetic stars have Hα emission! Magnetic O stars may have even stronger emission because of their higher mass-loss rates, although the question arises as to how much material a star can constrain in its magnetosphere. In any case, given the tentative detection of a magnetic field in β Cep (Henrichs *et al.* 1993) and the suggestion that fields on the order of 100 G in some O stars (Kaper *et al.* 1994) are needed to explain the phase relationship between discrete absorption components and variable Hα emission components, the current survey should likely be extended to include emission line stars.

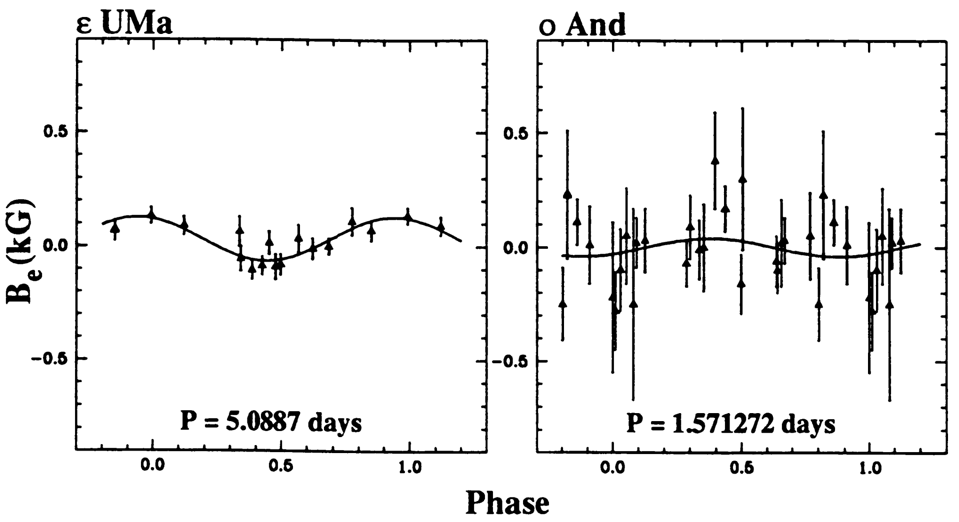


Fig. 7. Magnetic field measurements of the Be star *o* And phased on the photometric period of the star. The least-squares sinusoidal fit to the observations indicated by the solid curve is *not* statistically significant. On the left, the very small magnetic field variation of the bright Ap star $\epsilon$ UMa is shown to illustrate the smallest magnetic field that has been positively detected in a magnetic star.

## References

Angel, J.R.P. and Landstreet, J.D.: 1970, *Astrophys. J. Let.* **160**, 147.
Babcock, H.W.: 1947, *Astrophys. J.* **105**, 105.
Babcock, H.W.: 1949, *Astrophys. J.* **110**, 126.
Babcock, H.W.: 1951, *Astrophys. J.* **114**, 1.
Barker, P.K.: 1986, in Slettebak, A. Snow, T.P., eds., *IAU Colloquium 92, The Physics of Be Stars*, Cambridge Univ. Press: Cambridge, 38.
Bohlender, D.A.: 1988, *PhD Thesis*, Univ. Western Ontario: Canada.
Bohlender, D.A.: 1989, *Astrophys. J.* **346**, 459.
Bohlender, D.A., Brown, D.N., Landstreet, J.D., and Thompson, I.B.: 1987, *Astrophys. J.* **323**, 325.
Bohlender, D.A. and Landstreet, J.D.: 1990a, *Astrophys. J.* **358**, 274.
Bohlender, D.A. and Landstreet, J.D.: 1990b, *Astrophys. J. Let.* **358**, 25.
Bohlender, D.A. and Landstreet, J.D.: 1994, in preparation.
Bolton, C.T., Fullerton, A.W., Bohlender, D.A., Landstreet, J.D. and Gies, D.R.: 1986, in Slettebak, A. and Snow, T.P., eds., *IAU Colloquium 92, The Physics of Be Stars*, Cambridge Univ. Press: Cambridge, 82.
Borra, E.F., Landstreet, J.D. and Thompson, I.B.: 1983, *Astrophys. J. Suppl.* **53**, 151.
Gray, D.F.: 1988, *Lectures on Spectral-Line Analysis: F, G, and K Stars*, The Publisher: Arva, Ontario., 6-1.
Harmanec, P.: 1984, *Bull. Astron. Inst. Czechosl.*, **35**, 193.
Henrichs, H.F., Bauer, F., Hill, G.M., Kaper, L., Nichols-Bohlin, J.S. and Veen, P.M.: 1993 in *IAU Colloquium 139, New Perspectives on Stellar Pulsation and Pulsating Variable Stars*, in press.
Kaper, L., Henrichs, H.F., Ando, H., Bjorkman, K., Fullerton, A.W., Gies, D.R., Hirata, R., Kambe, E., McDavid, D. and Nichols, J.S.: 1994, *Astron. Astrophys.* submitted.

Landstreet, J.D.: 1980, *Astron. J.* **85**, 611.
Landstreet, J.D.: 1992, *Astron. Astrophys. Rev.* **4**, 35.
Landstreet, J.D., Barker, P.K., Bohlender, D.A. and Jewison, M.S.: 1989, *Astrophys. J.* **344**, 876.
Linsky, J.L., Drake, S.A. and Bastian, T.S.: 1992, *Astrophys. J.* **393**, 341.
Mathys, G.: 1988, *Astron. Astrophys.* **189**, 179.
Mathys, G.: 1989, *Fund. of Cosmic Physics*, **13**, 143.
Mathys, G.: 1991, *Astron. Astrophys. Suppl.* **89**, 121.
Saar, S.H.: 1990, in Stenflo, J.O., ed., *Solar Photosphere: Structure, Convection, and Magnetic Fields*, Kluwer: Dordrecht, 427.
Shore, S.N. and Brown, D.N.: 1990, *Astrophys. J.* **365**, 665.
Shore, S.N., Brown, D.N., Sonneborn, G., Landstreet, J.D. and Bohlender, D.A.: 1990, *Astrophys. J.* **348**, 242.
Thompson, I.B. and Landstreet, J.D.: 1985, *Astrophys. J. Let.* **289**, 9.
Walborn, N.R.: 1982, *Publ. Astr. Soc. Pacific* **94**, 322.

## Discussion

**Peters:** I'm curious about the nature of the phase dependence in the photometric variations. Typically, do they correlate with extrema in field strengths?

**Bohlender:** No. The photometric variations are generally more closely correlated with the surface abundance geometries. These, of course, are in turn influenced by the magnetic field geometry, but also depend quite sensitively on the effective temperature as well as the age of the star.

**Peters:** Is it true that the equivalent width of the C IV wind line tends to anticorrelate with field strength?

**Bohlender:** This is certainly true in a few helium-weak stars and 36 Lyn is one example. It is more difficult to interpret the observations of the hotter helium-strong stars since some of the line variations observed in these objects may have a photospheric origin.

**Bolton:** Hunger has argued, I think persuasively, that the intensification of the C IV at the magnetic equator is due to photospheric abundance inhomogeneities.

**Peters:** In the Be stars that show short-term photometric variability the strength of the C IV line tends to correlate with the continuum flux.

**Balona:** Is there any conflict between the observed periods in the magnetic B stars and magnetic braking?

**Bohlender:** No. Walborn demonstrated that the $v \sin i$ distributions of helium-strong stars and non-magnetic B stars are indistinguishable, but Wolff also pointed out that magnetic braking in B stars is likely to be very inefficient because of the rapid evolution of such massive stars.

**Henrichs:** Is there any observational evidence that field strength depends on the line strength? I would expect this as a consequence of the steep radial dependence of the field strength over the atmosphere.

**Bohlender:** This is an interesting idea which has been investigated in late-type stars but, as far as I'm aware, not in upper main sequence magnetic stars. It might be possible to search for such an effect with a Balmer line polarimeter by making measurements of strongly magnetic stars with the interference filters sampling different portions of the line wings, or by looking at a widely separated pair of Balmer lines so that you sample a different level in the photosphere. My feeling, however, is that such an effect would be small when you consider the limited extent of the photosphere relative to the envelope of the star as a whole.

**Baade:** If magnetic fields are deduced from observations of a few line profiles, can one be confident that no confusion with other causes of line profile variability occurs? I am thinking in particular of the Be stars *o* And and LQ And mentioned by you.

**Mathys:** The best way to distinguish between various mechanisms possibly responsible for line profile variations and magnetic field effects is to observe in polarized light. The effect of a magnetic field will be different in different polarizations, contrary to the effect of pulsation, for instance.

**Henrichs:** In spite of your null detections among your OB-star survey, I would like to encourage you to continue this program, especially in view of the results by Grant Hill on $\beta$ Cep, where he detected a significant field only after seven attempts. Because one expects the field to be at maximum once or twice per rotation period it might be worth while to concentrate first on the rapid rotators.

**Bohlender:** I'm in complete agreement, but it will require a significant amount of 4-m class telescope time since each data point in the various magnetic curves I've shown required on the order of 2 hours of observation.

**Anandarao:** There have been reports of rapid (on timescales of minutes) variability of emission lines (H$\alpha$ etc.) in several Be stars. Is there a possibility that magnetic fields present in these stars could be responsible for these variabilities?

**Bohlender:** We certainly see variations in H$\alpha$ emission on hourly timescales for the helium-peculiar stars and these are definitely a result of the strong magnetic fields of these stars. I suspect that rapid variability could be a result of small scale magnetic fields in Be stars but such complex fields will be virtually impossible to detect directly.