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OBSERVATIONS OF THE TRANSVERSE ZEEMAN EFFECT IN THE MAGNETIC STAR BETA CORONAE BOREALIS: EVIDENCE FOR THE OBLIQUE ROTATOR MODEL

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ABSTRACT

We present photoelectric measurements of the transverse Zeeman effect in the magnetic star β CrB. The electric vector of the observed polarization in the 4520.2 Å line of Fe II describes a 360° rotation per magnetic cycle, as predicted by the oblique rotator model.
Subject headings: stars: magnetic — stars: rotation — Zeeman effect

I. INTRODUCTION

More than a quarter century has elapsed since H. W. Babcock (1947) announced the first discovery of a stellar magnetic field in an Ap star. Many other magnetic Ap stars have since been found. Among the competing theories to explain the magnetic variations of these stars (Ledoux and Renson 1966), the oblique rotator model is now generally regarded with the most favor. Still, in a recent review Preston (1971) felt obliged to remark that the model does not meet universal acceptance because no crucial test has been devised, so that the evidence for it is mostly circumstantial.

It is well known that in an absorption line formed in the presence of a magnetic field, the π component is linearly polarized, with the electric vector perpendicular to the field. The σ components are usually elliptically polarized, and the linearly polarized component has its electric vector parallel to the field. Observation of the transverse Zeeman effect in a magnetic star can thus provide a powerful test of the oblique rotator model because the mean transverse magnetic field, and therefore the electric vector of the linearly polarized light, should describe a 360° rotation throughout a magnetic cycle.

In this *Letter* we report the outcome of such a test applied to the magnetic Ap star β CrB. This star was chosen because it is bright and has a large H_s/H_e ratio (Wolff and Wolff 1970) that suggests a sizable transverse component.

II. OBSERVATIONS OF THE TRANSVERSE ZEEMAN EFFECT

We used the coudé polarimeter of the Mount Wilson 100 inch (2.5 m) telescope (Borra and Landstreet 1973; Borra, Landstreet, and Vaughan 1973) equipped with a Fabry-Perot interferometer having an instrumental half-power bandwidth of 0.086 Å to obtain the observations reported here. A detailed description of the instrument, along with extensive observations of the Zeeman effect in β CrB, is in preparation and will appear elsewhere (Borra and Vaughan 1977). The spectral line used for our study is Fe II 4520.2 Å. In what follows we use the Stokes vector representation of polarized light (Shurcliff 1962). The reference direction (Q positive) is chosen to lie in the plane of constant right ascension passing through the star, with angles increasing counterclockwise, as seen by an observer facing the star. The parameter Q is measured by inserting a quarter-wave plate in the beam, following the Babinet-Soliel compensator, its optical axes at 45° to the reference direction. Light linearly polarized at 45° to the axes of the quarter-wave plate is thus transformed to circularly polarized light, which is then measured by the polarimeter. The parameter U is positive in the west quadrant. It could be measured by rotating the quarter-wave plate by 45°. In practice, it was measured by removing the quarter-wave plate and adding a quarter-wave retardation to the Babinet-Soliel compensator, which is used to eliminate the phase shift introduced by the flat coudé mirror (Borra and Landstreet 1973).

The observations consisted of intensity and polarization measurements across the spectral line in discrete steps of about 0.0862 Å at eight different phases of the magnetic cycle of β CrB (Table 1). The phases have

TABLE 1

SUMMARY OF THE OBSERVATIONS

Date (UT)	Phase	Q (%)	U (%)	θ	ψ
1974 July 31.20...	0.019	+0.48	−1.33	−35.1	−35.1
1974 June 25.31...	0.078	+1.87	−1.17	−16.0	−12.7
1974 June 26.30...	0.132	+1.66	−0.77	−12.5	+ 5.8
1974 June 28.30...	0.240	+0.20	+1.63	+41.5	+44.7
1974 June 29.29...	0.293	−0.85	+1.47	+60.0	+63.7
1974 June 30.29...	0.347	−1.39	+0.67	+77.0	+83.2
1974 July 28.23...	0.858	−1.20	+0.30	+83.0	+87.0
1974 May 15.44...	0.867	−1.17	−0.53	+102.0	+90.5

been computed from the ephemeris JD = 243417.5 + 18.487E (Preston and Sturch 1967). The full data will be presented elsewhere. As an illustration of the data obtained, we display in Figures 1 and 2 the U and Q signatures and line profiles obtained at phase 0.293. The instrumental polarization has been subtracted from

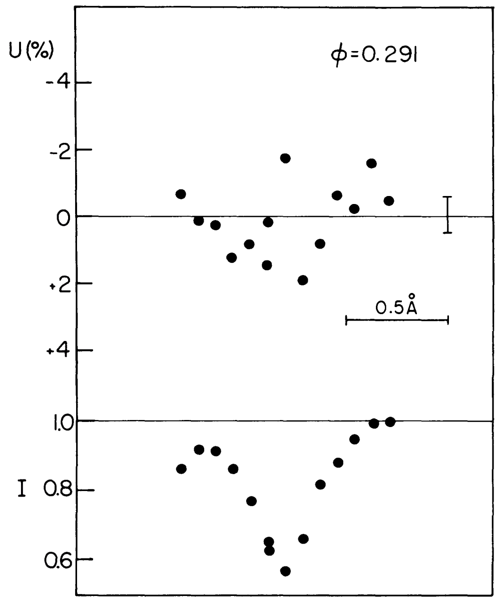

FIG. 1.—Observed variation of Stokes parameter U and intensity I with wavelength in the line Fe II 4520.2 Å in β CrB at phase 0.291. Error bar represents two standard deviations ($2\ \sigma$) calculated from photon Schott noise. The wavelength intervals between successive observations are 0.082 Å.

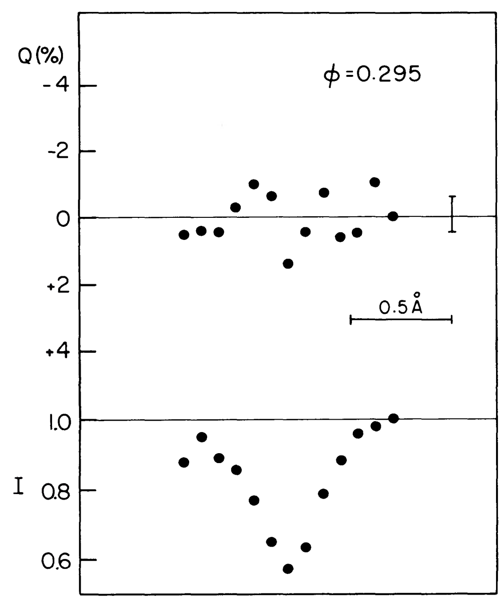

FIG. 2.—Observed variation of Stokes parameter Q and intensity I with wavelength in the line Fe II 4520.2 Å in β CrB at phase 0.295. Error bar has the same meaning as in Fig. 1.

the scans, using the technique of Borra and Landstreet (1973). The standard deviation per point is 0.5 percent on the assumption that photon noise is the only source of random error. Our experience with the polarimeter satisfies us that this is very nearly the case. There is cross talk of about 12 percent between the circular polarization and the observed Q parameter, but not the U parameter. This has been taken into account in the discussion that follows.

In Figures 1 and 2 we can see (albeit with low signal-to-noise ratio) the characteristic signature of the transverse Zeeman effect. The polarization has the same sign in both wings, abruptly changing sign at the line center. Fortunately, the rotation of β CrB is slow enough that the Doppler effect does not significantly distort the Zeeman signature.

We define the average values $U = (U_{\text{blue}} + U_{\text{red}} - U_{\text{center}})/3$ and $Q = (Q_{\text{red}} + Q_{\text{blue}} - Q_{\text{center}})/3$. The angle θ of the electric vector is given by $\tan 2\theta = U/Q$. In Table 1 we give, for each scan, the angle θ, together with the average transverse field angle $\psi = 360\ \Phi + \psi_0$ predicted by the oblique rotator model with simple geometry (such as a dipole), where Φ is the magnetic phase and ψ_0 is taken to be equal to the observed angle $\theta = -35°$ at phase 0.0185. Note that ψ and $\psi + 180°$ are observationally indistinguishable; thus in Table 1 we have subtracted multiples of 180° so that in all cases $0 \leq \psi < 180°$.

In Figure 3 we represent the rotation in the Q, U plane. Straight lines from the origin lie at the angles 2ψ appropriate to the phases of the given observations. Each plotted point representing an observation is labeled with its magnetic phase at mid-time of observation. Dashed lines show the sequence of phases from 0.019 to 0.867. With the single exception of the observation at phase 0.132, there is excellent agreement between the predictions and the observations. We

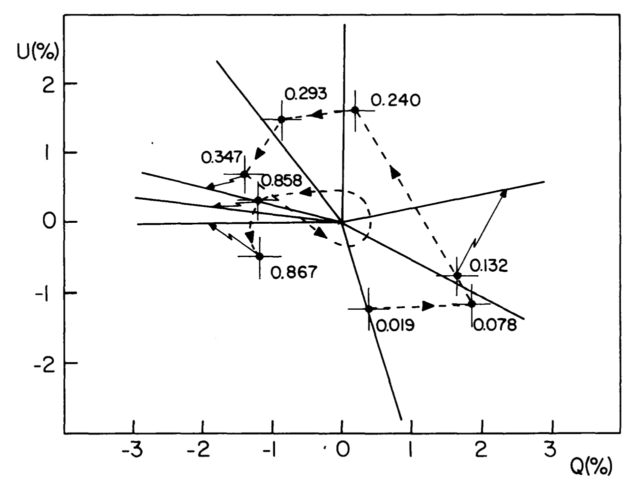

FIG. 3.—Comparison of observations with prediction of the oblique rotator model in the (Q, U) plane. The observations are plotted with estimated error bars in U and Q (see Table 1) at each indicated magnetic phase. Where ambiguity might arise, an arrow shows which angle the phase refers to. Dashed lines indicate the direction of rotation in the Q, U plane.

could slightly improve the agreement by changing ψ_0; this is certainly allowed by the experimental uncertainty in θ_0. The significance of Figure 3 is that it clearly shows a double 360° rotation in the QU plane per magnetic cycle, as required by the oblique rotator model. In particular, the points at phases 0.347 and 0.858, nearly a half-cycle apart, do indeed fall very near each other. Figure 3 also gives us the direction of rotation of β CrB: an observer looking at the star sees it rotate counterclockwise in the plane of the sky.

III. CONCLUSION

We have detected linear polarization caused by the transverse Zeeman effect in β CrB. Our observations show that the electric vector of the polarized light (and thus the mean transverse magnetic field) describes a rotation in the plane of the sky at a rate of 360° per magnetic cycle. This result adds direct support to the oblique rotator model for β CrB, and thus, presumably, for all Ap stars.

Kemp and Wolstencroft (1974) have reported a 360° per magnetic cycle rotation of the electric vector of the continuum polarization in 53 Camelopardalis. Finn and Kemp (1974) interpret this polarization as a magneto-optical effect (the Hanle effect). The rotation of the electric vector, in this case, would also describe the rotation of the mean transverse field, in agreement with the oblique rotator model. However, there are competing theories for this continuum polarization that do not involve the magnetic field (Finn and Kemp 1974). Our test has the advantage that there is no competing explanation for the strong polarization in Fe II 4520.2 Å and its characteristic Zeeman signature. The Kemp and Wolstencroft observations, whether or not of a magnetic nature, are also in agreement with the oblique rotator model.

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