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HIGH-RESOLUTION POLARIZATION OBSERVATIONS INSIDE SPECTRAL LINES OF MAGNETIC Ap STARS. III. OBSERVATIONS OF 78 VIRGINIS

ERMANNO F. BORRA
Département de Physique, Université Laval, and Observatoire du Mont Mégantic
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ABSTRACT

Circular polarization and intensity profiles have been obtained across the Fe II λ4520.2 line throughout the magnetic cycle of the Ap star 78 Virginis. The B_e curves obtained from the data are briefly discussed and compared to the B_e curves obtained with other techniques.

Subject headings: polarization — stars: individual — stars: magnetic — stars: peculiar A

I. INTRODUCTION

The bright Ap star 78 Virginis is the first star in which a magnetic field was discovered (Babcock 1947). Babock found that the field was always negative and variable. The star was originally thought to be an irregular variable; however, Preston (1969) has shown that it is actually a periodic variable having a period of 3.722 days. Preston found that the average longitudinal field B_e varies between -500 gauss and -1500 gauss, and that the crossover effect is very pronounced and is present throughout most of the magnetic cycle. Wolff and Bonsack (1972) found a similar magnetic curve having perhaps a smaller amplitude. The star is marginally variable in light, radial velocity, and spectrum (Preston 1969). However, Preston finds that Henry's (1966) *k* index curve shows a definite variation of the Ca II K line. Preston concludes that the star can be understood in terms of an oblique rotator model having a small inclination of the rotation axis with respect to the line of sight.

Borra and Landstreet (1979) recently measured the magnetic curve of 78 Vir with a photoelectric Balmer-line magnetograph. They confirm the nonreversal of B_e, but find that B_e measured in the wings of Hβ varies between about -100 and -900 gauss.

In this third paper of a series, I present high-resolution polarization and spectral flux scans across the Fe II λ4520.2 line of 78 Vir, taken throughout the magnetic cycle. The main use of the scans should be in computer modeling the magnetic geometry of the star.

II. THE OBSERVATIONS

In an earlier paper Borra and Vaughan (1977) described in detail the coudé polarimeter with Fabry-Perot interferometer of the 2.5 m Mount Wilson telescope. The instrument is used to scan the Fe II λ4520.2 line in discrete steps of 0.086 Å, equal to the half-power bandwidth of the instrument.

The circular polarization (Zeeman signature) and line profiles are shown in Figures 1 and 2. Each scan is identified with its magnetic phase at the midpoint of observation, computed from the ephemeris (Preston 1969) JD = 2,434,816.9 + 3.7220*E*. The heliocentric Julian date of each scan and the duration of the scans (in days) are listed in Table 1. The error bars associated with each polarization scan are shown in Figures 1 and 2 and represent two standard deviations ($\pm\sigma$). They are computed assuming that photon shot noise is the only source of random error. The uncertainty in the line profiles is larger and should typically be ~2%. The photomultiplier dark counts are a small fraction of the total acounts and have been removed from the profiles in Figures 1 and 2 and taken into account in computing σ. The standard deviations of the polarization measurements are the same throughout a single scan, but vary from scan to scan and are either 0.5%, 0.7%, or 1%.

We can see that, as remarked by Preston, the crossover effect is present during most of the magnetic cycle and is very pronounced. The only polarization profiles that show the simple S-shaped Zeeman signatures indicating a pure negative polarity are the ones at phases 0.54 and 0.56. If we compare Figures 1 and 2 to the scans of β CrB (Borra and Vaughan 1977), we can see less structure in the Zeeman signatures of 78 Vir. This is not necessarily indcative of a simpler magnetic geometry, but perhaps merely reflects the fact that 78 Vir has a higher value of $V \sin i$ and that Doppler motions tend to smooth out the Zeeman signatures. We can also recognize similarities between some of the crossover profiles of 78 Vir and α^2 CVn (Borra and Vaughan 1978); however, unlike in α^2 CVn, the Fe II λ4520.2 profiles of 78 Vir do not show noticeable spectral variations. This will make modeling easier.

III. THE LONGITUDINAL MAGNETIC FIELD VARIATIONS

Values of the average longitudinal magnetic field B_e have been computed using both methods described by Borra and Vaughan (1977). They are referred to as the differential and the integral method according to the type of formula used. The differential method computes B_e from a least squares fit to the equation

$$V = 4.67 \times 10^{-13} z B_e \lambda^2 \frac{dI(\lambda)}{d\lambda} \frac{1}{I(\lambda)}, \qquad (1)$$

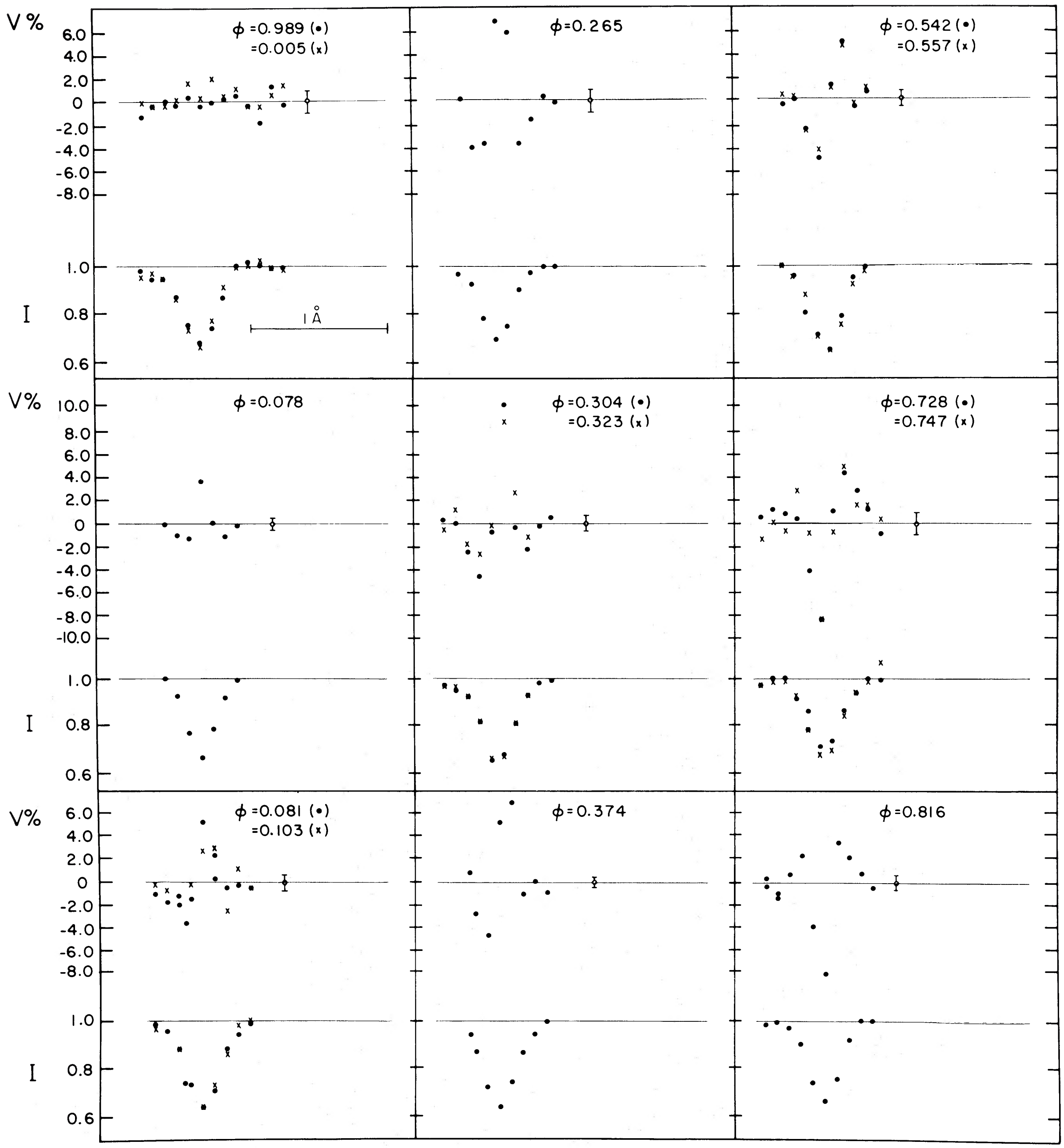

FIG. 1.—Circular polarization and line profiles obtained in Fe II λ4520.2. Each scan is identified with the phase at the midpoint of observation. Wavelength increases left to right and the spacing between data point is always 0.086 Å; the wavelength scale is shown in the first scan and is the same for all scans. The error bars accompanying each polarization scan are equal to two standard deviations ($\pm\sigma$).

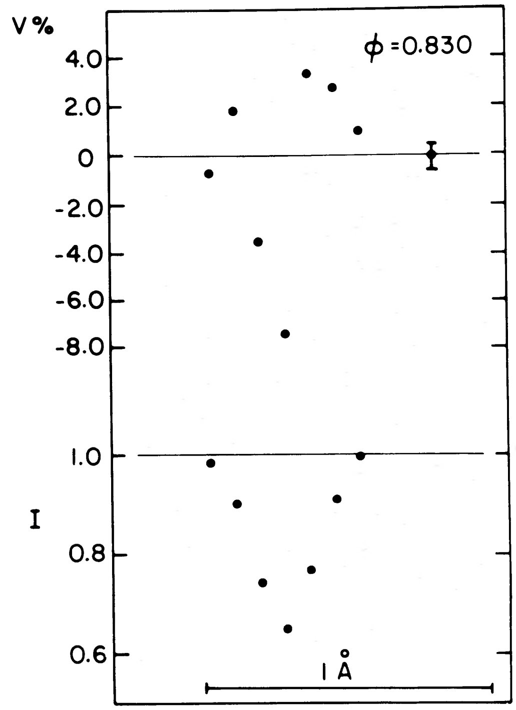

FIG. 2.—Same as Fig. 1

where z is the z factor of the line ($z = 1.5$ for Fe II 4520.2), B_e is in gauss, $I(\lambda)$ is the intensity profile normalized to 1 at the continuum, and V is the fractional polarization ($100\% = 1.0$). The integral method makes use of the integral equation

$$\Delta\lambda = \frac{\int \lambda V_c(\lambda) d\lambda}{\int r_I(\lambda) d\lambda}, \qquad (2)$$

where

$$r_I(\lambda) = 1 - I(\lambda), \qquad (3a)$$

and

$$V_c(\lambda) = V(\lambda) I(\lambda) \times 10^{-2}. \qquad (3b)$$

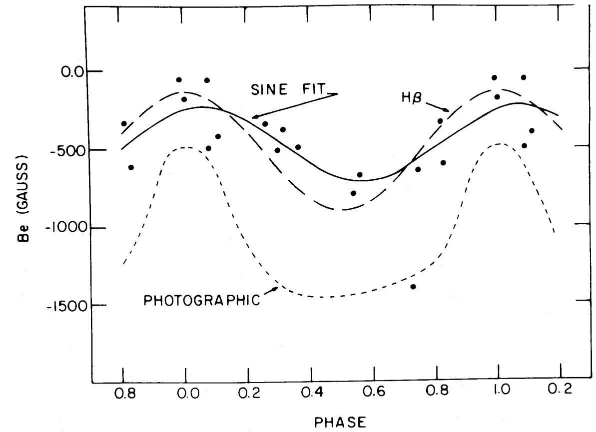

FIG. 3.—Longitudinal magnetic fields (B_e) in gauss, obtained with the integral method. The full line shows a sine curve fit to the data. The broken line shows the photoelectric B_e curve obtained by Borra and Landstreet (1979) in Hβ. The dashed line (small dashes) shows the photographic B_e curve from Preston (1969).

B_e is then given by

$$\Delta\lambda = 4.67 \times 10^{-13} z B_e \lambda^2. \qquad (4)$$

A more detailed discussion of the two methods is given by Borra and Vaughan (1977, 1978). The values of B_e obtained with the integral method are given in column (5) of Table 1 and are plotted in Figure 3, while the values of B_e obtained with the differential method are given in column (4) of Table 1 and are plotted in Figure 4. The sine wave fit to the Hβ B_e observations of Borra and Landstreet (1979) is shown in Figures 3 and 4 as a broken line. A hand-fit through Preston's (1969) photographic B_e observations is shown as a dashed line (small dashes) in Figures 3 and 4. The unbroken line in Figures 3 and 4 is a least squares fit to the data with the equation

$$B = B_1 \sin 2\pi(\Phi - \Phi_0) + B_0. \qquad (5)$$

TABLE 1

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JD$_\odot$ (2,440,000+)	Duration (Days)	Phase	B_e(Differential) (gauss)	B_e(Integral) (gauss)
2182.697.........	0.06	0.989	−32	−64
2182.757.........	0.06	0.005	−171	−187
1784.774.........	0.10	0.078	−182	−58
2145.819.........	0.07	0.081	−252	−503
2145.903.........	0.09	0.103	−380	−415
2183.726.........	0.05	0.265	−695	−348
2142.929.........	0.07	0.304	−911	−510
2142.999.........	0.07	0.323	−831	−394
1785.875.........	0.15	0.374	−933	−502
2143.815.........	0.05	0.542	−950	−790
2143.869.........	0.05	0.557	−911	−684
2181.725.........	0.07	0.728	−1685	−1379
2181.797.........	0.07	0.747	−605	−633
2144.835.........	0.08	0.816	−544	−337
1783.850.........	0.15	0.830	−647	−621

TABLE 2
PARAMETERS OF SINE WAVE FITTING

Method Parameter	$B_0 \pm \sigma$ (gauss)	$B_1 \pm \sigma$ (gauss)	$\phi_0 \pm \sigma$
Hβ (Borra and Landstreet 1979)......	-512 ± 60	380 ± 87	-0.241 ± 0.034
Integral method....................	-475 ± 42	245 ± 58	-0.180 ± 0.038
Differential method.................	-632 ± 32	415 ± 44	-0.249 ± 0.017

The values of B_0, B_1, and Φ_0 obtained are given in Table 2, where they can be compared to the corresponding values for the Hβ B_e curve of Borra and Landstreet (1979). The anomalous point at phase 0.728 has been omitted in the fitting.

The integral method seems to give a smaller extremum of B_e and a smaller amplitude to the magnetic curve than the differential method. The B_e curve obtained with the differential method gives the best agreement with the Hβ B_e curve. The photographic B_e curve disagrees with all curves by nearly a factor of 2. The photoelectric B_e curves obtained with both methods appear to be reasonably well fitted by a sine curve. The variance obtained from fitting equation (5) is 114 gauss for the differential B_e curve and 140 gauss for the integral B_e curve. Thus, the scatter is the largest in the integral B_e values.

The observation at JD 2,442,181.725 is obviously anomalous, as it deviates from the mean curve by several standard deviations. One might therefore be tempted to speculate that it is caused by irregular variations of the magnetic field. This observation is followed 2 hours later by the observation on JD 2,442,181.797 that falls within one standard deviation of the best-fit sine curve. It is hard to believe that such a drastic rearranagement of the lines of force can occur in such a short time. An inspection of the two scans does not reveal striking differences between the two profiles. We can see that most of the difference occurs on two points on the blue wing of the line. It is likely that the anomalous observation can be explained by a temporary malfunction of the system (perhaps interference from an electrical source in the dome) or human error.

Throughout this discussion, I have made the implicit assumption that the Fe II λ4520.2 line is unblended. Because the Ap stars have spectra that are very rich in absorption lines, this assumption is not necessarily correct. However, this assumption is supported by private communications with several spectroscopists (S. J. Adelman, P. W. Bidelman, and C. R. Cowley) who have analyzed high-dispersion spectrograms of 78 Vir; the Fe II λ4520.2 line does not appear to suffer from detectable blends in spectra of 78 Vir.

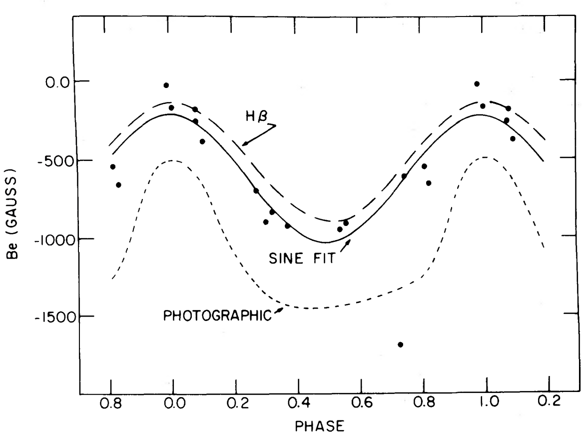

FIG. 4.—Longitudinal magnetic fields (B_e) in gauss, obtained with the differential method. The unbroken line shows a sine curve fit to the data. The broken line shows the photoelectric B_e curve obtained by Borra and Landstreet (1979) in Hβ. The dashed line (small dashes) shows the photographic B_e curve from Preston (1969).

IV. CONCLUSIONS

Observations of the circular polarization across the spectral line Fe I λ4520.2 have been obtained in the magnetic Ap star 78 Virginis at different phases of the magnetic cycle. The crossover effect is very pronounced, is present throughout most of the cycle, and varies in shape.

Values of B_e, the average longitudinal magnetic field, have been obtained from the scans using two different methods. The B_e curves thus obtained are well fitted by a sine curve and are in much better agreement with the photoelectric B_e curves obtained in Hβ than with the photographic B_e curves. In the following paper the polarization profiles will be modeled in the framework of the oblique rotator model.

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ERMANNO F. BORRA: Département de Physique, Université Laval, Québec, P.Q., Canada G1K 7P4