THE ASTROPHYSICAL JOURNAL, 358:L25–L28, 1990 July 20

THE WEAK MAGNETIC FIELD OF THE Ap STAR EPSILON URSAE MAJORIS

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Received 1990 April 4; accepted 1990 May 10

ABSTRACT

High signal-to-noise ratio circular polarization measurements in the wings of Hβ have been obtained for the bright A0pCr star ϵ UMa, throughout its $5^{d}.0887$ rotation period. These data suggest that ϵ UMa possesses an approximately dipolar magnetic field with magnetic extrema of $+128$ and -64 G. If the inclination of the rotation axis of the star is in the range $i = 65° \pm 15°$, then the obliquity of the magnetic field axis to the rotation axis is between 19° and 84°. The observations are compared with recent Doppler imaging studies of the surface abundances of ϵ UMa.

Subject headings: stars: individual (ϵ UMa) — stars: magnetic — stars: peculiar A

I. INTRODUCTION

The A0pCr star ϵ UMa (HD 112185, HR 4905) is the brightest ($V = 1.77$) member of the Ap class and one of the most intensively studied. Guthnick (1934) established a period of $5^{d}.0887$ from variations in the intensity of the Ca II K line, and also noticed a periodic splitting of some lines. Struve and Hiltner (1943) subsequently reported doubling of lines of Cr II, Fe II, V II, and other elements at certain phases. Since the overall widths of the lines do not change and not all lines double, they ruled out orbital motion as the cause of the doubling and instead suggested that the phenomenon is related to rotation of the star. Swensson (1944) and Deutsch (1947) confirmed Guthnick's observations and period determination. Provin (1953) measured a double wave light variation of approximately 0.025 mag with the same $5^{d}.0887$ period. The star is brightest when the Ca II K line intensity is near its minimum and Cr and other elements are near their maximum strength, and faintest near phases at which Struve and Hiltner (1943) observed the line doubling.

Tektunali (1981) carried out an abundance analysis of ϵ UMa and found that Al, Si, and Ca are underabundant; Sc, Ti, Fe, and Sr have normal abundances; and Mg, Ni, and, especially, V, Cr, Mn, Y, Zr, Ba, and rare earths are overabundant, by factors up to 1000. Woszczyk and Jasiński (1980) measured the radial velocity variations of many lines in the star and found sinusoidal variations in the radial velocities of Fe, Cr, and Ti lines with amplitudes of about 20 km s^{-1} and attributed this, and the previously observed line splitting, to the existence of at least one spot of enhanced abundances of these elements.

Recently, extensive effort has been made to map the surface abundance distribution of ϵ UMa by applications of various Doppler imaging methods (Wehlau *et al.* 1982; Hatzes 1988; Rice, Wehlau, and Khokhlova 1989; Rice and Wehlau 1990). Hatzes (1988) finds a prominent arc of depleted Cr II and three overabundant spots of Cr II, and postulates that the depleted region represents the magnetic equator of the star. The work of Rice and Wehlau (1990) indicates a geometry with Fe and Cr most abundant in two rings located approximately 50° away from two diametrically opposite regions on the star and roughly axisymmetric with respect to these regions. They suggest that these "poles" may represent the magnetic poles of a dipolar magnetic field. As in Hatzes's (1988) model, there is also an equatorial region of depleted abundances.

Perhaps the most interesting and controversial aspect of ϵ UMa is its magnetic field. Not surprisingly, Babcock (1958) was not able to measure a field. The substantial rotation velocity of the star ($v \sin i = 33$) is near the limit at which his photographic technique is useful. However, Landstreet *et al.* (1975) and Borra and Landstreet (1980), using a solar magnetograph technique on the Hα, Hβ, and Hγ lines, were also unable to detect a field in the star larger than a few hundred gauss. On the other hand, Glagolevsky *et al.* (1982, 1983) have reported observations of a magnetic field that varies from -300 to $+600$ G from polarization of Hγ, and, on the basis of a limited amount of data, a substantially different field variation from observations of polarization in the Fe II 4520.2 line. They attribute the difference to the nonuniform distribution of iron over the surface of the star. Finally, Hubrig (1988) has measured the magnetic field of ϵ UMa with Babcock's photographic technique and lines of Fe I, Fe II, Cr I, Cr II, and Ti II. He finds values for the field ranging from $+708$ to -1100 G.

The five Hβ polarization measurements of Borra and Landstreet (1980) have the smallest errors of previous attempts to detect a magnetic field in ϵ UMa. They reported that they could not detect any field in the star even with errors of approximately 50 G. This was a surprising result considering the strong spectrum variations observed for ϵ UMa. However, the measurements of Borra and Landstreet cover less than one-third of the star's rotation period when phased with Provin's ephemeris. Of interest to us, however, was the fact that these five measures do suggest a magnetic field varying smoothly from -90 to $+110$ G that went unnoticed because of the low signal-to-noise ratio of the individual measurements. Because of this, and because of the apparent inconsistencies in the various attempts to determine the magnetic field of ϵ UMa, as well as the urging of our colleagues, the authors decided to obtain additional magnetic field measurements of ϵ UMa with the UWO photoelectric Balmer-line Zeeman analyzer throughout its rotation cycle, and at a higher S/N than had previously been obtained. The results of these observations are reported in this *Letter*. During the course of this work we learned that an independent attempt to measure the magnetic field of ϵ UMa was also being carried out by Donati and his collaborators (Donati, Semel, and del Toro Iniesta 1990) using a considerably different method. As will be shown below, the results of both investigations are in excellent agreement and suggest that ϵ UMa possesses a weak, dipolar field with a maximum observed field strength of approximately 130 G.

II. OBSERVATIONS

The magnetic field measurements reported here were obtained with the UWO photoelectric Balmer-line Zeeman analyzer on the UWO 1.2 m telescope. The observing and reduction procedures have been described in detail elsewhere (e.g., Borra and Landstreet 1980) and so will not be repeated here. All circular polarization measurements were obtained in the wings of Hβ, with total integration times ranging from 1.6 to 3.6 hr. With the exception of the last observation, the interference filters used to isolate the Hβ profile have a half-power bandwidth of 5.0 Å and were tilt-tuned to points 3.5 Å to the blue and red side of the line center. The last measurement was acquired using a new pair of filters with a half-power bandwidth of 8.0 Å and set 5.0 Å from line center. A scan of the Hβ profile gives a conversion factor between the fractional circular polarization and the field strength of 12,650 G per percent for the old filters and 12,900 G per percent for the new ones. Table 1 gives the nine new magnetic field measurements. The Julian dates of the midpoints of each observation, the magnetic field strengths and uncertainties (counting noise is assumed to be the only source of error), and the phases calculated from Provin's (1953) ephemeris, JD = 2,434,131.124 + 5.0887E, are contained in columns (1)–(3), respectively. On this ephemeris, phase 0.000 corresponds to Ca II K line intensity minimum and light maximum.

We consider a star to be magnetic if the test statistic

$$\frac{\chi^2}{n} \equiv \frac{1}{n} \sum_{i=1}^{n} \frac{(B_e)_i^2}{\sigma_i^2} \tag{1}$$

is larger than the value expected for n degrees of freedom at the 99% confidence level. Borra and Landstreet's (1980) five previous Hβ observations yield a χ^2/n that is only significant at the 90% level. Combined with the new data in Table 1, we now find that the 14 Hβ observations give a χ^2/n of 3.25 that is significant at a confidence level exceeding 99.996%. We can quite safely say that a magnetic field has finally been detected on ϵ UMa.

The rotation period of ϵ UMa is well determined at $5^{\rm d}.0887 \pm 0^{\rm d}.0003$ (see references in Catalano and Renson 1984, 1988). With our limited magnetic data we did not expect to be able to improve upon this. Indeed, a period search of our data combined with the Hβ observations of Borra and Landstreet (1980) provides many suitable periods for the magnetic data alone. One of these is $5^{\rm d}.0887 \pm 0^{\rm d}.0013$, which is in complete agreement with the accepted period and therefore provides additional confirmation of the reality of the star's magnetic field.

TABLE 1

MAGNETIC FIELD DATA FOR ϵ URSAE MAJORIS

JD (2,440,000+) (1)	$B_e \pm \sigma_B$ (G) (2)	Phase (3)
7231.737.........	15 ± 50	0.452
7251.744.........	−105 ± 40	0.383
7598.711.........	35 ± 60	0.567
7607.732.........	−55 ± 55	0.340
7612.796.........	65 ± 65	0.335
7630.681.........	70 ± 45	0.850
7638.692.........	−85 ± 40	0.424
7723.658.........	90 ± 40	0.121
7941.820.........	140 ± 35	0.993

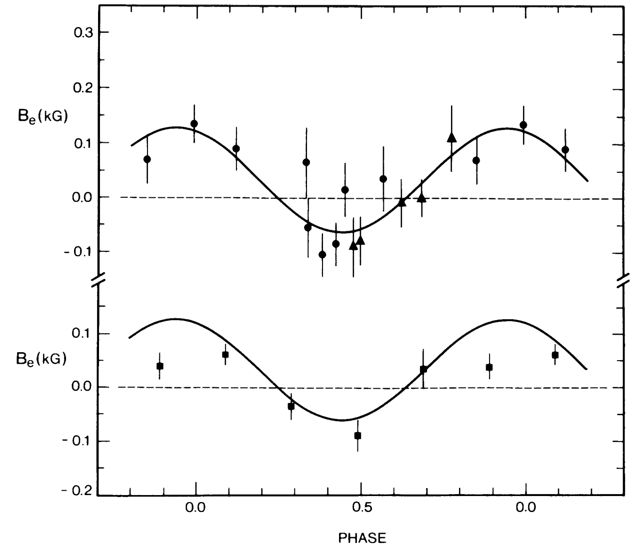

FIG. 1.—*Top:* The magnetic field curve of ϵ UMa. Symbols: *triangles*, Hβ observations of Borra and Landstreet (1980): *circles*, Hβ observations from this *Letter*. The curve through the magnetic observations is the best-fit sinusoid discussed in the text. *Bottom:* $B_{\rm eff}$ measurements of Donati *et al.* (1990). The solid curve is taken from the top panel.

The complete set of Hβ magnetic field measurements plotted on the above ephemeris is illustrated in Figure 1. The best-fit sinusoid given by the equation

$$B_e = B_0 + B_1 \sin 2\pi(\phi - \phi_0) \tag{2}$$

with $B_0 = 32 \pm 22$ G, $B_1 = 96 \pm 3$ G, and $\phi_0 = 0.691 \pm 0.100$ is also plotted and gives an excellent reduced χ^2 for the fit of 0.96.

For a magnetic field dominated by the dipole component the ratio of the magnetic extrema, r, can be used to provide a relationship between the inclination of a star's rotation axis, i, and the obliquity of the magnetic axis to the rotation axis, β (Preston 1967):

$$\tan \beta = (1 - r)/[(1 + r) \tan i] \ . \tag{3}$$

Acceptable sinusoidal fits to the magnetic data permit a range in r from -0.30 to -0.97 for ϵ UMa with a best-fit value of $r = -0.50$. The inclination of the star is poorly determined. Wehlau *et al.* (1982) adopt a value of 80°, Hatzes (1988) uses $i = 54°$, while Rice *et al.* (1989) and Rice and Wehlau (1990) find $i = 65°$. If we conservatively let the inclination lie in the range $i = 65° \pm 15°$ and allow for the uncertainty in r, we find only a weak constraint on the magnetic obliquity: $19° < \beta < 84°$.

As mentioned above, Donati, Semel, and del Toro Iniesta (1990) have recently carried out an independent study of the magnetic field geometry of ϵ UMa. They have obtained extremely high S/N spectropolarimetry of a magnetically sensitive Fe II line which clearly shows the presence of a variable surface magnetic field on the star. By numerical integration of the magnetic field distribution determined from the circularly polarized line profiles, they have derived estimates of the effective magnetic field of ϵ UMa at several phases. We have plotted these below our measurements in Figure 1 superposed on our

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best-fit sinusoid. Except for a slightly smaller amplitude, their B_e estimates are in excellent agreement with our Hβ measures. This difference in amplitude might be a result of the nonuniform distribution of Fe over the surface of the star.

III. DISCUSSION

It is obviously of interest to compare the magnetic geometry of ϵ UMa derived above with the surface abundance distributions found from Doppler imaging, especially the work of Hatzes (1988) and Rice and Wehlau (1990).

Hatzes (1988) has suggested that Cr is depleted near the magnetic equator of ϵ UMa. From the ephemeris of Provin (1953) that we have adopted for this work, the positive and negative magnetic poles of the star cross the line of sight to the observer at $\phi = 0.941$ and $\phi = 0.441$, respectively. These correspond to phases of $\phi_{\rm H} = 0.122$ and $\phi_{\rm H} = 0.622$ on Hatzes's ephemeris (A. Hatzes, private communication). For his value of $i = 54°$ our magnetic geometry gives $\beta = 65°$. The positive pole then approaches to within 11° of the subsolar point at $\phi_{\rm H} = 0.122$, and the negative pole to within only 61° of the subsolar point at $\phi_{\rm H} = 0.622$. Hatzes's (1988) Figure 1*a* illustrates surface equivalent width maps of ϵ UMa near these two phases (at $\phi_{\rm H} = 0.125$ and $\phi_{\rm H} = 0.625$). At $\phi_{\rm H} = 0.125$ he finds that Cr is depleted in an arc far from the subsolar point and hence far from the positive magnetic pole. At $\phi_{\rm H} = 0.625$ the same arc is in almost the same location as our proposed magnetic equator. We conclude that Cr does appear to be depleted at the magnetic equator of ϵ UMa. Several spots of high Cr abundance in Hatzes's (1988) model are then at intermediate magnetic latitudes.

Rice and Wehlau (1990) use a different period to calculate phases for their observations and models of ϵ UMa but find an abundance distribution of Cr and Fe quite similar to that found by Hatzes (1988) for Cr. Rice and Wehlau's (1990) geometry consists of two rings of enhanced Cr and Fe abundances on opposite sides of the star, separated by a region of depleted abundances. They suggest that the symmetry points of their abundance distribution represent the magnetic poles of ϵ UMa. To test this, we use their ephemeris to find that the positive magnetic pole of the star we have identified crosses the line of sight at $\phi_{\rm RW} = 0.059$, and the negative pole half a rotation later at $\phi_{\rm RW} = 0.559$. They use a value of $i = 65°$, from which we find $\beta = 54°$ from our magnetic curve. On their surface maps the positive magnetic pole is then located at longitude 21°, latitude +36°, and the negative pole at longitude 201°, latitude −36°. If allowance is made for uncertainties in our magnetic geometry, these are certainly compatible with the poles they have identified (longitude 10°, latitude +45°; longitude 190°, latitude −45°) as the symmetry points of the rings of enriched Fe and Cr abundance in their maps. The Rice and Wehlau (1990) model therefore also suggests that Fe and Cr have enhanced abundances at intermediate magnetic latitudes in ϵ UMa, and low abundances near the magnetic equator.

Our magnetic geometry is also in good agreement with that determined independently by Donati, Semel, and del Toro Iniesta (1990) from spectropolarimetric observations of a magnetically sensitive Fe II line. They find that the magnetic pole crosses the line of sight at $\phi = 0.96 \pm 0.01$ compared to our value of $\phi = 0.941 \pm 0.100$, and their value for the magnetic obliquity ($\beta = 74° \pm 6°$) is within our error range ($19° < \beta < 84°$). They do, however, find a polar field strength of 186 G for their dipole model, while a polar field strength on the order of 400 G would seem to be needed to produce the +128 G maximum field we have observed (Schwarzschild 1950). We suspect that this difference is the result of the nonuniform distribution of Fe over the surface of ϵ UMa. If the magnetic field geometry is predominantly dipolar, a concentration of Fe in intermediate magnetic latitude bands rather than at the magnetic poles will lead to a smaller integrated longitudinal magnetic field when the magnetic pole crosses the line of sight than a uniformly distributed element such as hydrogen.

IV. CONCLUSION

We have succeeded in measuring a weak, reversing magnetic field on the bright Ap star ϵ UMa. The magnetic field undergoes a sinusoidal variation from about +128 to −64 G and therefore appears to be dominated by a dipole component with a polar field strength on the order of 400 G. These measurements agree with recent work by Donati, Semel, and del Toro Iniesta (1990) but do not support the large (600–1100 G) field measurements reported by Glagolevsky *et al.* (1982, 1983) and Hubrig (1988). Our magnetic geometry appears to be consistent with the surface maps of the star calculated by Hatzes (1988) and Rice and Wehlau (1990). Fe and Cr have their lowest abundance near the magnetic equator and are most abundant in intermediate magnetic latitude spots or rings.

Epsilon UMa clearly remains an interesting object. It has a very inhomogeneous surface abundance distribution, as demonstrated by its pronounced spectrum and photometric variations, despite the fact that its surface magnetic field is quite weak (≈400 G). Apparently, even a weak field is sufficient to stabilize a star's atmosphere so that diffusion processes can occur. Previous theoretical investigations have suggested that surface magnetic fields of a few thousand to tens of thousands of gauss are needed not only to stabilize the atmosphere of an upper main-sequence star, but to have an appreciable effect in changing the diffusion velocity and direction, enabling the formation of nonuniform surface abundance distributions (Michaud 1970; Michaud, Mégessier, and Charland 1981). The weak field of ϵ UMa suggests that the atmospheres of Ap stars may be more stable than has previously been suspected.

The authors would like to thank J. B. Rice and W. H. Wehlau for encouragement to carry out this project and for helpful suggestions throughout the course of the investigation, and Mrs. Mira Rasche for assistance in preparing the figure for publication. J.-F. Donati is also acknowledged for providing us with his observations prior to publication as well as for suggesting improvements in the manuscript. This work has been supported by the Natural Sciences and Engineering Research Council of Canada.

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