THE ASTROPHYSICAL JOURNAL, 352:L5–L8, 1990 March 20

THE VERY STRONG AND UNUSUAL MAGNETIC FIELD OF THE Bp SILICON STAR HD 133880

J. D. LANDSTREET[1]
Department of Astronomy, University of Western Ontario
Received 1989 October 26; accepted 1989 December 28

ABSTRACT

The Ap Si star HD 133880 is found to have a very nonsinusoidal magnetic field curve. It is argued that this star is one of a very small number of Ap stars that have predominantly nondipolar field geometries. One possible family of models that reproduces the observed magnetic curve may be found using a collinear dipole and quadrupole; these models suggest that the quadrupolar field component is at least 1.3 times larger than the dipolar component.

Subject headings: stars: individual (HD 133880) — stars: magnetic — stars: peculiar A — stars: variables

I. INTRODUCTION

The star HD 133880 (=HR 5624) is a southern peculiar A (actually B) star with the Si λ4200 peculiarity. It is peculiar enough to have been classified as A0p by Miss Cannon in the Henry Draper catalog, but it is sufficiently faint ($V = 5.78$) and southerly ($\delta = -40°$) that it has received rather little individual attention. A longitudinal magnetic field was detected in HD 133880 by Borra and Landstreet (1975) which ranged between -3 and $+4$ kG in three measurements. This is a sufficiently large field to place the star well above the 95th percentile in the distribution of observed Ap star magnetic fields (see Thompson, Brown, and Landstreet 1987, Table 9).

Photometric observations of HD 133880 in the Geneva system were reported by Waelkens (1985). He found several interesting characteristics. The star is a photometric variable with a very short period, 0.87746 days. The amplitude of the variation is extremely large, reaching $0^m.15$ (peak to peak) in the U band, and the light curve is strikingly nonsinusoidal. The mean value of the peculiarity parameter Z, which measures photometrically the strength of the broad 5300 Å feature found in Ap stars but not in normal ones and which is also sensitive to the surface magnetic field (Cramer and Maeder 1979, 1980), is about -0.074, one of the largest values known for an Ap star. Furthermore, the value of Z varies by about $0^m.04$, which is quite unusual; normally this parameter is nearly constant even for large-amplitude light variables.

Because of its unusual nature, I obtained extensive longitudinal magnetic observations of HD 133880 in 1987 and 1988. These data confirm the existence of a large magnetic field in this star. Furthermore, they reveal a very unusual variation of the longitudinal magnetic field with phase, which strongly suggests the presence on the surface of the star of a dominant nondipolar component to the magnetic field structure, a feature discovered so far in only a few Ap and Bp stars. These data and their interpretation are the subject matter of this *Letter*.

II. OBSERVATIONS

Magnetic observations of HD 133880 were obtained using the University of Western Ontario photoelectric polarimeter as a Balmer-line Zeeman analyzer. The polarimeter was used on the 2.5 m Dupont telescope of the Las Campanas Observatory in 1987 February and 1988 May and June. Circular polarization measurements were made at ± 3.6 Å from the center of Hβ. The data were obtained and reduced as described for example by Landstreet (1982) or by Thompson, Brown, and Landstreet (1987). The conversion factor between measured circular polarization and inferred longitudinal magnetic field B_l is about 11,900 G per percent circular polarization. The measurements are listed in Table 1.

A plot of the new magnetic data using the ephemeris of Waelkens (1985) defines a smooth (but nonsinusoidal) magnetic field curve. However, when the three magnetic observations of HD 133880 reported by Borra and Landstreet (1975) are added to the plot, the measurement of $+3680 \pm 470$ G reported for JD 2,442,123.88 appears discordant. The phase calculated for this point places it quite close to the positive-going zero crossing of the new magnetic curve, a discrepancy of some 7.8 σ. This measurement was checked in the original reduction records by E. F. Borra (private communication), and appears to be correctly reported. The simplest explanation of the discrepancy is that Waelkens's estimate of the uncertainty of his period is somewhat too optimistic and that the period of HD 133880 is actually slightly longer than reported. If Waelkens's period is lengthened to 0.877485 days (an increase of $+0.000025$ days, 2.5 times Waelkens stated uncertainty), the old and new magnetic data are in much better agreement, although the discordant magnetic point is still some 3.7 σ above the magnetic curve defined by the new data. The source of the remaining difference is uncertain.

The longer period also appears to be consistent with Waelkens's photometry. The small uncertainty of Waelkens's period is determined by the phasing of four early observations relative to mean curves based on more than 30 observations. The new phasing leads to one measurement of mB magnitude that lies about $0^m.015$ above the mean light curve, blurring somewhat the sharp light minimum, but this is not seriously inconsistent with the observed width of the light curves. The three other points that move relative to the mean light curves remain about as acceptable as before.

Combining the constraints from Waelkens's photometry and my magnetic observations, I estimate that the best period is about 0.877485 ± 0.00002 days. I prefer a slightly different

[1] Guest Observer at Las Campanas Observatory, which is owned and operated by the Carnegie Institution of Washington.

TABLE 1

MAGNETIC MEASUREMENTS OF HD 133880

JD (2,440,000+)	Phase	B_l (G)	σ (G)
6835.880.........	0.291	990	170
6836.880.........	0.431	1790	170
6837.886.........	0.577	1920	210
6839.879.........	0.848	−1750	160
6840.830.........	0.932	−3720	160
7312.672.........	0.653	1880	170
7312.738.........	0.728	1230	170
7313.638.........	0.754	570	160
7314.585.........	0.833	−2260	150
7314.751.........	0.022	−4440	160
7315.710.........	0.115	−2930	150
7315.797.........	0.214	−240	150

zero point for the ephemeris as well: Waelkens chooses his zero point to coincide with maximum light, which for this star is poorly defined. A better defined choice for the zero point is the negative extremum of the magnetic field variation. With this choice the ephemeris becomes

$$\text{JD (negative } B_l \text{ extremum)} = 2{,}445{,}472.013\ (\pm 0.01) + 0.877485\ (\pm 0.00002)\ .$$

Phases calculated with this ephemeris are listed in Table 1 and used to plot the magnetic data in Figure 1. In the same figure I show for comparison the variations of the mV magnitude and of the peculiarity index Z from the data of Waelkens (1985), with phases calculated from the new ephemeris. Because of the small uncertainty in the period, the uncertainty in the relative phases of the magnetic and photometric data is also small, only ~0.04 cycle. On this ephemeris, the phases of reflection symmetry at 0.0 and 0.5 in the magnetic variation coincide quite closely with photometric extrema.

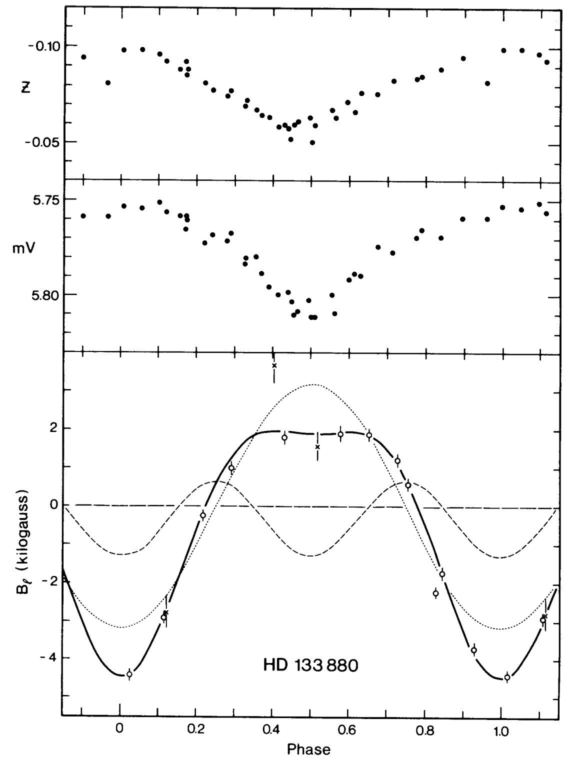

FIG. 1.—Variation of observed longitudinal field B_l (*bottom panel*; open circles are new measurements, crosses are observations from Borra and Landstreet 1975), Geneva mV magnitude (*middle panel*), and Z-parameter (*top panel*; data in both photometric panels are from Waelkens 1985). The heavy smooth curve in the bottom panel is the longitudinal field variation calculated from eq. (1) for $i = \beta = 90°$, $B_d = 8125$ G, $B_q = 10{,}900$ G, and $\cos\theta$ weighting; the lighter curves show separately the contribution to the calculated field curve of the dipole component (*dots*) and the quadrupole (*dashes*).

III. DISCUSSION

The variation of longitudinal magnetic field with phase shown in Figure 1 is clearly not well represented by a sine wave, unlike the magnetic curves found by photoelectric measurements for the great majority of well-studied magnetic Ap and Bp stars (see Borra and Landstreet 1980; Borra, Landstreet, and Thompson 1983; Thompson, Brown, and Landstreet 1987; and Bohlender *et al.* 1987). The only other stars known to have nonsinusoidal magnetic curves when measured using the Balmer-line Zeeman analyzer are HD 32633 (Borra and Landstreet 1980; Renson 1984), HD 175362 (Borra, Landstreet, and Thompson 1983; Bohlender *et al.* 1987), and HD 37776 (Thompson and Landstreet 1985). The former two have magnetic curves that are qualitatively similar to sine waves but are distorted somewhat in shape; the latter has a magnetic curve with two maxima and two minima per cycle.

The real interest of a nonsinusoidal magnetic curve is of course what it reveals about the distribution of magnetic field strength over the surface of the star. I shall argue below that the most straightforward interpretation of the observed magnetic curve is that the surface field geometry is not at all well approximated by the field geometry of a simple (centered) magnetic dipole.

It has been previously shown (Landstreet 1982) that in the Milne-Eddington approximation, the line wing circular polarization measured with a Balmer-line Zeeman analyzer is proportional to a simple moment of the line-of-sight component B_z of the local magnetic field vector on the stellar surface. This moment, called the longitudinal field, is given by

$$B_l = \frac{3}{2\pi} \int_0^{2\pi} \int_0^{\pi/2} B_z \cos^2\theta \sin\theta \, d\theta \, d\phi\ , \qquad (1)$$

where θ and ϕ are the usual spherical polar coordinates, and one of the $\cos\theta$ factors is effectively the weighting function over the visible stellar disk. It is important to realize that the Milne-Eddington model is a rather rough approximation to the actual situation, and equation (1) should be regarded as only a lowest order approximation to the field moment actually measured by the Balmer-line Zeeman analyzer. The longitudinal field moment B_l contains a fairly severe weighting toward disk center (the limb makes no contribution at all) and may well underestimate to some extent the degree to which the observed line wing polarization actually samples B_z near the limb. However, equation (1) should offer some useful guidance in interpreting the observed field curve.

Now if a distribution of magnetic field strength over the stellar surface is assumed and if the angle i between the stellar rotation axis and the line of sight is known, equation (1) may be used to calculate the expected magnetic curve that would be observed as the star rotates. If the field distribution is chosen to be that of a magnetic dipole located at the center of the star with its axis of symmetry inclined to the rotation axis by a (nonzero) value β, the predicted variation of B_l is found to be a sine wave, regardless of the values of i and β (Stibbs 1950). The nonsinusoidal magnetic curve that is observed for HD 133880 then clearly indicates that a dipolar field distribution is not an adequate approximation to the actual field geometry.

However, it is not hard to find a field geometry that does reproduce rather closely the observed magnetic curve. A simple generalization of a centered dipole field distribution is to add the next term in an (axisymmetric) multipole expansion, a linear quadrupole aligned with the dipole. If one calculates numerically the variation of B_l from equation (1) as a function of colatitude α from the magnetic field axis, it is found that for quadrupole-to-dipole ratios $q = B_q/B_d$ (where B_d and B_q are the polar strengths of the dipole and quadrupole component respectively) greater than about 1, the longitudinal field is roughly constant over a range of 20° or 30° in α near one pole, while the longitudinal field near the other pole reaches strengths of more than twice that at the weaker pole. These two characteristics make it possible for this type of field distribution to reproduce the observed field curve of HD 133880.

Working from curves of $B_l(\alpha)$ for various ratios q, it is easy for a particular value of q to identify a range of α which at one end has B_l approximately constant over a range of 20° or so (to describe the positive part of the observed B_l curve) and which at the other end reaches far enough toward the opposite pole to give a value of B_l about 2.4 times larger than that near the weak pole. The two limiting values of α are identified with the angles $i + \beta$ and $i - \beta$, so that i and β may be determined, and finally the field is scaled to the observed one.

In this way, a family of possible models is found. An example of the type of fit found is shown in Figure 1 as a heavy solid curve. This particular fit is for the smallest value of q, about 1.34, for which the shape of observed curve can be well reproduced. Smaller values of q all lead to magnetic curves that are too sinusoidal in shape. It is clear that the the fit to the observations is quite reasonable.

Adequate models can be found at least in the range $q = 1.34$–2.0. At $q = 1.34$, both i and β must be close to 90°. As q is increased, the best fit has a value of i which decreases slightly to about 80° at $q = 2.0$, while β decreases more rapidly to about 55° at $q = 2.0$. (The values of i and β may be interchanged without altering the shape of the calculated curve.) All the calculated magnetic curves are closely similar. I thus do not find a unique model for the observed magnetic curve of HD 133880, but I do find that all acceptable models have $q = B_q/B_d > 1.3$, so that the magnetic field distribution over the stellar surface inferred from modeling is *predominantly quadrupolar*.

The actual value of quadrupolar field required to reproduce the observed magnetic curve is a fairly sensitive function of the weighting function that describes the effects of limb darkening and line weakening. If instead of the severe cos θ weighting of equation (1), simple limb darkening of the form $1 - e(1 - \cos\theta)$ with a limb-darkening coefficient $e = 0.5$ is used, the ratio q must be increased to nearly 3 for $i = \beta = 90°$. Thus, any less severe weighting than that of equation (1) results in a *strengthening* of the conclusion that the field distribution is strongly nondipolar.

Actual choice of one of the family of models described (or clear proof that this family does not contain an appropriate model) will require further constraints on the field geometry such as may be provided by observations of differential Zeeman intensification in spectral lines (e.g., Kuznetsova 1987) or polarimetry of velocity-broadened Zeeman-sensitive metal lines.

There is of course always a question as to whether even the family of magnetic models discussed above provides a unique representation of the actual magnetic field geometry of HD 133880. Very likely it does not. In particular, any kind of small-scale structure such as sunspots or high-order multipoles would make a negligible contribution to the longitudinal field and hence could almost certainly not be detected from my data. Constraints on small-scale field structure may best be obtained from other types of measurements, such as differential Zeeman line intensification or polarimetry of metal lines. On the other hand, the large reversing field variation observed certainly points to the presence of an important dipole component, and the reflection symmetry of the observed magnetic curve about phases 0.0 and 0.5 strongly suggests that at least the large-scale field structure is axisymmetric (see Landstreet 1970). Certainly the assumed dipole-quadrupole model provides a good fit to the available magnetic observation. Thus it seems reasonable to believe that one of the family of models discussed may provide a good approximation to the large-scale field geometry of HD 133880. At the least, it seems quite fair to conclude from the present modeling that the field geometry of the star, although it includes an important dipole component, still departs quite strongly from the geometry of a simple centered dipole.

It is worth emphasizing that although the contribution of the quadrupole (or at least the nondipole) component of the field distribution to the observed longitudinal field variation is not very great (see Fig. 1), the quadrupole component is large enough to dominate the global field distribution even for the minimum q field that reproduces the observed magnetic curve. As a result, the field morphology is really different from that of a dipole, and the local field strength may be significantly larger than would normally be associated with the observed effective field. In the particular case shown in Figure 1, if the magnetic curve were sinusoidal and the limb darkening coefficient were given by equation (1) (effectively $e = 1$), a polar field strength of the order of 11,000 G would suffice to give the observed B_l. In contrast, the model of Figure 1 has a polar field at the strong pole of about 19,000 G. Furthermore, the model field configurations considered can have dramatic field strength variations from pole to pole. The model of Figure 1 has a field strength of only 2800 G at the weak pole. Clearly any atmospheric parameters, such as diffusion velocities or mass flux in a stellar wind, that may depend on magnetic field strength will be quite different at the two poles, and we may expect that the atmospheric abundances of important trace elements (Si, Ca, Ti, Cr, Fe) at the two poles may also be quite different.

The unusual field structure of HD 133880 makes this an extremely interesting star for further spectroscopic and polarimetric observations and modeling.

It is a pleasure to acknowledge the assistance of Angel Guerra, Fernando Peralta, and Brian Ventrudo in obtaining the observations reported here at Las Campanas, and to thank Mrs. Anne Brooks, Mrs. Gwen Laine-Bailey, and Mrs. Mira Rasche for help in preparing the manuscript. This research has been supported financially by the National Sciences and Engineering Research Council of Canada.

REFERENCES

Bohlender, D. A., Brown, D. N., Landstreet, J. D., and Thompson, I. B. 1987, *Ap. J.*, **323**, 325.
Borra, E. F., and Landstreet, J. D. 1975, *Pub. A.S.P.*, **87**, 961.
———. 1980, *Ap. J. Suppl.*, **42**, 421.
Borra, E. F., Landstreet, J. D., and Thompson, I. B. 1983, *Ap. J. Suppl.*, **53**, 151.
Cramer, N., and Maeder, A. 1979, *Astr. Ap.*, **78**, 305.
———. 1980, *Astr. Ap.*, **88**, 135.
Kuznetsova, T. N. 1987, *Soviet Astr. Letters*, Vol. **13**, No. 3, p. 212.
Landstreet, J. D. 1970, *Ap. J.*, **159**, 1001.
———. 1982, *Ap. J.*, **258**, 639.
Renson, P. 1984, *Astr. Ap.*, **139**, 131.
Stibbs, D. W. N. 1950, *M.N.R.A.S.*, **110**, 395.
Thompson, I. B., Brown, D. N., and Landstreet, J. D. 1987, *Ap. J. Suppl.*, **64**, 219.
Thompson, I. B., and Landstreet, J. D. 1985, *Ap. J. (Letters)*, **289**, L9.
Waelkens, C. 1985, *Astr. Ap. Suppl.*, **61**, 127.

J. D. LANDSTREET: The University of Western Ontario, Astronomy Department, London, ON, Canada N6A 3K7