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THE EXTRAORDINARY MAGNETIC VARIATION OF THE HELIUM-STRONG STAR HD 37776: A QUADRUPOLE FIELD CONFIGURATION

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ABSTRACT

Extensive longitudinal magnetic field measurements of the helium-strong B star HD 37776 have been obtained. It is found that when these data are phased with a period of 1.538 days derived from helium line variations, an extraordinary double-wave magnetic curve results. It is argued that this curve is in fact the real magnetic curve of the star and that HD 37776 is therefore the first known star in which a quadrupole-like field geometry dominates the usual dipole found in other magnetic stars.

Subject headings: stars: individual — stars: magnetic — stars: massive — stars: spectrum variables

I. INTRODUCTION

The star HD 37776 was found by Nissen (1976) to be a helium-strong star. Such stars are characterized by surface temperatures around 20,000 K and anomalously large photospheric He/H ratios. It was suggested by Osmer and Peterson (1974) that He-strong stars are high-temperature analogs of the Ap stars. The discovery of helium spectrum variability of a number of these stars (Pedersen and Thomsen 1977), and of large magnetic fields in several (Borra and Landstreet 1978), fully substantiates this hypothesis. About 23 helium-strong stars are presently known (Walborn 1983).

HD 37776 was found by Pedersen and Thomsen (1977) and Pedersen (1979) to be both a helium spectrum variable and a low-amplitude light variable, with a period of 1.5385 ± 0.003 days. The strength of the He I λ4026 line shows a distinctive double wave variation, and the star is faintest in the Strömgren *y* band at helium maximum. More recently, Walborn (1982) has presented data that suggest that Si and perhaps Mg also vary in the star. The star has *UBV* colors that (when unreddened) place it near *B*1 in the *U* − *B*, *B* − *V* diagram. It is thus one of the hottest He-strong stars.

A magnetic field was found in this star by Borra and Landstreet (1978) which ranges up to about 2 kilogauss in strength. When the observed longitudinal field measurements were plotted on the 1.5385 day period, a peculiar double-wave variation was found. This longitudinal field variation is so unlike the approximately sinusoidal magnetic curves observed for other magnetic stars that further magnetic observations of this star were obtained to establish more clearly the reality of the unusual magnetic variation or to find an alternative description of the magnetic observations. These new observations and their interpretation are discussed in this *Letter*.

II. OBSERVATIONS

Longitudinal magnetic field measurements of HD 37776 were obtained using the two-channel photoelectric Pockels cell polarimeter of the University of Western Ontario (Angel and Landstreet 1970) on the 2.5 m du Pont telescope at Las Campanas Observatory during two observing runs in 1982 November and 1984 February. The polarimeter was used as an Hβ Zeeman analyzer; circular polarization was measured in the wings of Hβ, which were isolated using two tilt-tuned 5 Å HPBW interference filters, one in each beam. These filters were set at ±3.6 Å from the line center. The circular polarization observations in each line wing, V_l/I and V_s/I, were combined to form a mean polarization $\langle V/I \rangle = \langle V_l - V_s \rangle / 2I$, which was converted into a longitudinal magnetic field strength measurement using the relationship $\langle V/I \rangle = 4.67 \times 10^{-13} B_\ell (dI/d\lambda)/I$, where $I(\lambda)$ is the observed line profile, λ is measured in Å, and B_ℓ is measured in gauss (Landstreet 1982).

Line profile measurements $I(\lambda)$ were obtained by tilt-scanning one of the filters while the other remained fixed. Such line scans were obtained on 10 nights in 1982 and one in 1984, and the average conversion factor γ in $B_\ell = \gamma \langle V/I \rangle$ was found to be 19,300 gauss per percent circular polarization, with an observed standard deviation of about ±9%. Since this standard deviation is very similar to the value observed for Ap stars of essentially constant Hβ line profiles, we conclude that the Hβ profile of HD 37776 is also constant and have converted all polarization observations to field measurements using the mean value of γ. Field strength errors are computed from the polarization errors determined from photon counting statistics. The observation and reduction procedure is essentially the same one used by Borra and Landstreet (1977, 1978, 1980), by Landstreet (1982), and by Borra, Landstreet, and Thompson (1983).

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TABLE 1

LONGITUDINAL FIELD MEASUREMENTS OF HD 37776

JD (2,440,000 +)	$B_\ell \pm \sigma_B$ (gauss)	Phase
3505.605	−1260 ± 290	0.823
3506.692	−450 ± 330	0.529
3507.723	−2180 ± 320	0.199
3509.563	840 ± 320	0.395
3510.595	250 ± 390	0.066
3510.763	−1460 ± 380	0.175
3511.618	−1230 ± 310	0.731
5297.714	−1290 ± 290	0.521
5297.834	−720 ± 310	0.599
5298.709	−1740 ± 400	0.167
5299.712	−1430 ± 300	0.819
5300.696	370 ± 310	0.459
5302.844	−1300 ± 380	0.855
5303.673	1180 ± 280	0.393
5304.645	1560 ± 290	0.025
5304.765	−510 ± 330	0.103
5304.815	−2140 ± 330	0.136
5304.854	−1610 ± 480	0.161
5305.631	−1100 ± 320	0.666
5305.736	−1660 ± 350	0.734
5306.632	1150 ± 510	0.317
5306.744	1340 ± 350	0.389
5307.663	1600 ± 440	0.987
5307.713	1380 ± 360	0.019
5307.763	540 ± 350	0.052
5307.854	−920 ± 490	0.111
5309.591	−1470 ± 380	0.240
5309.742	1460 ± 480	0.338
5309.798	890 ± 370	0.374
5724.546	−260 ± 440	0.920
5724.577	520 ± 440	0.940
5724.606	880 ± 440	0.959
5724.638	2020 ± 440	0.980
5724.669	2540 ± 440	0.000
5724.701	1550 ± 440	0.021
5724.735	540 ± 440	0.043
5724.763	−230 ± 630	0.061
5725.542	−360 ± 430	0.568
5725.577	−1680 ± 430	0.590
5725.609	−1360 ± 430	0.611
5725.640	−830 ± 430	0.631
5725.675	−750 ± 430	0.654
5725.708	−660 ± 430	0.675
5725.745	−1640 ± 430	0.700

The field strength measurements are presented in Table 1. For completeness the seven measurements from 1977–1978 of Borra and Landstreet (1978) are also included. The data reported by Borra and Landstreet (1978) were converted from polarization measurements to magnetic field measurements using one mean value of $\gamma = 18{,}000$ G $(1\%)^{-1}$ for all He-strong stars. The actual value of γ for HD 37776 for the observing arrangement used for these earlier data is $\gamma = 20{,}000$ G $(1\%)^{-1}$, and the first seven measurements have been renormalized to take this into account. The table lists in successive columns the Julian date at the midpoint of each observation, the measured longitudinal field strength B_ℓ and its associated standard error σ_B, and the phase of the observation (calculated as described below).

When the data from 1982 are plotted on the 1.5385 ± 0.0003 day period found by Pedersen (1979), they define a self-consistent (though rather bizarre) magnetic curve. The 1977–1978 and 1984 data each comprise less complete sets, but when plotted on Pedersen's period each can be superposed unambiguously on the 1982 data set. Since Pedersen's period is accurate enough to give definite cycle counts between the three magnetic data sets, these magnetic data may be used to improve Pedersen's period. The period that best phases together all observations is found to be 1.53869 days with an uncertainty estimated (from the uncertainty involved in superposing the various data sets) of about ±0.00007 days. Phase zero is chosen to occur at the positive magnetic extremum, which was observed to occur on JD 2,445,724.669. We therefore compute phases according to

$$\mathrm{JD}(B_\ell^+) = 2{,}445{,}724.669\,(\pm 0.02) + [1.53869\,(\pm 0.00007)]\,E. \tag{1}$$

All the magnetic field measurements are plotted with this emphemeris in Figure 1. A hand-drawn representation of the mean magnetic curve is shown in correct phase relation to the He I λ4026 line strength variation as measured by Pedersen and Thomsen (1977) and Pedersen (1979), and to the (not quite complete) light curve measured in the Strömgren y band by Pedersen and Thomsen, in Figure 2.

III. DISCUSSION

The magnetic data for HD 37776 define a unique and extraordinary magnetic curve when they are plotted on the 1.53869 day period. The magnetic curve is well defined and internally consistent (the scatter seen in Fig. 1 around the mean curve is about the same as for other, sinusoidal, magnetic curves), and in fact the same shape is observed in all three data sets, which cover a total span of about 6 years. However, the curve is quite different from the longitudinal field curves observed for other magnetic stars, except perhaps for the Ap star HD 32633 (Renson 1984). It is not obvious how to reconcile this curve with the usual oblique rotation model with its conventional (possibly decentered) dipole magnetic field distribution. For this reason we must consider various possible alternative descriptions and/or explanations of the data we have obtained.

One possible alternative to the description of the magnetic data presented so far is that we may have chosen the wrong period for variation of the field. In other words, there may exist a period for which the magnetic data do fall on a sinusoidal or nearly sinusoidal curve. To test this hypothesis, we have computed the parameters of the least squares best fit sine wave $B(t) = B_0 + B_1 \sin[(2\pi t/P) - \phi_0]$ for all independent periods P between 100 and 0.25 days, for both the

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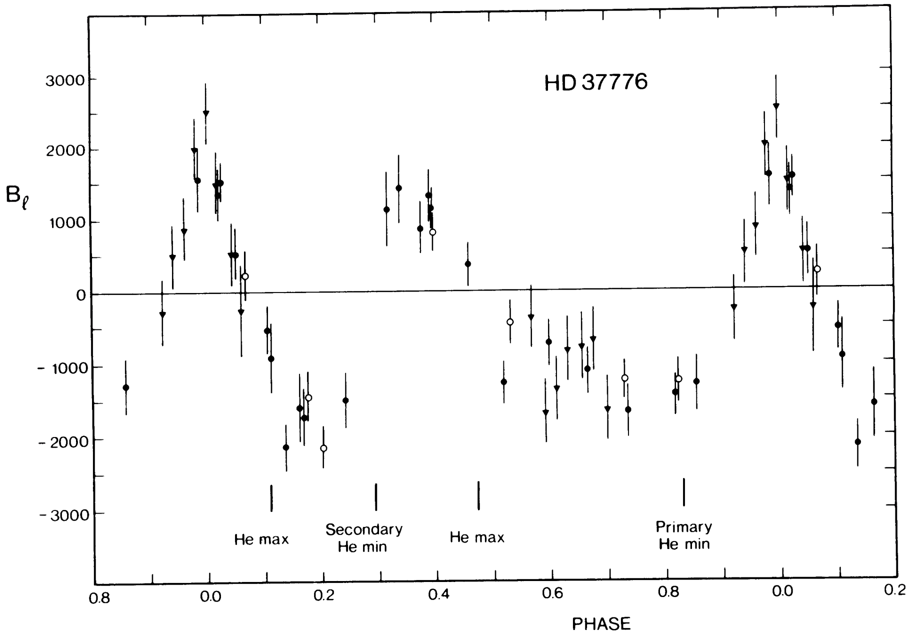

FIG. 1.—All measurements of the longitudinal magnetic field of HD 37776 plotted against phase determined from eq. (1). Different symbols denote different observing runs: *open circles*, 1977 December–1978 January (from Borra and Landstreet 1978); *filled circles*, 1982 November; *filled triangles*, 1984 January. The phases of He line strength extrema are marked with tick marks below the data. Field strengths are in gauss.

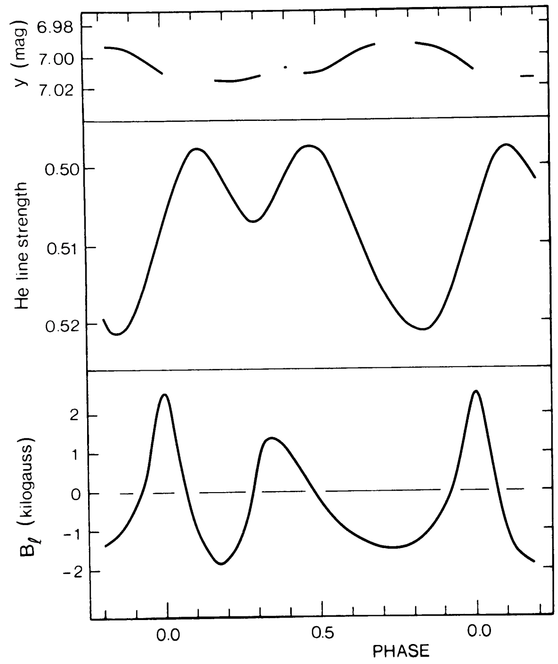

FIG. 2.—Smoothed variation of light (Strömgren *y* band), spectrum (He I λ4026 line strength; maximum line strength at top of panel), and longitudinal magnetic field strength of HD 37776, phased with ephemeris of eq. (1). The smooth fits to these data are drawn by hand. Gaps in the light curve are phases for which photometric data are not available.

1977–1978 and the 1982 data sets. We then calculated the value of $\chi^2/\nu = (n-3)^{-1}\{\Sigma[B_{\ell i} - B(t_i)]^2/\sigma_i^2\}$, where $B_{\ell i}$ is the ith magnetic observation obtained at time t_i with standard error σ_i, and n is the total number of measurements in the data set. As discussed by Borra and Landstreet (1980), and Borra, Landstreet, and Thompson (1983), it is normally possible to find (at least) one period on which the magnetic observations of a particular Ap or He-weak star may be phased with $\chi^2/\nu \lesssim 2.0$.

The two χ^2/ν spectra each have several relative minima for periods of less than 1 day. However, except for a period of 0.76 days (exactly half of Pedersen's period) the best periods found for the 1977–1978 data are mutually exclusive of the best periods found for the 1982 data. Furthermore, none of the minima in the χ^2/ν spectrum of the large 1982 data have values of χ^2/ν of less than 5. When the 1982 data are actually plotted on the best periods found from the curve fitting procedure, it is found that the resulting magnetic curves are always noticeably nonsinusoidal, that they show a rather large scatter around the mean curve, and that there are always two or three points that lie more than 5 σ away from the mean curve. We conclude that there does not exist any period on which the magnetic data for HD 37776 vary sinusoidally; the peculiar magnetic curve cannot be made to go away by a better choice of period. This is consistent with the fact that Pedersen and Thomsen (1977) found that only the single unique period of 1.538 days would fit their He line variation data.

A further test of the reality of the magnetic curve of Figure 1 is provided by the data set of 1984. This data set consists of about 5.7 hr of continuous observation of HD 37776 on each of two successive nights. These data thus sample segments of the magnetic curve of phase length about 0.14 in real time (assuming a period of 1.539 days). In each case, the observed variation follows the mean curve defined by phased observations very well (see Fig. 1, where each data set is distinguished by a separate symbol). Furthermore, the data from JD 2,445,724 vary rapidly from slightly below zero to +2500 gauss and back to below zero, while the data of JD 2,445,725 stay nearly constant at about −1000 gauss. If the star in fact varied with a short period (such as the period of about 0.4 days suggested by the data from JD 2,445,724), it should do so on both days, not one. We conclude that all the evidence available strongly supports the reality of the extraordinary magnetic curve depicted in Figure 1.

If we now accept the reality of the magnetic curve of Figure 1, we shall want some plausible description of the underlying stellar magnetic field that produces that curve. Two types of models suggest themselves: some sort of binary system, or a single oblique rotator with an unusually complex field strength distribution.

Various possible versions of the binary hypothesis seem possible. The observed magnetic curve might be the composite curve resulting from the combination of the individual magnetic curves of two stars. If this model were correct, the fact that the magnetic curve has a single well-defined period suggest that the two stars should have orbitally locked rotation periods with an orbital period of 1.5 days. This in turn would imply that the spectrum should be double lined with a velocity amplitude of the order of 250 km s^{-1}. This would certainly have been noted by Walborn (1982, 1983) but was not. If the orbit of the hypothetical binary were nearly in the plane of the sky, to reduce the velocity amplitude of the stars, then not only the orbital but also the rotational axes would be expected to point nearly at the observer, and little magnetic variation would be observed. Finally, on this binary model both individual magnetic curves should be sine waves with the 1.539 day period. In fact, any two sine waves, both having the 1.539 day period, of whatever relative amplitude and phase, can not produce the observed magnetic curve. A double-lined binary model thus does not seem very appealing.

Alternatively, the magnetic curve might be due to a single magnetic star which is eclipsed by a low-mass faint secondary. On this hypothesis, the magnetic variation of the visible magnetic star could be essentially sinusoidal with the 1.539 day period, as the magnetic curve is between phase 0.3 and phase 0.85, and the rapid changes between phase 0.9 and 0.2 could be due to eclipse of some of the stellar surface by an unseen companion. An immediate observational difficulty with this idea is that the light curve observed by Pedersen and Thomsen (1977), although incomplete, shows no trace of eclipse-like variation at the critical phases (see Fig. 2). A further problem with this hypothesis arises when one considers the geometry in detail. The synchronized occulting companion would have to be located roughly above the magnetic equator of the visible star, so that the eclipse would be most nearly central around $\phi = 0.05$, half a cycle from the middle of the sinusoidal part of the magnetic curve. But prior to this phase the occulting star would eclipse mainly field lines from the positive pole's hemisphere so the net B_ℓ observed should be more negative than the value just before eclipse starts (say at $\phi = 0.80$); and after $\phi = 0.05$ the unseen companion would mostly occult field lines from the negative pole's hemisphere and so again the field should have the same sign it would have without eclipses but of larger amplitude. This model does not appear capable of accounting for the extra field reversal between $\phi = 0.90$ and $\phi = 0.30$.

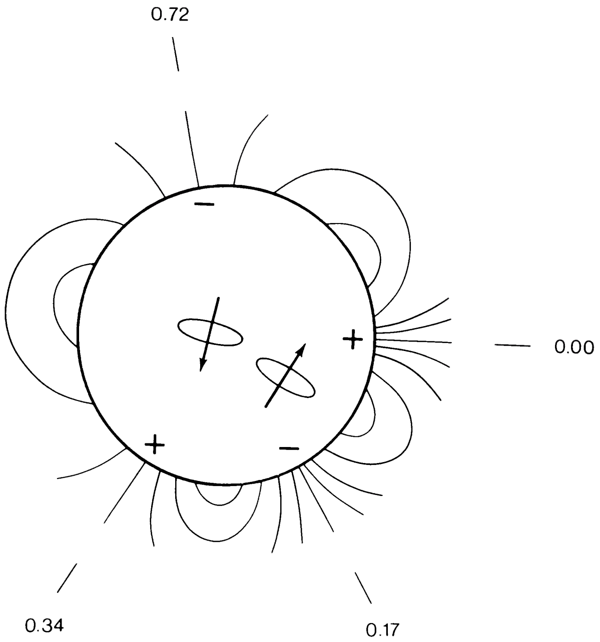

FIG. 3.—Location on HD 37776 of regions of strong vertical magnetic field as suggested by the observed magnetic curve. The rotation axis of the star is roughly normal to the plane of the figure. Directions of the line of sight at various phases as the star rotates are indicated by tick marks labeled by phase around the star. Plausible field lines are sketched outside the star, and the possible location of two dipoles (i.e., current loops) in the star are indicated. This combination of dipoles has an obvious resemblance to a two-dimensional quadrupole.

If we abandon multiple star models, we must then consider whether a variant of the usual oblique dipole rotator model will do. Clearly the field distribution cannot be essentially dipolar, whether centered or decentered, as such a distribution leads to a single-wave sinusoidal magnetic curve. Phenomenologically we appear to have a situation rather like that sketched in Figure 3, where + (or −) signs denote regions of mainly positive (or negative) magnetic field lines. Such a field distribution has a fairly close resemblance to a quadrupole field distribution (Panofsky and Phillips 1955), and the star might well generate it by means of two internal current loops perhaps located roughly as sketched in Figure 3. (Note that the figure assumes that the observer views the star more or less in the plane of the rotational equator. Assuming that the star has a radius of, say, 4–7 $R_\odot$, the observed period and $v \sin i = 160$ km s^{-1} [Walborn 1983] lead to an inclination $i \geq 45°$.)

Thus we conclude that HD 37776 has a field geometry which is essentially quadrupolar, in contrast to the usual dipole field distributions inferred for other magnetic stars. It is the first star discovered in which the quadrupole dominates the dipole.

We note that both the maxima and the minima of helium line strength occur near phases of zero longitudinal field. This suggests that the greatest concentrations of high helium and the regions of greatest helium depletion abundance are found not at polelike regions but more or less midway between poles.

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