1987ApJ...323..325B

THE ASTROPHYSICAL JOURNAL, **323**:325-337, 1987 December 1

MAGNETIC FIELD MEASUREMENTS OF HELIUM-STRONG STARS

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Received 1987 January 12; accepted 1987 May 27

ABSTRACT

We present results of a continuing program of photoelectric magnetic field measurements of helium-strong stars. Nine of the 11 helium-strong stars so far observed for circular polarization in the wings of Hβ (and sometimes He I λ5876) have shown evidence of large, ordered magnetic fields. The discovery of two new magnetic helium-strong stars and observations of seven other members of the class are reported here. We also discuss new measurements of the helium-weak star HD 175362 = HR 7129. Improved periods are derived for three of these stars, and the frequent occurrence of constant or nonreversing fields in helium-strong stars is confirmed. Magnetic curves have been obtained using the He I λ5876 line for four stars; these are identical to those obtained at Hβ, which suggests that the difference in line strength between regions of high and low helium abundance is small.

As a group, the helium-strong stars have fields about 3 times larger than the classical magnetic peculiar A stars. Members of the class with low and high $v \sin i$ have comparable field strengths, in contrast to a possible anticorrelation between $v \sin i$ and field strength found for the Ap stars. While an appreciable fraction of the helium-strong stars observed to date have constant magnetic fields, suggestive of a small inclination of the magnetic axis to the rotation axis, the available sample is too small to allow us to conclude that the obliquities of the helium-strong stars are significantly different from those of the helium-weak or Ap objects. It appears that the distribution of $v \sin i$ for the helium-strong stars is similar to that of normal early B stars, confirming the relative unimportance of magnetic braking before or on the main sequence in these massive, short-lived stars.

Possible origins of the magnetic fields are discussed.

Subject headings: stars: magnetic — stars: peculiar A

I. INTRODUCTION

The helium-strong stars are a small group of stars with spectral types near B2 V that show anomalously strong helium lines for their colors. Comparison of their intrinsic colors with blanketed model atmospheres of Kurucz (1979) indicate effective temperatures between 18,000 and 23,000 K. (There is some inconsistency in estimating the temperatures of these stars using Kurucz's solar abundance models, but available helium-rich model atmospheres are unblanketed [Klinglesmith *et al.* 1970; Klinglesmith 1971]. Groote and Hunger 1982, however, have demonstrated that helium enrichment in this temperature and abundance range has little effect on the fluxes from these stars. Uncertainties in the quoted temperatures are probably on the order of 1000 K.) The first member of the class to be recognized was σ Orionis E (Berger 1956). A recent review now lists over 20 with $V < 11$ (Walborn 1983). These objects appear to have $0.5 \lesssim n(\mathrm{He})/n(\mathrm{H}) \lesssim 1.0$ in their atmospheres but seem to be main-sequence objects, unrelated to the evolved extreme helium stars (Hunger 1986).

Since their discovery, the helium-strong stars have been found to demonstrate a rich variety of phenomena. Most are spectrum variables. Helium line strengths vary with periods on the order of days, as do those of hydrogen, silicon, and, less conclusively, carbon, nitrogen, and oxygen (Pedersen and Thomsen 1977; Lester 1979; Walborn 1982). When variable, line strengths of hydrogen and the metals all vary out of phase with the helium line strengths. Most of the spectrum variables also vary photometrically with periods identical to those of the spectral variations and amplitudes of less than 0.1 mag (Pedersen and Thomsen 1977; Adelman and Pyper 1985). A few have variable Hα emission (Walborn 1974). The star σ Ori E displays an eclipse-like light curve and a periodically variable shell spectrum (Hesser, Walborn, and Ugarte 1976; Groote and Hunger 1976).

Osmer and Peterson (1974) first suggested that the helium-strong stars could form an extension of the Ap star phenomena to higher temperatures. The ensuing discovery by Landstreet and Borra (1978) and Borra and Landstreet (1979) that almost all helium-strong stars are detectably magnetic gave strong

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support to this idea. It is now firmly established that magnetic peculiar stars occur at all temperatures between 7500 K (SrCrEu Ap stars) and 23,000 K (helium-strong stars). At least three of the magnetic helium-strong stars are nonthermal radio sources (Drake *et al.* 1987).

Theoretical work has suggested that downward radiative diffusion of helium in the presence of a weak stellar wind could support the observed helium overabundances in helium-strong stars (Vauclair 1975; Shore 1978; Michaud *et al.* 1987). The winds have been detected from ultraviolet observations of the C IV and Si IV resonance lines (Shore and Adelman 1981; Barker *et al.* 1982). For some objects the P Cygni profiles of these lines show remarkable variability, again with periods equal to those of the spectroscopic, photometric, and magnetic variations. Current estimates of the mass-loss rates range from $5 \times 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$ (Michaud *et al.* 1987) to $4 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$ (Shore and Adelman 1981). These appear to be much larger than the $10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$ rate required for the helium overabundances in the models of Vauclair (1975) and Michaud *et al.* (1987). Clearly a strong magnetic field must be included in future models.

The oblique rotator model appears to provide a satisfactory conceptual framework for understanding these observations. A magnetic field inclined to the rotation axis interacts with diffusion processes and the stellar wind. Diffusion in the presence of a strong magnetic field is expected to lead to surface distributions of various ions that are patchy (Michaud, Megessier, and Charland 1981), so that the spectral variations are caused by stellar rotation presenting different portions of the surface to the observer. These patches presumably alter the atmospheric structure and flux distribution sufficiently to create the low-amplitude light fluctuations observed. The wind escapes from the magnetic poles which sweep through the observer's line of sight as the star rotates, and creates the ultraviolet resonance line variations.

It has been several years since magnetic data were published for some of the helium-strong stars (Landstreet and Borra 1978; Borra and Landstreet 1979). It is appropriate at the present time to make available the more recent results of our continuing program of field measurements for these stars. We report the discovery of two new magnetic helium-strong stars, δ Ori C and HD 66522. Improved periods are given for three stars with varying magnetic fields, and constant fields are confirmed for three objects. The fields of two helium-strong stars, HD 37776 (which has a remarkable quadrupolar field geometry) and HD 184927, are discussed elsewhere by Thompson and Landstreet (1985) and Brown *et al.* (1987), respectively, and are not included in the observations presented here. We have, however, included new observations of the helium-weak star HD 175362, an object similar to a Cen = HD 125823 in that its colors place it just on the lower temperature boundary of the helium-strong stars. In addition, new magnetic observations using the He I λ5876 line are presented for four stars with variable fields, and the significance of these measurements is discussed. Finally, after revising the measured $v \sin i$ values of three of the helium-strong stars, we demonstrate that the $v \sin i$ distribution for the helium-strong stars is similar to the distribution for normal early B stars.

II. OBSERVATIONS

The magnetic field observations were obtained at three sites: the du Pont 2.5 m telescope of Las Campanas Observatory, the 1.5 m telescope of Palomar Observatory, and the University of Western Ontario 1.2 m telescope. The 2.5 m and 1.2 m observations were obtained using the UWO photoelectric Pockels cell polarimeter. The Palomar data were acquired with the similar Laval University polarimeter. The instruments and observing techniques are discussed in detail elsewhere (e.g., Landstreet 1980, 1982; Borra and Landstreet 1977). Briefly, the circular polarization in the line wings of Hβ or He I λ5876, caused by the longitudinal Zeeman effect, is measured by using tilt-tuned interference filters set on the short- and long-wavelength wings of the relevant line. The filters used have HPBWs of 5 Å and 2.8 Å for Hβ and He I λ5876, respectively.

The polarization measurements for a single star are converted to a longitudinal magnetic field, B_e, using the relation (Bray and Loughhead 1964; Landstreet 1982)

$$(V_r - V_b)/2 = 4.67 \times 10^{-13} z B_e \lambda^2 [dI(\lambda)/d\lambda]/I(\lambda)\ , \qquad (1)$$

where V_r and V_b represent the fractional circular polarization in the long- and short-wavelength wings, respectively; z is the Landé factor of the line (Babcock 1962); λ is the wavelength; and $I(\lambda)$ is the profile observed. The line profile is obtained by using the polarimeter as a two-channel photoelectric scanner. One filter is set on the stellar continuum near the line, while the other is tilt-tuned to various wavelengths over a total range of about 40 Å.

For Hβ, which has a central depth of about 0.7 of the continuum through the 5 Å filters, it is accurate enough to draw a freehand curve through the observed points and measure the value of $dI/d\lambda$ from the drawing. For the He I λ5876 line, which has a central depth of about 0.9 of the continuum for helium-strong stars and 0.95 for HD 175362, the scatter in the observed points makes such a procedure less attractive. Instead, we have rectified the profile using continuum points on both sides of the line, fitted each rectified line with a Gaussian (this is actually usually quite a good approximation, especially in the line core), and then evaluated I and $dI/d\lambda$ numerically at the points in the profile where observations were made.

Errors σ_B for the magnetic measurements tabulated below are computed from photon counting statistics. An additional source of error not included in σ_B is a possible overall scale error of 10% or 20% in B_e values due to inaccuracy in $I(\lambda)$ or in equation (1).

We have supplemented the Hβ magnetic observations with observations using the He I λ5876 line in an attempt to map the surface distribution of helium by comparing magnetic curves obtained with (assumed) uniformly distributed hydrogen with the curves determined from λ5876. It has long been known (Deutsch 1958; Pyper 1969) that magnetic field curves are affected not only by the effective longitudinal field but also by nonuniform distribution of the element used to measure the field. The results of the λ5876 magnetic measurements are discussed in § IV.

Throughout the remainder of this paper we have used the combined helium and hydrogen polarization data to refine the periods of the magnetic field variations. Because of the possible systematic difference between the amplitudes of the helium and hydrogen measurements, however, the amplitudes of the best-fitting sinusoids for the data discussed below have been calculated using only the Hβ measurements.

Table 1 lists all of the helium-strong stars and related objects that have been observed photoelectrically for magnetic fields at the time of writing, their visual magnitudes, intrinsic *UBV* colors, periods, $v \sin i$ (from Walborn 1983 unless otherwise

TABLE 1

HELIUM-STRONG AND RELATED HELIUM WEAK STARS OBSERVED

Star	V	$(B-V)_0$	$(U-B)_0$	Period $\pm\ \sigma_P$ (days)	$v \sin i$ (km s^{-1})	n	Hβ	He I λ5876	B_e Extrema (G)	Typical σ_B (G)	χ^2/n	Reference
δ Ori C	6.85^{a}	-0.20^{a}	-0.74^{a}	...	32^{b}	6	6	...	-3400, constant	300	117.95	
HD 37017	6.56	-0.22	-0.84	0.901195 ± 0.000050	$\lesssim 95^{c}$	40	23	5	-350 to -2170	250	26.36	1
σ Ori E	6.65	-0.24	-0.90	1.19081 ± 0.00001	162^{d}	22	8	6	$+2810$ to -1490	290	25.49	2
HD 37776	6.98	-0.25	-0.94	1.53869 ± 0.00007	95^{b}	44	...	...	$+2540$ to -2180	400	12.02	3
HD 58260	6.73	-0.22	-0.81	...	18^{b}	10	5	...	$+2300$, constant	250	65.81	1
HD 60344	7.71	-0.23	-0.88	...	$\lesssim 30$	4	1	...	B_e below detection	...	0.56	1
HD 64740	4.63	-0.25	-0.95	1.33026 ± 0.00006	160	21	9	6	$+490$ to -890	110	25.38	1
HD 66522	7.18			...	$\lesssim 30$	4	4	...	$+1030$ to -80	360	3.63	
HD 96446	6.68	-0.25	-0.92	...	$\lesssim 30$	11	5	...	-1650, constant	230	42.14	1
HD 133518 ...	6.39^{e}	-0.10^{e}	-0.72^{e}	...	$\lesssim 30$	5	2	...	B_e below detection	...	1.22	1
HD 184927 ...	7.46	-0.23	-0.86	9.52973 ± 0.00078	$\lesssim 18^{f}$	19	...	...	$+2250$ to 0	400	13.26	4
HD 125823 ...	4.42	-0.21	-0.77	8.8171 ± 0.003	18^{g}	9	...	...	-430 to -470	100	11.92	5
HD 175362 ...	5.38	-0.20	-0.75	3.6738 ± 0.0004	30^{h}	28	8	8	$+4020$ to -6860	200	413.43	5

REFERENCES.—(1) Borra and Landstreet 1979. (2) Landstreet and Borra 1978. (3) Thompson and Landstreet 1985. (4) Brown *et al.* 1987. (5) Borra, Landstreet, and Thompson 1983.

[a] Hoffleit and Jaschek 1982.

[b] This paper.

[c] Bolton 1987.

[d] Bolton *et al.* 1986.

[e] Underhill and Doazan 1982.

[f] Barker 1986.

[g] Wolff and Morrison 1974.

[h] Hensler 1979.

noted), the total number of magnetic observations and the number of new Hβ and λ5876 observations presented here, magnetic extrema (weighted averages in the case of stars with constant fields), typical standard deviations of the observations, and the reduced χ^2 of all the magnetic data. The intrinsic colors are derived from the observed colors (Egret and Jaschek 1981, unless otherwise noted) using the Q method (Mihalas and Binney 1981) to correct for interstellar reddening. The statistic χ^2/n is defined by

$$\frac{\chi^2}{n} = \frac{1}{n} \sum_i \left(\frac{B_{ei}}{\sigma_{Bi}}\right)^2 .$$

Stars for which χ^2 exceeds the value expected for n degrees of freedom at the 99% confidence level are almost certainly magnetic. Previous photoelectric magnetic field measurements are contained in the references listed in the last column of the table. Table 2 contains our new magnetic observations, and gives the Julian Date of each individual observation, the measured longitudinal field and its standard deviation, and the phase of the observation calculated from the ephemeris given for each star in the next section.

III. INDIVIDUAL STARS

a) δ Orionis C = HD 36485 = HR 1851

There has been some confusion in the literature with the identification of this star. Walborn (1982, 1983) refers to it as δ Ori B. The δ Orionis system actually consists of four stars (Hoffleit and Jaschek 1982). The primary, δ Ori A = HR 1852 = HD 36486, is a spectroscopic binary with $V = 2.23$; the B component is 33″ from A and has $V = 14.0$; while the helium-strong star, δ Ori C = HR 1851 = HD 36485, is 51″.7 from A with $V = 6.85$.

The star δ Ori C was classified as helium-strong by Morgan, Abt, and Tapscott (1978). Walborn (1982) has confirmed its membership in the class and notes that its spectral lines are very sharp but that the helium lines have very extensive wings. One spectrogram shows a blueshifted component to the helium lines which he suggests may be a result of a mass-ejection episode (Walborn 1983). The C IV ultraviolet resonance doublet is not variable in HD 36485 and may not even be present (Barker 1986). Drake *et al.* (1987) have recently found δ Ori C to be a nonthermal radio source.

Six magnetic observations over a three and one-half year interval show that δ Ori C possesses a constant longitudinal field of -3400 G. Walborn (1983) estimates a $v \sin i$ of 80 km s^{-1} for this star. However, by modeling line profiles of Si III in two high signal-to-noise spectra obtained by two of us (D. A. B. and J. D. L.) at the Canada-France-Hawaii Telescope, we find a considerably lower value of 32 ± 4 km s^{-1}.

Since δ Ori C is a member of the Orion OB1 association, its distance is about 450 pc. The intrinsic colors in Table 1 agree reasonably well with the 18,000 K, $\log g = 4$, solar abundance, blanketed model atmosphere of Kurucz (1979). The bolometric correction is then -1.8 (Code *et al.* 1976). With a color excess $E(B-V) = 0.04$, we find $\log (L/L_\odot) = 3.24$ and $R = 4.34\ R_\odot$ (assuming $M_{\text{bol}_\odot} = 4.76$). The main uncertainty in this radius determination arises from a possible error in T_{eff} as discussed in § I. We adopt a conservative error of 1500 K for the temperature determination and, as a result, find $R = 4.4 \pm 0.3\ R_\odot$. The simple relation

$$\sin i = Pv \sin i/50.6R , \qquad (2)$$

with P expressed in days, $v \sin i$ in km s^{-1}, and the radius, R, in solar units, then gives an upper limit of 7.4 days for the rotation period of HD 36485. The lack of variation is therefore almost certainly real, and not an artifact of poor spacing of observations. Now if we assume that the largest true equatorial velocity that occurs in the helium-strong stars is not much bigger than the largest observed value of $v \sin i$ for a normal early B star (see below), say $v_{\text{eq}} \lesssim 240$ km s^{-1}, then $i \gtrsim 8°$.

TABLE 2

MAGNETIC DATA

JD (2,440,000+)	$B_e \pm \sigma_B$ (G)	Phase
δ Ori C		
Hβ:		
5299.794....	-3770 ± 270	...
5303.728....	-3200 ± 290	...
5305.690....	-3350 ± 310	...
5306.801....	-3110 ± 310	...
5309.838....	-3720 ± 450	...
6512.513....	-3180 ± 310	...
HD 37017 (2,444,583.009 + 0.901195E)		
Hβ:		
4947.966....	-2680 ± 250	0.970
4948.748....	-2040 ± 250	0.838
4950.703....	-1090 ± 300	0.007
4951.913....	-1360 ± 190	0.350
4952.938....	190 ± 250	0.487
4953.820....	-300 ± 230	0.466
4953.979....	-920 ± 490	0.642
4954.701....	-210 ± 230	0.444
4954.958....	-930 ± 350	0.729
4955.730....	-540 ± 280	0.585
4955.839....	-720 ± 460	0.706
4956.701....	-580 ± 260	0.663
4956.925....	-2290 ± 320	0.911
5296.764....	-2330 ± 300	0.010
5297.643....	-2000 ± 260	0.985
5297.774....	-2030 ± 220	0.130
5298.649....	-1640 ± 230	0.101
5299.636....	-1150 ± 240	0.196
5300.827....	-230 ± 240	0.518
5302.763....	-920 ± 220	0.666
5303.793....	-1720 ± 220	0.809
5304.732....	-1790 ± 220	0.851
5308.808....	-730 ± 250	0.374
He I λ5876:		
5718.738....	-1700 ± 480	0.248
5719.725....	-1170 ± 380	0.343
5720.669....	-320 ± 350	0.391
5721.740....	-550 ± 330	0.579
5723.734....	-1790 ± 390	0.792
σ Ori E (2,442,778.819 + 1.19081E)		
Hβ:		
4947.024....	3740 ± 560	0.782
4947.774....	80 ± 250	0.412
4948.915....	-500 ± 540	0.370
4951.735....	2490 ± 290	0.738
4952.782....	2140 ± 290	0.617
4953.915....	1850 ± 270	0.569
4954.825....	-960 ± 310	0.333
4956.815....	440 ± 330	0.004
He I λ5876:		
5718.644....	2410 ± 350	0.761
5719.630....	1970 ± 410	0.589
5720.580....	110 ± 490	0.387
5721.655....	-1670 ± 280	0.289
5722.578....	340 ± 270	0.064
5723.571....	2190 ± 270	0.898
HD 58260		
Hβ:		
5068.592....	2290 ± 250	...
5069.588....	2510 ± 240	...
5070.594....	2470 ± 260	...
5308.859....	2660 ± 470	...
6514.545....	2050 ± 260	...
HD 60344		
Hβ:		
5070.544....	-160 ± 400	...
HD 64740 (2,444,611.859 + 1.33026E)		
Hβ:		
5065.547....	-860 ± 120	0.052
5066.576....	-660 ± 110	0.826
5067.558....	650 ± 110	0.564
5067.662....	170 ± 110	0.642
5068.492....	-230 ± 130	0.266
5068.681....	350 ± 120	0.408
5069.493....	-840 ± 120	0.019
5069.685....	-650 ± 110	0.163
5072.666....	500 ± 120	0.404
He I λ5876:		
5719.814....	-820 ± 120	0.886
5720.745....	350 ± 120	0.586
5721.569....	-760 ± 120	0.205
5721.836....	250 ± 100	0.406
5722.660....	-680 ± 110	0.026
5723.647....	-410 ± 110	0.767
HD 66522		
Hβ:		
5303.851....	250 ± 390	...
5305.850....	-80 ± 400	...
5306.846....	750 ± 360	...
5307.815....	1030 ± 330	...
HD 96446		
Hβ:		
4780.496....	-1970 ± 230	...
4781.488....	-1510 ± 230	...
4782.496....	-2130 ± 230	...
5062.648....	-2140 ± 270	...
6512.668....	-1590 ± 240	...
HD 133518		
Hβ:		
5069.788....	370 ± 230	...
5072.764....	310 ± 230	...
HD 175362 (2,444,637.039 + 3.6738E)		
Hβ:		
5534.738....	1280 ± 260	0.352
5535.623....	3980 ± 220	0.593
5536.697....	-6150 ± 170	0.885
5537.626....	-4840 ± 220	0.138
5540.797....	-5940 ± 140	0.001
5541.688....	-2290 ± 140	0.243
5542.740....	4990 ± 260	0.530
5543.663....	-4280 ± 200	0.781
He I λ5876:		
5534.799....	1550 ± 210	0.368
5535.690....	1710 ± 180	0.611
5536.766....	-5740 ± 410	0.904
5537.721....	-3990 ± 330	0.164
5540.742....	-4770 ± 230	0.986
5541.744....	-2280 ± 260	0.259
5542.797....	2690 ± 210	0.545
5543.772....	-4150 ± 330	0.811

For a dipolar magnetic field the ratio of the values of B_e at magnetic extrema is given by

$$r \equiv \frac{B_e(\min)}{B_e(\max)} = \frac{\cos(\beta + i)}{\cos(\beta - i)} \tag{3}$$

(Preston 1967), so that

$$\tan \beta = (1 - r)/[(1 + r) \tan i] \; . \tag{4}$$

Then if the extrema of the actual magnetic curve are smaller than -2500 G (the largest observed value plus a 2 σ error) and larger than -4400 G (the smallest observed value minus a 2 σ error), so that $r > 0.57$, then from equation (4) we find $\beta \lesssim 63°$. Thus δ Ori C appears to be a star in which the inclination between magnetic and rotation axes is relatively small.

b) *HD 37017 = HR 1890*

This Orion OB1 association star was discovered to be helium-strong by Morgan and Lodén (1966). Lester (1972) carried out an analysis of the helium lines and found that helium is overabundant by approximately a factor of 2. Walborn (1974) suggested that a weak, variable emission feature redward of Hα is present, similar to that seen in σ Ori E. It is a unique object of the class in that it is a spectroscopic binary with a radial velocity period of 18.65 days (Blaauw and van Albada 1963). Pedersen and Thomsen (1977) and Pedersen (1979) obtained photoelectric measurements of the helium line strength variations and found that the He I λ4026 line varies with a period of 0.901175 ± 0.000130 days. The star also has a small light variation with the same period and an amplitude of 0.05 mag in the *u* band (Pedersen and Thomsen 1977; Adelman and Pyper 1985). Barker *et al.* (1982) have detected a stellar wind that may be slightly variable.

In an earlier paper (Borra and Landstreet 1979) it was shown that the magnetic field of this star varies with the same period as the helium lines. A fit of the observations to the equation

$$B_e = B_0 + B_1 \sin 2\pi(\phi - \phi_0) \tag{5}$$

yielded an anomalously large $\chi^2/n = 2.3$ as a result of considerable scatter about the mean magnetic curve. We have redetermined the period by combining our new magnetic observations with the old magnetic and spectrophotometric data, thereby eliminating several spurious periods present in the individual data sets. According to the photometric data, helium line strength maxima occur at JD 2,442,817.619 and JD 2,443,071.715 (Pedersen and Thomsen 1977; Pedersen 1979). This difference amounts to 281.96 ± 0.04 cycles using Pedersen's (1979) 0.901175 day period. The nearest sidelobe periods (i.e., periods derived assuming that the cycle count is uncertain by ± 1) are then 0.904256 and 0.897865 days, each with an uncertainty of about 0.000130 days. The combined helium and hydrogen magnetic data, obtained over a considerably longer time than the photometric observations, permit many possible periods. Two of these, 0.901195 and 0.897989($\pm$0.000050) days, are consistent with the above photometric periods. However, the latter fit is very poor ($\chi^2/n > 6$). Using only the Hβ magnetic data, we then arrive at a revised fit to equation (5): $B_1 = 910 \pm 50$ G, $B_0 = -1260 \pm 30$ G, and $\phi_0 = 0.25$. The phase ϕ is determined from the new ephemeris

$$\mathrm{JD}(B_e^-) = 2{,}444{,}583.009(\pm 0.061) + 0.901195(\pm 0.000050)E \; .$$

The notation B_e^- indicates the negative magnetic extremum. The reduced χ^2 of the best sine wave fit is 2.15.

The magnetic observations are plotted in Figure 1 with our least-squares fit superposed. The magnetic curves defined by the Hβ and He I observations are very similar for those phases for which He I observations are available. Also included in the figure are photometric (Strömgren *u*) observations of Adelman and Pyper (1985), and the helium λ4026 line strength index *R* curve of Pedersen (1979). (Helium line strength increases with decreasing values of *R*.) For HD 37017 maximum helium line strength occurs near the negative magnetic extremum, at phase 0.05 ± 0.06. The large value of χ^2 reflects the large amount of scatter of the magnetic data about the best-fit sine curve. This may indicate the presence of a magnetic field structure more complex than a simple centered dipole (although additional quadrupolar and octupolar components do not improve the fit significantly), some poorly understood source of errors, or a complication arising from the binary nature of the star.

Without measurements of the surface magnetic field, we cannot uniquely define a model of the magnetic geometry of a star. However, using equation (2) we can find the inclination *i* of the rotation axis to the line of sight. Bolton (1987) suggests that the helium-strong star component of this binary has a $T_{\rm eff}$ similar to σ Ori E, or about 23,000 K, and is approximately 1 mag brighter than the secondary. With $E(B-V) = 0.09$ and a distance of 450 pc, we then find $R = 3.5 \pm 0.7\ R_\odot$, where the uncertainty is estimated from errors in $T_{\rm eff}$ and the luminosity ratio of the system. (Lester 1972 found $R = 4\ R_\odot$.) Using $v \sin i \lesssim 95$ km s^{-1} (Bolton 1987), we find that the inclination is in the range $23° \lesssim i \lesssim 37°$. Bolton (1987) estimates the orbital inclination to be between 30° and 50°. Since a sinusoid fits the magnetic data fairly well, we assume that the dipole component of the field is dominant. In this case, with $r = 0.180$ and $23° \lesssim i \lesssim 37°$, we find $42° \lesssim \beta \lesssim 59°$ from equation (4). Again the obliquity is low compared with typical values observed in Ap stars.

c) *σ Orionis E = HD 37479 = HR 1932*

Virtually every phenomenon observed in this star varies with time. Helium variability was first noted by Hunger (1974). Variable Hα emission was reported by Walborn (1974). A period of about 1.19 days was determined from spectroscopy and an eclipse-like photometric light curve (Walborn and Hesser 1976). The period was quickly improved to 1.19081 ± 0.00001 days (Hesser, Walborn, and Ugarte 1976; Hesser, Moreno, and Ugarte 1977). Groote and Hunger (1976) discovered a variable shell spectrum in the higher Balmer lines; these shell lines appear only during the eclipses seen in the light curves. Kemp and Herman (1977) observed an identical period for variation of the linear polarization of continuum light from the star. σ Ori E was the first helium-strong star found to have a magnetic field (Landstreet and Borra 1978). The magnetic data yield a reasonable magnetic curve for the above period.

Landstreet and Borra (1978) presented a schematic model of σ Ori E with circumstellar material orbiting in a ring or in isolated clouds above the stellar surface explaining the optical observations. This model has also been discussed in some detail by Groote and Hunger (1982), Nakajima (1981, 1985), and Bolton *et al.* (1986). After the discovery of the P Cygni nature of the ultraviolet resonance lines (Shore and Adelman 1981; Barker *et al.* 1982) Barker (1986) reexamined the model incorporating the ultraviolet data. The C IV and Si IV ultraviolet resonance doublets are highly variable, with extended blue-

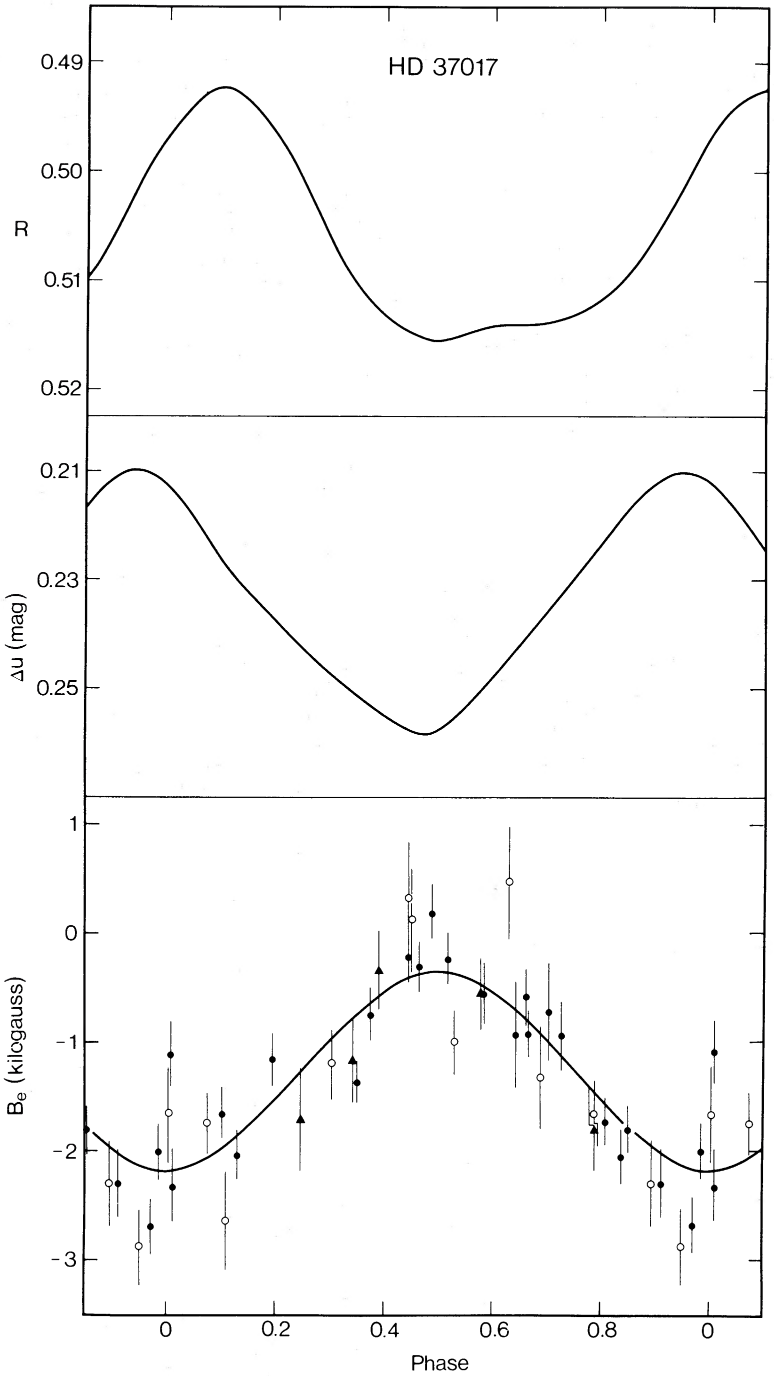

FIG. 1.—Helium strength index R and photometric and magnetic curves of HD 37017. The first two are hand-drawn fits to the data. Magnetic data symbols: (*open circles*) Hβ observations of Borra and Landstreet (1979); (*filled circles*) Hβ observations from this paper; (*triangles*) He I λ5876 observations from this paper. The curve through the magnetic observations is given in the text.

ward absorption, indicating the presence of a wind. Emission is not obvious in these lines. The star is also a nonthermal radio source (Drake *et al.* 1987).

We have combined our magnetic observations with the spectrophotometric observations of Pedersen and Thomsen (1977) and Pedersen (1979) as for HD 37017 to determine a new period for σ Ori E. We find a unique period of 1.190816 ± 0.000056 days and a reduced χ^2 of 1.48 for the fit of the sine wave to the Hβ magnetic observations. The period of Hesser, Moreno, and Ugarte (1977) is still more accurate, so we have plotted the magnetic data using their ephemeris. Using equation (5) and the entire set of magnetic data, we find that the best least-squares fit is given by $B_1 = 2150 \pm 120$ G, $B_0 = 660 \pm 60$ G, and $\phi_0 = 0.474$ for the ephemeris

$$\text{JD (primary minimum)} = 2{,}442{,}778.819 + 1.19081(\pm 0.00001)E\,.$$

This fit is plotted in Figure 2, along with smoothed curves representing the helium strength index R (Pedersen 1979), the number n of the last visible Balmer shell line (Groote and Hunger 1976), and the photometric measurements of Hesser, Walborn, and Ugarte (1976). Again, we note that the effective field as measured in λ5876 is very close to that observed in Hβ. As previously found (Landstreet and Borra 1978), the two "eclipse" minima coincide accurately with $B_e = 0$ (the magnetic equator); the shell lines may lag slightly.

Bolton *et al.* (1986) find that $v \sin i$ is 162 ± 2 km s^{-1} for HD 37479. Using a distance of 450 pc and an angular diameter of 0.079 milliarcsec, we find $R = 3.9\ R_\odot$. Equation (2) gives a lower limit of $R = 3.8\ R_\odot$. The inclination must then be in the range $78° \lesssim i \lesssim 90°$. The appearance of very distinctive phenomena, such as shell lines, when $B_e = 0$ strongly suggests that the line of sight passes far from the magnetic equator at times, so that $\beta \gg 0°$.

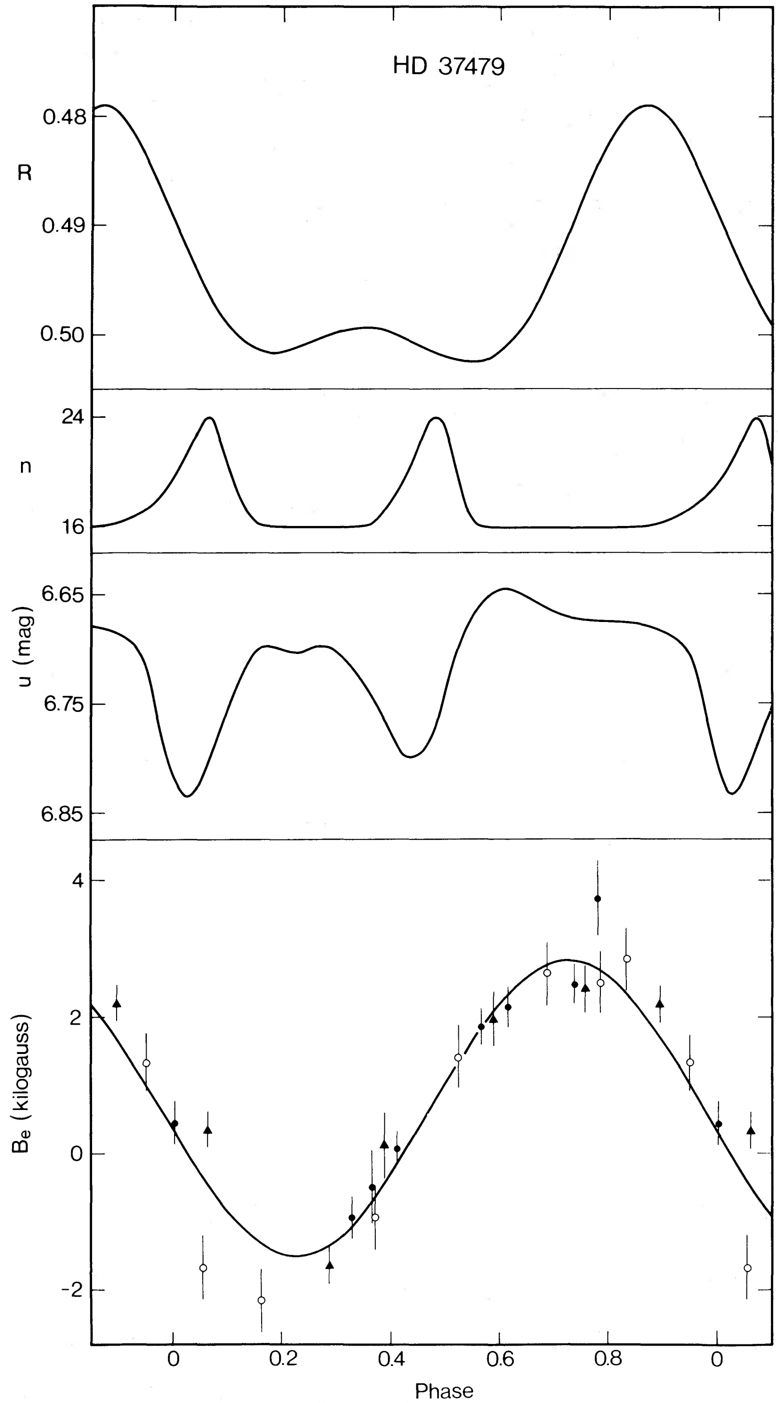

FIG. 2.—Helium strength index R, shell line, and photometric and magnetic curves of HD 37479. The first three are hand-drawn fits to the data. Magnetic data symbols are as in Fig. 1, except that open circles represent Hβ observations of Landstreet and Borra (1978). The curve through the magnetic observations is given in the text.

d) *HD 58260*

Garrison, Hiltner, and Schild (1977) first identified this star as helium-strong and noted that the helium line strengths may be variable. Walborn (1974) detected no Hα emission in the star. Pedersen's (1979) observations suggest a small-amplitude helium variation with a possible period of 1.657 days. The star shows strong, constant C IV emission (Barker *et al.* 1982; Barker 1986). The magnetic field of HD 58260 has been constant at 2300 G for the nearly 9 years for which we have data. A χ^2 test reveals no evidence for variability about this mean at the 99% confidence level for 9 degrees of freedom. Walborn (1983) suggests that the $v \sin i$ of this star is less than 30 km s^{-1}. We have one high signal-to-noise spectrum obtained at the Canada-France-Hawaii Telescope for which we have again modeled Si III profiles as we did for HD 36485. We find $v \sin i = 18 \pm 2$ km s^{-1}.

Since the distance of this star is poorly determined, we can make only a rough estimate of its radius. The star's colors suggest a $T_{\rm eff}$ of 18,000 K by comparison with Kurucz's (1979) log $g = 4$ model atmospheres. If we assume that line blanketing in the helium-strong stars is normal, then we can use this temperature and the results of Code *et al.* (1976) to find $R_{\rm ZAMS} = 2.8\ R_\odot$. We arbitrarily adopt an upper limit of $2R_{\rm ZAMS}$ or 5.6 $R_\odot$ to allow for uncertainty in the evolutionary status of the star. Equation (2) then gives an upper limit of 15.8 days for the rotation period of HD 58260. It seems unlikely that lack of variation is due to poor spacing of the observations. Again assuming $v_{\rm eq} \lesssim 240$ km s^{-1}, we find $i \gtrsim 4°$. With $r > 0.4$, the inclination of the magnetic axis to the rotation axis is found to be $\beta \lesssim 81°$.

e) *HD 60344*

This star was found to be helium-strong by MacConnell, Frye, and Bidelman (1970, 1972). Kaufman and Hunger (1975) carried out a fine analysis and found helium to be overabundant by a factor of 8, while metals appear underabundant. No field is evident in the three measurements reported by Borra and Landstreet (1979) or in the one new measurement given here. Considering the low $v \sin i$ (≤ 30 km s^{-1} [Walborn 1983]) and lack of spectral variations (Pedersen and Thomsen 1977), this may either be a long-period object or nonvariable, in which case it may be a helium-strong analog of the PGa helium-weak stars (Borra, Landstreet, and Thompson 1983).

f) *HD 64740*

This star was discovered to be helium-strong by Hiltner, Garrison, and Schild (1969). Pedersen and Thomsen (1977) and Pedersen (1979) detected spectrum variations with a period of about 1.33 days. HD 64740 has very little photometric variation (Pedersen and Thomsen 1977). Weak, variable Hα emission is also reported (Walborn 1974; Pedersen 1979). Lester (1976, 1979) has examined the ultraviolet spectrum of this star and reported variations in the strengths of C II, N II, Si III, and Si IV lines with the same period as the optical data. He finds a factor of 7 overabundance of nitrogen but normal amounts of carbon and silicon. Helium is enhanced by a factor of 3 or 4.

Borra and Landstreet (1979) found a variable, reversing magnetic field in this star. Again, we find a unique period by combining all magnetic and spectrophotometric observations. The Hα and λ5876 magnetic data yield several possible periods, 1.33589, 1.33026, and 1.32468(±0.00006) being the best three. The observations of Pedersen and Thomsen (1977) and Pedersen (1979) indicate maximum helium line strength at JD 2,442,806.691 and JD 2,443,064.838. Using Pedersen's (1979) period of 1.33016 ± 0.00016 days, this gives a cycle count of 194.072 ± 0.024 for this time period. The nearest sidelobe periods are then 1.33755 and 1.32383 days, each uncertain by approximately 0.00016 days. Neither of these is consistent with any of the magnetic curve periods. This leaves only $P = 1.33026 \pm 0.00006$ as a possible period. In Figure 3

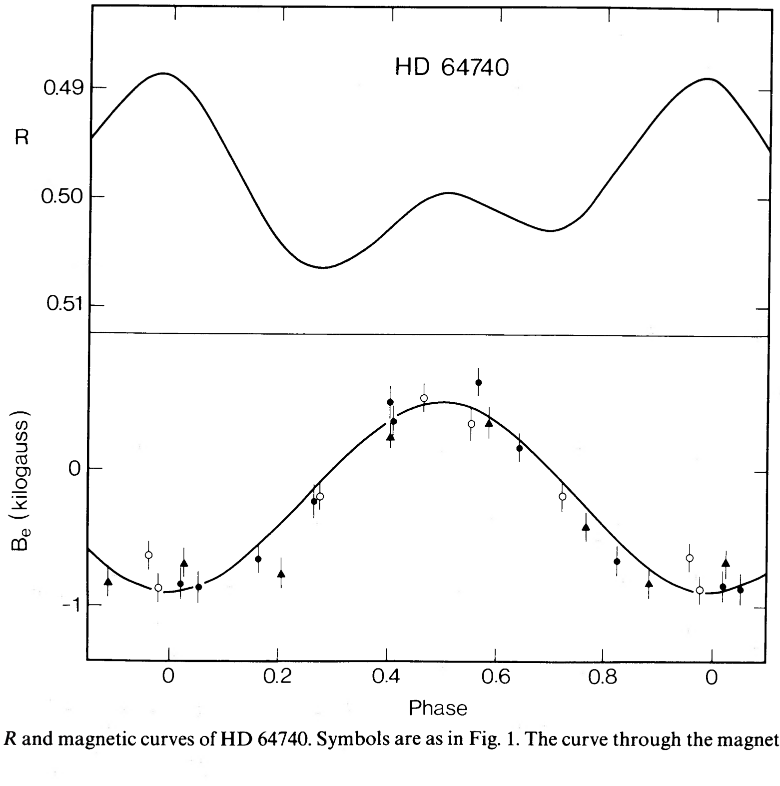

FIG. 3.—Helium strength index R and magnetic curves of HD 64740. Symbols are as in Fig. 1. The curve through the magnetic observations is given in the text.

we have plotted all magnetic data with the new least-squares ephemeris

$$\mathrm{JD}(B_e^-) = 2{,}444{,}611.859(\pm 0.042) + 1.33026(\pm 0.00006)E.$$

We find for equation (5) $B_0 = -200 \pm 10$ G, $B_1 = 690 \pm 10$ G, $\phi_0 = 0.25$, and a reduced $\chi^2 = 1.40$.

Using the method adopted for HD 58260, we determine a radius $3.2 < R < 6.4\ R_\odot$ (Lester 1976 adopted $R = 5\ R_\odot$), and if $v \sin i = 160 \pm 15$ km s^{-1} (Walborn 1983), we find that the inclination must be larger than 41°. With $r = -0.55$, equation (4) gives $\beta \lesssim 76°$. Maximum helium line strength occurs at $\phi = 0.98 \pm 0.06$ as shown by the R index curve in Figure 3. Also, the secondary helium maximum occurs very close to the positive magnetic extremum, and helium line strength minima coincide closely with the zero effective magnetic field. This suggests a particularly simple geometry of two polar patches of enhanced helium abundances for HD 64740.

g) HD 66522

This star was first noted as helium-strong by Thackeray, Tritton, and Walker (1973) and Kilkenny (1978). We have made four magnetic observations over a 5 day interval. One observation shows a 1 kG field at the 3.1 σ level. The χ^2/n for this star is 3.63, a result that is significant at the 99% confidence level, so it is reasonable to conclude that the star is magnetic. A period of <20 days is suggested by the magnetic data. Walborn (1983) finds $v \sin i \lesssim 30$ km s^{-1}. Further observations are clearly needed.

h) HD 96446

Jaschek and Jaschek (1959) first detected the helium overabundance of this star. Pedersen and Thomsen (1977) find a small variability in helium line strengths with the poorly determined period of 23 ± 6 days. Walborn (1983) measures $v \sin i \lesssim 30$ km s^{-1}. Wolf (1973) has performed an abundance analysis of HD 96446, and found $n(\mathrm{He})/n(\mathrm{H}) \approx 1$ and a factor of 13 underabundance of oxygen. C, N, Mg, Al, Si, S, and Fe abundances are normal. The star has strong C IV emission similar to that observed in HD 58260 (Barker *et al.* 1982; Barker 1986). Our magnetic observations together with those of Borra and Landstreet (1979) show an approximately constant field of −1650 G over an 8 year period. Some measurements deviate from the mean field by approximately 2 σ, suggesting that there may be a low-amplitude variation. We have performed a χ^2 test to examine this possibility. Using the above weighted mean field, we find $\chi^2/n = 1.8$, which, for 10 degrees of freedom, is significant only at the 90% confidence level. Additional data will be required before we can make a firm conclusion about this variability. In any event, the observations are consistent with a small obliquity of the magnetic axis to the rotation axis.

i) HD 133518

No field has been detected in three magnetic observations given by Borra and Landstreet (1979) or the two observations reported here for this star, discovered by MacConnell, Frye, and Bidelman (1970). Its low $v \sin i$ (Walborn 1983) gives $v \sin i \lesssim 30$ km s^{-1}, and lack of spectrum variations (Pedersen and Thomsen 1977) suggests that this may be a nonvariable object like HD 60344. Ultraviolet data show nonvariable C IV absorption and a stellar wind (Barker *et al.* 1982; Barker 1986).

j) HD 175362 = HR 7129 = Wolffs' Star

Classified as helium-weak by Nissen (1974), the star exhibits variations in the line strengths of helium and silicon (Balona and Martin 1974). Balona (1975) performed a fine analysis and found an effective temperature of 17,800 K; a normal carbon abundance; an overabundance of magnesium, silicon, titanium, and iron; and $0.015 \lesssim n(\mathrm{He})/n(\mathrm{H}) \lesssim 0.030$. Hartoog and Cowley (1979) determined a $^3\mathrm{He}/^4\mathrm{He}$ ratio of 1.6. A strong, variable magnetic field was discovered photographically by Wolff and Wolff (1976) and confirmed photoelectrically by Borra, Landstreet, and Thompson (1983). The field varies with a 3.67 day period, as does the helium line strength R index (Pedersen 1979). This star is apparently a member of a small group of objects, of which a Cen is the prototype, with photoelectric colors intermediate between those of the helium-strong and helium-weak stars.

Borra, Landstreet, and Thompson (1983) combined all available data and determined an improved period of 3.6740 ± 0.0015 days. Our new magnetic field observations allow us to refine this period still further. Combining all magnetic data, we derive an epoch of negative magnetic extremum at JD 2,444,637.04 ± 0.10 using the above period. Assuming that helium line strength maximum coincides with negative magnetic field extremum (Wolff and Wolff 1976) and using data contained in Borra, Landstreet, and Thompson (1983), we now find a best-fit period of 3.6738 ± 0.0004 days. Figure 4 is a plot of the data and the best-fit sinusoid. The solid curve (eq. [5]) is defined by $B_0 = -1420 \pm 20$ G, $B_1 = 5440 \pm 140$ G, and $\phi_0 = 0.25$, with ϕ given by the ephemeris

$$\mathrm{JD}(B_e^-) = 2{,}444{,}637.039(\pm 0.098) + 3.6738(\pm 0.0004)E\ .$$

Maximum helium line strength is coincident with the B_e negative extremum within 0.05 of a period. We adopt a stellar radius between 2.6 and 5.2 $R_\odot$ from the star's colors. Equation (2) and the observed $v \sin i$ of 30 km s^{-1} (Hensler 1979) then give $25° \lesssim i \lesssim 57°$. The magnetic curve gives $r = -0.59$, so that from equation (4) we find $68° \lesssim \beta \lesssim 83°$. Hensler used the values $i = 25°$ and $\beta = 87°$ in his model of HD 175362.

The reduced χ^2 value of 20 for the hydrogen line data indicates a considerable departure of the data from a simple sinusoid. As discussed by Borra, Landstreet, and Thompson (1983), much of this scatter might be caused by unidentified measurement errors. Such errors would only be seen in high signal-to-noise measurements such as we have for this star. If the noise for this star's data were 4 times larger, and approximately equal to that for the other objects discussed here, then the reduced χ^2 would become 1.25, as good as any of the other best fits derived above. However, inspection of Figure 4 shows that the 1983 Hβ observations and the Hβ measurements reported in this paper, taken separately, form well-defined curves of the same nonsinusoidal shape (indicated by the dashed curve). While a measurement problem could certainly produce one such curve, it is difficult to understand how an identical curve could be reproduced on a second observing run several years later. We therefore believe that the nonsinusoidal nature of the magnetic curve is real, indicative of a magnetic geometry somewhat more complex than a simple dipole.

The helium line observations of this star, when reduced by the line-profile fitting technique applied to the observations of helium-strong stars, show a surprisingly large scatter about a mean curve. We attribute this to relatively large errors in the conversion of observed polarizations to field strength, arising

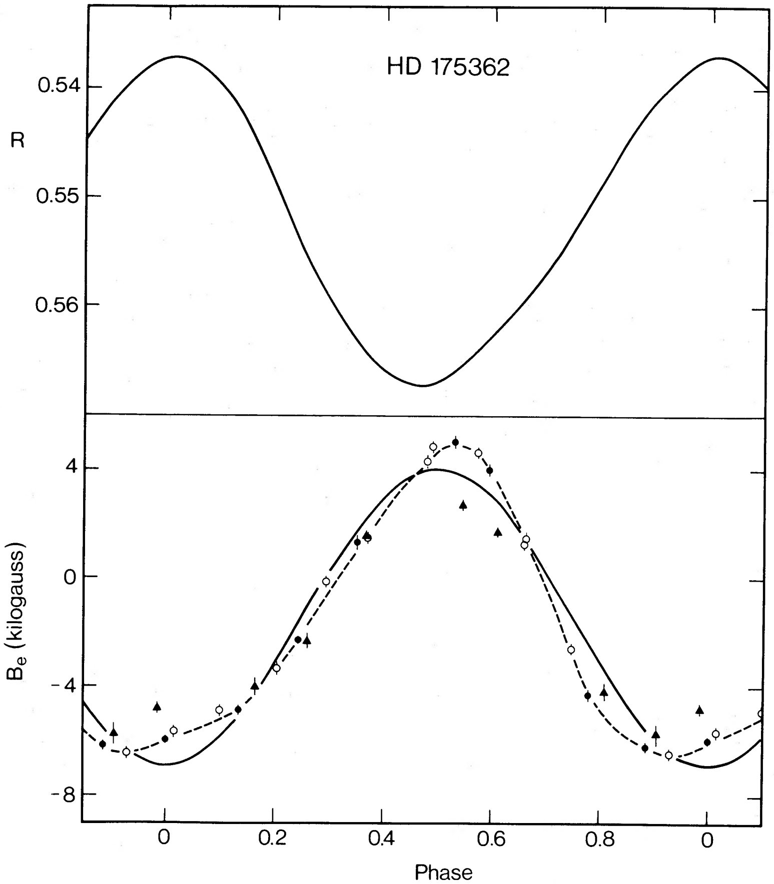

FIG. 4.—Helium strength index *R* and magnetic curves of HD 175362. Magnetic data symbols are as in Fig. 1, except that open circles represent H*β* observations of Borra, Landstreet, and Thompson (1983). The solid curve through the magnetic observations is given in the text. The dashed curve is a hand-drawn fit through the H*β* magnetic observations.

from the uncertainty of the value of $dI/d\lambda$ of the very weak lines. When all helium line observations are reduced using the mean conversion factor (eq. [1]) of 26,100 G per percent circular polarization, the scatter of the helium line magnetic measurements about their mean curve decreases substantially, even though the equivalent width variation of this line implies that in fact the value of $dI/d\lambda$ and the conversion constant must vary somewhat. We therefore present in Table 2 and Figure 4 the helium line measurements reduced with the mean conversion factor. It is seen that the helium lines define a magnetic curve rather close to that defined by H*β* observations, but perhaps with systematically slightly smaller values of B_e near the field extrema, especially the positive one which corresponds to the weakest helium line strength.

IV. DISCUSSION AND CONCLUSIONS

In principle, measurements of B_e using lines of various elements can provide important constraints for abundance distribution geometries of variable elements (Michaud, Megessier, and Charland 1981). However, it is evident from Figures 1–4 that the magnetic observations of helium-strong and helium-variable stars obtained from H*β* and He I λ5876 can be superposed and yield nearly identical curves. This suggests that, in this class of stars at least, although helium is certainly unevenly distributed, the contrast in line strength between regions of high and low abundance is small. For example, consider a single region of enhanced helium abundance that covers one-half of the visible surface of a nonrotating star. The observed He I line strengths of helium-strong stars vary by only about ±20% about the means. Ignoring limb darkening, this suggests that the local equivalent width is a minimum of 2.0 times larger in the spot than on the surrounding surface. For these strong lines $W_\lambda \propto (\epsilon_{\rm He})^{1/2}$, so the local abundances might differ by a factor of 4. For HD 175362 the observed helium line variations are ±30% or a bit more around the mean, and the helium and H*β* magnetic curves differ by a larger amount, especially near the pole with weak helium. In this star the local equivalent width contrast is probably rather more than a factor of 2.

A second point to note is that five of eight helium strong stars with definite fields have constant or nonreversing magnetic fields indicative of a small *β*. The tendency toward nonreversal of effective fields is conveniently discussed using the parameter *r*, given by equation (3), which ranges from -1 for fields with equal positive and negative extrema to $+1$ for constant fields. Preston (1967, 1971) and Landstreet (1970) calculated this value for a sample of Ap stars with known magnetic curves and concluded that the resulting distribution of *r* was consistent with either a bimodal population of stars with *β* near 20° or 80°, or a random distribution of *β*, irrespective of the assumed magnetic geometry.

In a study of the magnetic fields of the hotter helium-weak stars, Borra, Landstreet, and Thompson (1983) suggested that there seems to be a greater tendency toward positive *r*-values and hence small *β* in these objects. To clarify the situation, we

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have determined *r*-values for the Ap, helium-weak, and helium-strong stars and plotted histograms for each class in Figure 5*a*. The Ap stars are objects with well-determined magnetic curves from Borra and Landstreet (1980) and Thompson, Brown, and Landstreet (1987). The helium-weak star data are from this paper (HD 175362), Borra, Landstreet, and Thompson (1983), and Borra (1981). The *r*-values determined from observations contained in the latter paper are based on a small number of magnetic observations and are therefore possibly overestimated. The distribution for the helium-strong stars includes data from this paper, Thompson and Landstreet (1985), and Barker *et al.* (1982).

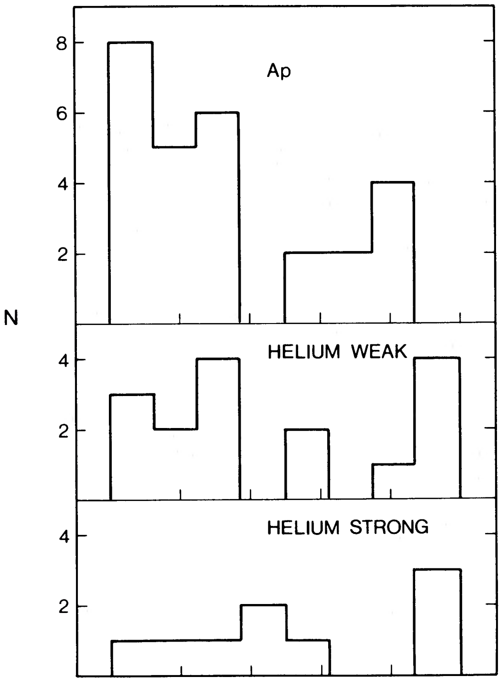

FIG. 5*a*

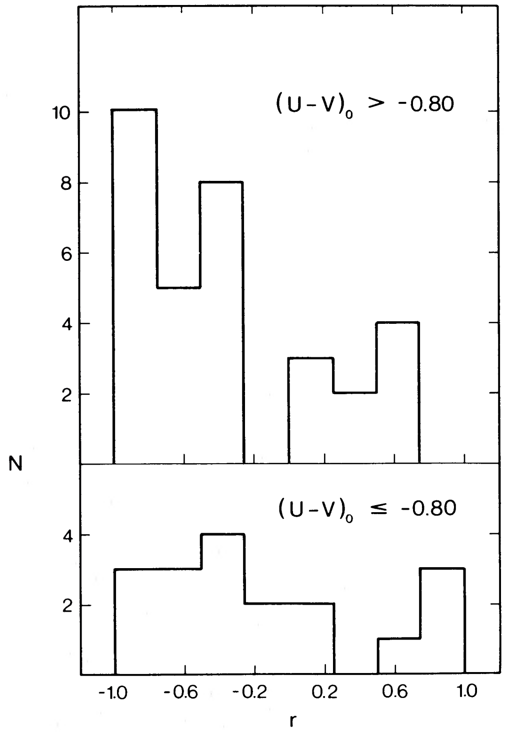

FIG. 5*b*

FIG. 5.—Histograms of the distribution of *r*-values (the ratios of B_e extrema) (*a*) for the Ap, helium-weak, and helium-strong stars and (*b*) for magnetic stars with $(B-V)_0 > -0.80$ and $(U-V)_0 \leq -0.80$.

Figure 5*a* does seem to indicate a general increase in the fraction of positive *r*-values from the Ap stars to the helium-strong ones. Because of the small number of stars involved, however, it is necessary to test the reality of this trend. A Kolmogorov-Smirnov (KS) two-tailed, two-sample test was performed on each pair of distributions to determine whether the parent distributions are significantly different. We find that we cannot reject the hypothesis that the distributions are identical at even a 20% significance level. Using the probability distribution given by Landstreet (1970), we also find that the individual *r* distributions are consistent with a random distribution of β for each class of objects. Preston's bimodal distribution is also in acceptable agreement with all three observed distributions, so the nature of the true parent distribution is still uncertain.

We have also grouped this sample of stars in a different fashion. Thompson, Brown, and Landstreet (1987), using some of the magnetic data presented here, suggest that the magnetic fields of peculiar stars with $(U-V)_0 \leq -0.80$ (corresponding to a spectral type near B4) are stronger than the cooler magnetic stars. In Figure 5*b* we have divided the magnetic Ap, helium-weak, and helium-strong stars into two groups determined by this color boundary. Again, the histograms suggest larger *r*-values for the hotter component. Once more, however, a KS test fails to reveal a difference in the two *r* distributions at the 20% significance level. The *r*-values could well be independent of temperature as well as field strength.

Walborn (1983) has compared the helium-strong stars with normal early B stars observed by Wolff, Edwards, and Preston (1982) and suggests that there is a possible excess of rapid rotators in the peculiar group. The rapidly rotating objects that we have observed have all been found to be magnetic. Some of the line broadening in these stars may therefore be the result of the Zeeman effect. For example, recent high signal-to-noise spectra of HD 37776 obtained at the Canada-France-Hawaii Telescope show a variation in strength of the He I λ4121 line of about 30%. Using this line to measure rotation is therefore perhaps undesirable. The line Si III λ4552 shows sharp components clearly associated with several regions of enhanced silicon abundances and is consistent with a $v \sin i$ of approximately 95 km s^{-1}, whereas Walborn quotes 160 km s^{-1}. Moreover, Bolton (1987) suggests a $v \sin i \lesssim 95$ km s^{-1} for HD 37017, compared with Walborn's value of 170 km s^{-1}. Walborn's secondary peak at high $v \sin i$ for the helium-strong stars all but disappears with these modifications. Furthermore, a two-tailed, two-sample KS test establishes that the $v \sin i$ distributions of the helium-strong and normal early B stars discussed in Walborn's paper are indistinguishable. We conclude that the distributions of $v \sin i$ for the normal and peculiar early B stars are similar. This supports the suggestion that magnetic braking before or during the main sequence is insignificant in these objects (Borra and Landstreet 1979; Wolff, Edwards, and Preston 1982). If such braking were important, then we might expect the helium-strong stars to have a $v \sin i$ distribution slower than normal stars of the same spectral class.

The observations represented here reinforce the conclusion (Borra and Landstreet 1979; Thompson, Brown, and Landstreet 1987) that the magnetic fields of the helium-strong stars are, on the average, about 3 times as strong as those of the classical Ap stars, while the field strengths of the helium-weak objects are intermediate between the two. This trend should indicate something about the origin of the magnetic field. If the observed fields are dynamo-generated, then we might well expect more efficient field generation in more massive stars because of the larger convective cores in these objects. Other observations suggest that this is not the case. Dynamo theory predicts a positive correlation between angular velocity and magnetic field strengths. Observations of Ap stars instead seem to indicate a marginal decrease in magnetic field strengths as the rotation periods decrease (Borra and Landstreet 1980). Unfortunately, the data sample is too small to decide whether this trend holds for the helium-weak and helium-strong stars as well. There are four rapidly rotating helium-strong stars with strong fields, so perhaps the relationship between $v \sin i$ and field strength for this class is not the same as for the Ap stars. However, there is no obvious trend for B to increase with $v \sin i$. Interestingly, Moss (1980) has suggested that a dynamo may be oscillatory in the most rapidly rotating stars, so that the net magnetic flux reaching the stellar surface is zero. Finally, time scales for the diffusion of the magnetic field through the radiative envelope of the star may be too long for the more massive stars to have observable dynamo fields at the surface (Schüssler and Pahler 1978).

Perhaps instead the fields we observe are not dynamo-generated but are the fossil remnant of the field in the interstellar medium prior to the stellar formation process. D. F. Gray (1986, private communication) suggests that the more massive the star, the larger the Jeans radius, R_J, of the cloud from which it formed, and hence the larger the total flux of the interstellar field swept into the protostar. R. Mitalas (1986, private communication) suggested a simple calculation, assuming a mass-radius relationship of the form $R \propto M^a$ with $a = 0.58$. If the magnetic flux, $\phi = 4\pi BR^2$, where B is the magnetic field and R is the outer radius of the cloud or star, is conserved during the star's contraction, then $B(t = 0)/B_{\mathrm{ZAMS}} = (R_{\mathrm{ZAMS}}/R_J)^2$. For an interstellar cloud of mass M, density ρ, and temperature T, we have $R_J = GM\rho m_{\mathrm{H}}/5\,kT$, where m_{H} is the mass of atomic hydrogen. We then arrive at the result $B_{\mathrm{ZAMS}} \propto M^{2-2a}$. A 9 $M_\odot$ (helium-strong) star is therefore expected to have a field strength 3.2 times larger than a 2.25 $M_\odot$ Ap star upon reaching the main sequence, a number that is in good general agreement with the observations.

But why are all stars not magnetic if this is the correct picture? Why is there an apparent anticorrelation between $v \sin i$ and field strength for the Ap stars? Mestel and Moss (1977) suggest that the latter question might be answered by circulatory currents, created by rotation, burying the field lines below the stellar surface if the star rotates rapidly.

Perhaps we are seeing different field generation mechanisms in the helium-strong and Ap stars. Because of their larger convective cores, the dynamo-generated field might be of equal or greater magnitude than the fossil field in the helium-strong stars. Competition between circulation and dynamo dependencies on $v \sin i$ might strike a balance so that there is little net correlation or anticorrelation between $v \sin i$ and field strength. Of course, the problem with the diffusion time scale for the field to reach the surface still exists. The smaller core size of the Ap stars could mean that the fossil field is of primary importance, so that the observed $v \sin i$ versus $\langle B_e \rangle$ anticorrelation is preserved.

One of the strongest tests to decide upon the best theory for the origin of the magnetic fields in peculiar stars is the distribution of r-values. Centrally condensed magnetic fields such as those generated in a dynamo situated in the core are expected to have a bimodal distribution of β near 0° and 90°, depending on whether the poloidal or toroidal component of the magnetic field is dominant. Less centrally concentrated fossil fields should have essentially random obliquities (Mestel *et al.* 1981). Unfortunately, we have demonstrated that no conclusion can be determined from the data currently in hand. There is obviously a need for searches for more magnetic stars as well as continued observations of known magnetic stars with poorly determined magnetic geometries.

We wish to thank Drs. R. Mitalas and D. F. Gray for helpful discussions, Dr. C. T. Bolton for a critical reading of an early version of the manuscript, and Dr. E. F. Borra for the use of the Laval University polarimeter. We also acknowledge the assistance of Srs. A. Guerra and F. Peralta at Las Campanas Observatory, Mrs. M. Rasche for preparation of the figures, and Mr. T. Kennelly for some of the data reductions. This research has been supported in part by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Adelman, S. J., and Pyper, D. M. 1985, *Astr. Ap. Suppl.*, **62**, 279.
Babcock, H. W. 1962, in *Stars and Stellar Systems*, Vol. **2**, *Astronomical Techniques*, ed. W. A. Hiltner (Chicago: University of Chicago Press), chap. 5.
Balona, L. A. 1975, *M.N.R.A.S.*, **173**, 605.
Balona, L. A., and Martin, W. L. 1974, *M.N.R.A.S.*, **166**, 35P.
Barker, P. K. 1986, in *IAU Colloquium 87, Hydrogen Deficient Stars and Related Objects*, ed. K. Hunger, D. Schönberner, and N. Kameswara Rao (Dordrecht: Reidel), p. 277.
Barker, P. K., Brown, D. N., Bolton, C. T., and Landstreet, J. D. 1982, in *Advances in Ultraviolet Astronomy: Four Years of IUE Research*, ed. Y. Kondo, J. M. Mead, and R. D. Chapman (NASA CP-2238), p. 589.
Berger, J. 1956, *Contr. Inst. Ap. Paris, A*, No. 217.
Blaauw, A., and van Albada, T. S. 1963, *Ap. J.*, **137**, 791.
Bolton, C. T. 1987, private communication.
Bolton, C. T., Fullerton, A. W., Bohlender, D. A., Landstreet, J. D., and Gies, D. R. 1986, in *IAU Colloquium 92, The Physics of Be Stars*, ed. A. Slettebak and T. P. Snow (Cambridge: Cambridge University Press), p. 82.
Borra, E. F. 1981, *Ap. J. (Letters)*, **249**, L39.
Borra, E. F., and Landstreet, J. D. 1977, *Ap. J.*, **212**, 141.
———. 1979, *Ap. J.*, **228**, 809.
———. 1980, *Ap. J. Suppl.*, **42**, 421.
Borra, E. F., Landstreet, J. D., and Thompson, I. B. 1983, *Ap. J. Suppl.*, **53**, 151.
Bray, R. J., and Loughhead, R. E. 1964, *Sunspots* (New York: Dover), chap. 5.
Brown, D. N., Landstreet, J. D., Bolton, C. T., and Thompson, I. B. 1987, in preparation.
Code, A. D., Davis, J., Bless, R. C., and Brown, H. R. 1976, *Ap. J.*, **203**, 417.
Deutsch, A. J. 1958, in *IAU Symposium 6, Electromagnetic Phenomena in Cosmical Physics*, ed. B. Lehnert (Cambridge: Cambridge University Press), p. 209.
Drake, S. A., Abbott, D. C., Bastian, T. S., Bieging, J. H., Churchwell, E., Dulk, G., and Linsky, J. 1987, preprint.
Egret, D., and Jaschek, M. 1981, in *Upper Main Sequence Chemically Peculiar Stars* (Liège: Institut d'Astrophysique), p. 495.
Garrison, R. F., Hiltner, W. A., and Schild, R. E. 1977, *Ap. J. Suppl.*, **35**, 111.
Groote, D., and Hunger, K. 1976, *Astr. Ap.*, **52**, 303.
———. 1982, *Astr. Ap.*, **116**, 64.
Hartoog, M. R., and Cowley, A. P. 1979, *Ap. J.*, **228**, 229.
Hensler, G. 1979, *Astr. Ap.*, **74**, 284.
Hesser, J. E., Moreno, H., and Ugarte, P. P. 1977, *Ap. J. (Letters)*, **216**, L31.
Hesser, J. E., Walborn, N. R., and Ugarte, P. P. 1976, *Nature*, **262**, 116.
Hiltner, W. A., Garrison, R. F., and Schild, R. E. 1969, *Ap. J.*, **157**, 313.
Hoffleit, D., and Jaschek, C. 1982, *The Bright Star Catalogue* (4th ed.; New Haven: Yale University Observatory), p. 388.
Hunger, K. 1974, *Astr. Ap.*, **32**, 449.

Hunger, K. 1986, in *Upper Main Sequence Stars with Anomalous Abundances*, ed. C. R. Cowley, M. M. Dworetsky, and C. Megessier (Dordrecht: Reidel), p. 257.
Jaschek, M., and Jaschek, C. 1959, *Pub. A.S.P.*, **71**, 465.
Kaufman, J. P., and Hunger, K. 1975, *Astr. Ap.*, **38**, 351.
Kemp, J. C., and Herman, L. C. 1977, *Ap. J.*, **218**, 770.
Kilkenny, D. 1978, *M.N.R.A.S.*, **182**, 629.
Klinglesmith, D. A. 1971, *Hydrogen Line Blanketed Model Stellar Atmospheres* (NASA SP-3065).
Klinglesmith, D. A., Hunger, K., Bless, R. C., and Millis, R. L. 1970, *Ap. J.*, **159**, 513.
Kurucz, R. L. 1979, *Ap. J. Suppl.*, **40**, 1.
Landstreet, J. D. 1970, *Ap. J.*, **159**, 1001.
———. 1980, *A.J.*, **85**, 611.
———. 1982, *Ap. J.*, **258**, 639.
Landstreet, J. D., and Borra, E. F. 1978, *Ap. J.* (*Letters*), **224**, L5.
Lester, J. B. 1972, *Ap. J.*, **178**, 743.
———. 1976, *Ap. J.*, **210**, 153.
———. 1979, *Ap. J.*, **233**, 644.
MacConnell, D. J., Frye, R. L., and Bidelman, W. P. 1970, *Pub. A.S.P.*, **83**, 730.
———. 1972, *Pub. A.S.P.*, **84**, 388.
Mestel, L., and Moss, D. 1977, *M.N.R.A.S.*, **178**, 27.
Mestel, L., Nittmann, J., Wood, W. P., and Wright, G. A. E. 1981, *M.N.R.A.S.*, **195**, 979.
Michaud, G., Dupuis, J., Fontaine, G., and Montmerle, T. 1987, preprint.
Michaud, G., Megessier, C., and Charland, Y. 1981, *Astr. Ap.*, **103**, 244.
Mihalas, D., and Binney, J., 1981, *Galactic Astronomy* (San Francisco: Freeman), p. 187.
Morgan, W. W., Abt, H. A., and Tapscott, J. W. 1978, *Revised MK Spectral Atlas for Stars Earlier then the Sun*, Yerkes Observatory and Kitt Peak National Observatory.
Morgan, W. W., and Lodén, K. 1966, *Vistas Astr.*, **8**, 83.
Moss, D. 1980, *Astr. Ap.*, **91**, 319.
Nakajima, R. 1981, *Tohoku, Univ. Sci. Rept.*, **2**, 129.
———. 1985, *Ap. Space, Sci.*, **116**, 285.
Nissen, P. E. 1974, *Astr. Ap.*, **36**, 57.
Osmer, P. S., and Peterson, D. M. 1974, *Ap. J.*, **187**, 117.
Pedersen, H. 1979, *Astr. Ap. Suppl.*, **35**, 313.
Pedersen, H., and Thomsen, B. 1977, *Astr. Ap. Suppl.*, **30**, 11.
Preston, G. W. 1967, *Ap. J.*, **150**, 547.
———. 1971, *Pub. A.S.P.*, **83**, 571.
Pyper, D. M. 1969, *Ap. J. Suppl.*, **18**, 347.
Schüssler, M., and Pahler, A. 1978, *Astr. Ap.*, **68**, 57.
Shore, S. N. 1978, Ph.D. thesis, University of Toronto.
Shore, S. N., and Adelman, S. J. 1981, in *Upper Main Sequence Chemically Peculiar Stars* (Liège: Institut d'Astrophysique), p. 429.
Thackeray, A. D., Tritton, S. B., and Walker, E. N. 1973, *Mem. R.A.S.*, **77**, 199.
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.
Underhill, A., and Doazan, V. 1982, *B Stars with and without Emission Lines* (NASA SP-456), p. 159.
Vauclair, S. 1975, *Astr. Ap.*, **45**, 233.
Walborn, N. R. 1974, *Ap. J.* (*Letters*), **191**, L95.
———. 1982, *Pub. A.S.P.*, **94**, 322.
———. 1983, *Ap. J.*, **268**, 195.
Walborn, N. R., and Hesser, J. E. 1976, *Ap. J.* (*Letters*), **205**, L87.
Wolf, R. E. A. 1973, *Astr. Ap.*, **26**, 127.
Wolff, S. C., Edwards, S., and Preston, G. W. 1982, *Ap. J.*, **252**, 322.
Wolff, S. C., and Morris, N. D. 1974, *Pub. A.S.P.*, **86**, 935.
Wolff, R. J., and Wolff, S. C. 1976, *Ap. J.*, **203**, 171.

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