THE ASTROPHYSICAL JOURNAL, 358:274–281, 1990 July 20

OPTICAL SPECTRUM VARIATIONS OF THE HELIUM-STRONG STAR HD 64740

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Received 1989 April 10; accepted 1990 January 24

ABSTRACT

High signal-to-noise coudé Reticon spectra of the helium-strong star HD 64740 have been obtained for several rotational phases, in two spectral regions ($\lambda\lambda$3980–4160 and $\lambda\lambda$4400–4580) at the Canada-France-Hawaii telescope. These data, and previously published Zeeman analyzer observations, have been used to determine tentative abundance and magnetic field geometries of the star. Profile modeling has been performed with a line synthesis program that incorporates the effects of an assumed magnetic field and abundance distribution into the calculation of the line profiles. Helium appears to be overabundant in two spots near the magnetic poles of HD 64740. Silicon and magnesium show evidence for a high magnetic latitude band of enhanced abundances. Nitrogen and oxygen have roughly uniform abundances. Our model suggests an inclination of 36° for the star's rotation axis, and a magnetic obliquity of approximately 78°. No constraint can be obtained on the surface magnetic field of HD 64740 with the current data. Additional observations are recommended.

Subject headings: stars: individual (HD 64740) — stars: magnetic — stars: peculiar A — stars: spectrum variables

I. INTRODUCTION

At $V = 4.62$, HD 64740 (HR 3089) is the brightest of the known helium-strong stars. These objects are characterized by abnormally strong helium lines (corresponding to $N_{\rm He}/N_{\rm H}$ on the order of unity), and effective temperatures in the range 18,000 to 25,000 K, or roughly B2 spectral type. Some recent reviews are given by Bolton (1983), Hunger (1986*a*, *b*), Barker (1986), and Bohlender *et al.* (1987). As first suggested by Osmer and Peterson (1974), the helium-strong stars (or intermediate helium stars) are thought to represent extensions of the Ap and helium-weak star phenomena to higher temperatures. Many are spectroscopic and photometric variables, possess strong and variable magnetic fields, and have weak, variable winds (see Bohlender *et al.* 1987, and references therein).

The helium richness of HD 64740 was discovered during a southern hemisphere MK classification survey (Hiltner, Garrison, and Schild 1969). Nissen (1974) confirmed its anomalous helium abundance photometrically and suggested that $\epsilon_{\rm He} > 0.20$ ($\epsilon_{\rm He} = N_{\rm He}/N_{\rm total}$). According to Hunger (1975), Kaufmann and Schacht analyzed four coudé spectrograms and determined $T_{\rm eff} = 23{,}500$ K, $\log g = 3.9$, $v \sin i = 160$ km s^{-1}, $N_{\rm He}/N_{\rm H} = 0.67$, $r = 200$ pc, $\log (L/L_\odot) = 3.62$, $R/R_\odot = 4.0$, and $M/M_\odot = 4.5$. Oxygen and silicon show normal abundances, carbon is deficient and nitrogen enhanced. Unfortunately, this work has never been published. The first ultraviolet spectrum of the star was obtained from the *TD-1* satellite (Swings, Jamar, and Vreux 1973; Vreux, Malaise, and Swings 1973). Because of the low (30 Å) resolution, only the strongest lines could be identified, such as Si IV and C IV. Walborn (1974) reported the possible detection of Hα emission, similar to that observed in the prototypical helium-strong star σ Ori E. Lester (1976) analyzed both ground-based and *Copernicus* ultraviolet spectra of the star and performed a differential abundance analysis relative to the normal star λ Sco. His adopted model has $T_{\rm eff} = 22{,}500$ K, $\log g = 4.15$, and $N_{\rm He}/N_{\rm H} = 0.30$. The helium lines $\lambda\lambda$4026, 4387, and 4471 yield a $v \sin i$ of 160 ± 20 km s^{-1}. As compared to λ Sco, carbon and silicon abundances are normal, while nitrogen is overabundant by a factor of 7 in HD 64740. He also suggested that a magnetic field might be the mechanism responsible for the peculiar atmospheric abundances. Finally, Groote, Kaufmann, and Hunger (1978) have reported the unpublished results of Groote and Kaufmann, based on eight coudé spectrograms obtained near helium minimum with the ESO 1.52 m telescope: $T_{\rm eff} = 28{,}500$ K, $\log g = 4.15$, $N_{\rm He}/N_{\rm H} = 0.32$, and $v \sin i = 150$ km s^{-1}. Because of the high temperature, they performed a non–LTE analysis of silicon lines in the spectrum and suggested a slightly lower effective temperature of 27,000 K. This temperature is considerably higher than other determinations, and if correct, would make HD 64740 one of the hottest known helium-strong stars and the hottest known magnetic star. They also suggested that the star could be a candidate for the X-ray source 4U 0750−49.

Borra and Landstreet (1979) discovered a strong magnetic field in HD 64740, which shows a sinusoidal variation with an amplitude of about 700 G. Bohlender *et al.* (1987) have recently discussed the variable nature of the star. By combining magnetic, spectroscopic, and narrow-band photometric observations from several epochs, they find a unique period of $1^{\rm d}33026 \pm 0^{\rm d}00006$ for all of the variations. Published *uvbyβ* photometry suggests little or no change in brightness or color, unlike other members of the class (Pedersen and Thomsen 1977).

The generally accepted interpretation of the helium-strong stars is the oblique rotator model (Babcock 1949*a*; Stibbs 1950). In this model a (usually) predominantly dipolar magnetic field is inclined at an angle, β, to the rotation axis so that as the star rotates, typically with a rotation period on the order of a few days, different portions of its magnetic field are presented to the observer and magnetic variations are observed. The surface magnetic field stabilizes the star's atmosphere to a sufficient degree so that diffusion processes (Michaud 1970) may take place; however, it is thought that diffusion can only

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lead to a helium overabundance in the line-forming region if mass loss is occurring, and then for only a narrow range of mass-loss rates (Vauclair 1975; Michaud *et al.* 1987). In addition, the magnetic field influences where various ions accumulate so that the surface abundances are in general not uniform or symmetric with respect to the rotation axis. Hence the star is a spectrum variable. These nonuniform atmospheric abundances cause low-level photometric variations, probably because of changes in the continuous opacity and the temperature structure over the stellar surface (e.g., Bolton 1983). In the case of the helium-strong stars, the weak stellar outflows that are observed are also controlled by the magnetic field, so that the largest mass loss occurs at the magnetic poles. This explains the rotational modulation of the satellite UV lines of C IV and Si IV (Barker 1986; Shore 1978, 1987).

In this paper we present recently obtained high S/N Reticon spectra of the helium-strong star HD 64740, and use these observations to model the abundance distributions of several elements over the photosphere, as well as constrain more closely the magnetic geometry of the star. Previous optical spectral investigations of this star have used photographic detectors so that quantitative analyses in the past have been limited to somewhat noisy data, and have neglected effects due to variations of abundances over the stellar surface. Here, using modified versions of a line synthesis program developed by Landstreet (1988), we have carried out an analysis of HD 64740 and attempted to map its surface abundance and magnetic field geometries. In the remainder of the paper we present our observations and reduction techniques, discuss our method of analysis, and present our resulting model for HD 64740. Preliminary results of this work have been reported by Bohlender and Landstreet (1988).

II. OBSERVATIONAL DATA

a) *Spectroscopy*

Spectra of HD 64740 and several other helium-strong stars were obtained at the Canada-France-Hawaii 3.6 m telescope during 1986 January. The f/7.4 camera was used with the 600 line per millimeter grating in first order and the 1872 diode Reticon detector (Campbell *et al.* 1981). This configuration gives a spectrum about 180 Å long with 0.3 Å resolution. A typical exposure time for HD 64740 was 10 minutes, and yielded a S/N of about 200. Two spectral windows were observed in the program stars: $\lambda\lambda$4400–4580 which contains the Zeeman sensitive second multiplet of Si III ($\lambda\lambda$4552, 4567, and 4574) as well as strong and weak helium lines (He I $\lambda\lambda$4471 and 4437), and $\lambda\lambda$3980–4160 centered on Hδ, which contains Si II and Si IV multiplets that, along with Si III lines, we hoped to use as a temperature indicator, a N II line (λ3995), and several more helium lines including the pair He I $\lambda\lambda$4009 and 4026.

A journal of the CFHT observations is given in Table 1. Phases are calculated from the ephemeris given by Bohlender *et al.* (1987).

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

The notation JD($B_e^{\,-}$) represents the time of the negative extremum of the magnetic field. The uncertainty in the above period gives a negligible phase uncertainty of 0.033 in the CFHT data, relative to the epoch of the most recent magnetic field data. The low altitude of HD 64740 from CFHT permitted observations for only ~2 hr each night. This, and the roughly 4/3 day period of the star, resulted in only fair phase coverage during the five clear nights of our observing run.

TABLE 1

JOURNAL OF CFHT OBSERVATIONS OF HD 64740

Julian Data (2,446,000+)	Duration (s)	Wavelength Range (Å)	Phase
450.887..........	451	4395–4585	0.458
450.921..........	666	3985–4175	0.483
451.876..........	700	3985–4175	0.201
451.968..........	497	4395–4585	0.270
452.864..........	623	3985–4175	0.943
452.878..........	570	4395–4585	0.954
453.823..........	919	3985–4175	0.664
453.894..........	380	4395–4585	0.718

The observations were reduced using a reduction package developed for CFHT Reticon spectra by P. K. Barker (York University), with some modifications (see Bohlender 1988, 1989). Samples of spectra for HD 64740 are given by the solid lines in Figures 1 and 2. Helium, silicon, nitrogen, and magnesium are definitely variable, while oxygen is only marginally so. Hδ may be slightly variable but shows no indication of absorption by circumstellar material as is observed in σ Ori E (e.g., Bolton *et al.* 1986).

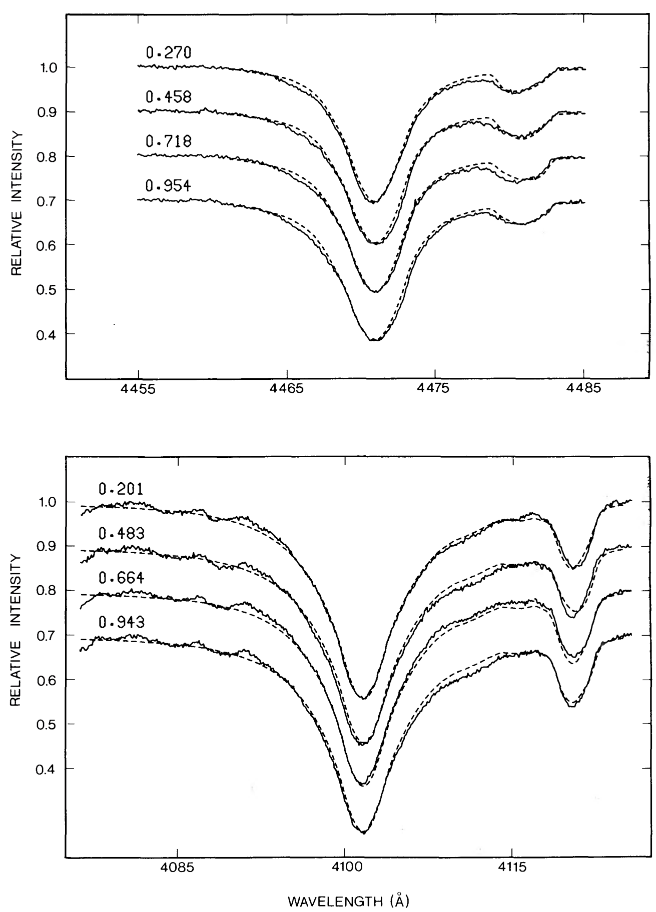

FIG. 1.—Observed (*solid*) and model (*dashed*) Hδ, He I $\lambda\lambda$4121 and 4471, and Mg II λ4481 line profiles of the helium-strong star HD 64740. The adopted abundance geometry for each element is discussed in the text.

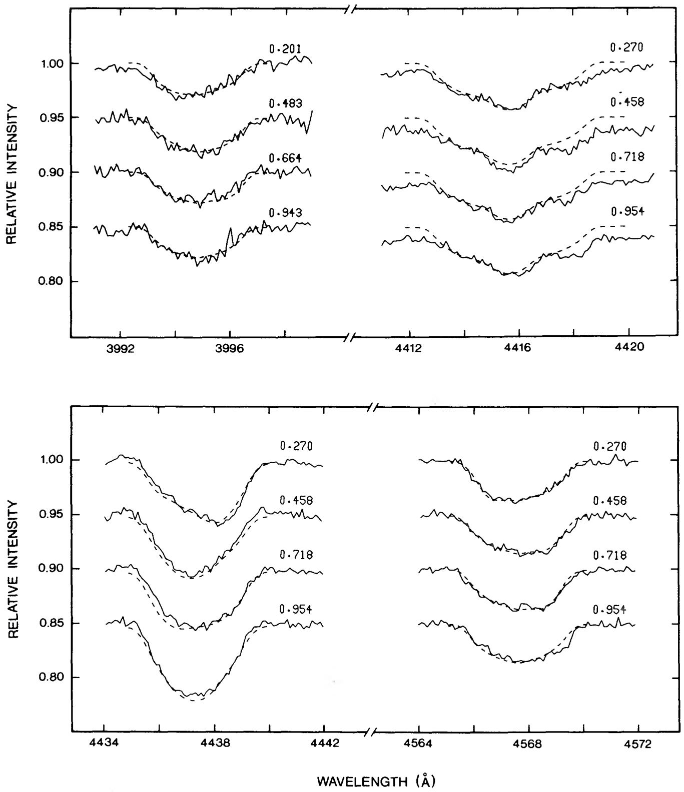

FIG. 2.—Observed (*solid*) and model (*dashed*) N II λ3995, O II λλ4415 and 4417, He I λ4437, and Si III λ4567 line profiles of HD 64740. The adopted abundance geometry for each element is discussed in the text.

b) Polarimetry

Extensive photoelectric Zeeman analyzer observations of HD 64740 have been previously published (Borra and Landstreet 1979; Bohlender *et al.* 1987). Polarization measurements for HD 64740 have been obtained in the wings of Hβ and He I λ5876. These yield virtually identical sinusoidal longitudinal magnetic field curves, whose variations can be described by the equation

$$B_e = B_0 + B_1 \sin 2\pi(\phi - \phi_0) , \quad (1)$$

with $B_0 = -200 \pm 10$ G, $B_1 = 690 \pm 10$ G, and $\phi_0 = 0.25$. The fit of this curve to the data yields a χ^2/n of 1.40, which suggests that the magnetic field configuration may be dominated by the dipole component. According to Bohlender *et al.* (1987), the effective magnetic field curve can be reproduced by a dipole with $i > 41°$ and $\beta < 76°$. The large uncertainty in the inclination and obliquity of the magnetic axis is due to a lack of knowledge of the surface magnetic field strength and an accurate radius. No information about the magnitude of the surface field, B_s, is given by these data. Of course, obtaining some constraints on the field geometry is one of the objectives of this work. The magnetic field observations, and the best fit sinusoid, are shown in figure 3 of Bohlender *et al.* (1987), along with the helium strength *R* index observations of Pedersen and Thomsen (1977) and Pedersen (1979). Maximum helium line strength occurs at the negative helium extremum, $\phi = 0.98 \pm 0.06$, and a secondary helium maximum occurs very close to the positive magnetic extremum. The helium line strength minima coincide closely with zero effective magnetic field. This suggests a possible geometry of two polar patches of enhanced helium abundances for HD 64740.

From the observed maximum longitudinal field of 890 G, the minimum value of the polar field strength of HD 64740 can be estimated using the results of Schwarzschild (1950). We find a minimum polar field strength, B_p, of approximately 3000 G, if a limb darkening constant of 0.40 is assumed. For a normal Zeeman triplet, a field of this magnitude would produce a Zeeman pattern with a separation between components of only 0.028 Å, while an element such as silicon at $T_{\rm eff} = 25{,}000$ K has a Doppler width of approximately 0.05 Å. Unless the inclination of HD 64740 is very close to 90°, so that β is small and the dipole is viewed only from near its equator, the polar field strength can not be more than perhaps 5 kG. The magnetic field therefore is not expected to have a large effect on line formation in the atmosphere of HD 64740. In particular, the Si III multiplet 2 lines are expected to be slightly strengthened because of the field, but differential intensification of the three lines in the multiplet, due to the desaturation of the various σ and π polarization components (Babcock 1949*b*; Preston 1970; Bohlender 1989), will be negligible. Thus we do not expect to be able to obtain much direct information about B_s from the present data.

III. ANALYSIS

a) Line Synthesis Program

We have employed modified versions of a line synthesis program written by one of us (J. D. L.) in this analysis of HD 64740. This program calculates the integrated intensity and polarization profiles of spectral lines of a star for an assumed model atmosphere, magnetic geometry, and surface abundance distribution, and has been described in detail by Landstreet (1988). Some of the modifications incorporated for this work can be found in Bohlender (1988, 1989) and below.

As in Landstreet's (1988) work for the Ap star 53 Cam, the magnetic field geometry of HD 64740 is assumed to be axially symmetric, and can include a combination of collinear dipole, linear or two-dimensional quadrupole, and linear octupole fields, or can consist of a dipole decentered along its axis. However, we have not required that the surface abundance geometry of HD 64740 be axisymmetric around the star's magnetic axis. Early models of the helium-line profiles suggested that the observed line profile variations could not be adequately modeled by such a geometry.

Instead, the surface abundances of the various elements are specified by an arbitrary number of circular spots. The location of the center of each spot for each element is specified by its magnetic colatitude and longitude relative to the magnetic pole visible at $\phi = 0.000$. (The magnetic longitude is defined to be 90° on the arc joining this magnetic pole and the nearest rotational pole.) The geometry is illustrated in Figure 3. The position, radius, and abundance of each spot is stored in an array by the program. Then, for each integration area on the stellar surface, and for each element, the program searches through this array in sequence and determines whether or not the current area is within one of the spots. If it is not, or if the element in question has a uniform surface abundance, a previously defined default abundance of the element is assumed. Such a geometry permits individual spots or bands of enhanced or depleted abundances to be modeled with an appropriate number of distinct or superposed spots. For example, an equatorial band 60° wide and with a factor of 10 over-

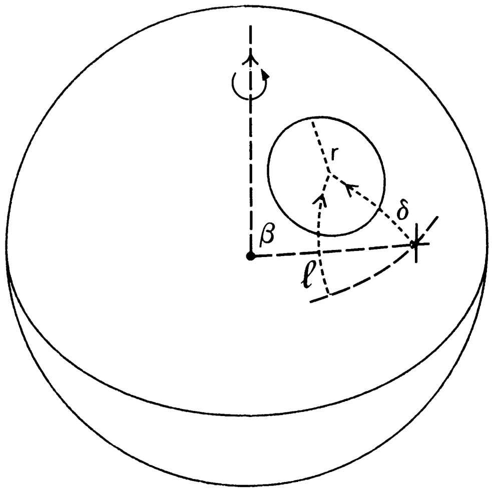

FIG. 3.—Illustration of the abundance and magnetic field geometry used in the line synthesis program. The angle β is the obliquity of the magnetic axis to the rotation axis. The magnetic colatitude is defined by the angle δ and the magnetic longitude by l. The longitude is defined as 90° on the arc between the rotation and magnetic poles visible at $\phi = 0$ (indicated by the + symbol) and is measured in the direction shown. The radius of the abundance spot is given by r.

TABLE 2

ADOPTED OSCILLATOR STRENGTHS

Ion	Multiplet	λ(Å)	log gf	Reference[a]
Hδ		4101.737	−0.7527	WSG
He I	14	4471.477	0.052	WSG
	16	4120.812	−1.53	WSG
		4120.993	−2.44	WSG
	50	4437.550	−2.034	WSG
N II	12	3994.996	0.28	WSG
O II	5	4414.909	0.305	WSG
		4416.975	0.044	WSG
	19	4121.48	−0.324	WSG
	20	4110.795	−0.90	WSG
		4119.221	0.478	WSG
		4120.279	−0.170	WSG
		4120.554	−1.124	WSG
	21	4112.029	−0.78	WSG
Mg II	4	4481.129	0.59	WM
		4481.327	0.75	WM
Si III	2	4567.872	0.07	WM
		4574.777	−0.41	WM
Si IV	1	4116.104	−0.10	CCA

[a] WSG = Wiese, Smith, and Glennon 1966; WM = Wiese and Martin 1980; CCA = Chapman, Clarke, and Aller 1966.

abundance of a given element relative to the rest of the star can be defined by two spots, each centered at the same magnetic pole: the first spot will have a radius of 120° and an abundance 10 times greater than the second spot with radius 60° and the default abundance of the element. To keep the number of free parameters to a minimum, the line profiles of HD 64740 have been modeled using the smallest number of spots necessary to give an adequate fit. In most cases two abundance patches (giving two spots or one band) are sufficient.

LTE is assumed in calculating line strengths. At an effective temperature appropriate for HD 64740 (≈25,000 K), this is a reasonably good assumption for helium and hydrogen (Auer and Mihalas 1973; Heasley and Wolff 1983) except in the line cores. However, non–LTE effects are important for Si III, N II, and O II (Kamp 1973, 1978; Dufton and Hibbert 1981; Brown, Dufton, and Lennon 1988) in that non–LTE line profiles result in lower abundances than would be obtained for LTE calculations. Estimates of the abundance errors resulting from ignoring non–LTE effects in the atmosphere of HD 64740 will be given below. Details of the profile calculations for hydrogen, helium, and the metals are given in Bohlender (1988, 1989). Our adopted gf-values are given in Table 2.

We do not calculate our own model atmospheres but instead employ Kurucz's (1979) grid of atmospheres in this work. As discussed by Bohlender (1988, 1989), a simple linear interpolation in temperature and log g has been used to generate atmospheres on a finer grid suitable for estimating the effective temperature and surface gravity of HD 64740. Naturally, the anomalous helium abundance of this star makes the use of Kurucz's solar abundance atmospheres somewhat inconsistent, since changing N_H/N_{He} results in significant changes in the continuous opacity, which in turn alters the $p(\tau)$ relationship. The most important effect of this problem is an overestimate of the surface gravity. However, $T(\tau)$ is quite insensitive to the helium abundance, so metal line strengths are altered very little. In addition, Groote and Hunger (1982) have demonstrated that the continuum fluxes are hardly affected by a moderate enrichment of the helium abundance at an effective temperature appropriate to HD 64740. In any event, we will show below that HD 64740 has the least anomalous helium abundance of any of our program helium-strong stars. Much of its surface appears to have a normal helium abundance, and we believe that our derived surface gravity is overestimated by, at most, 0.2 dex. We also feel that until observations having more complete phase coverage are obtained for HD 64740, a more comprehensive treatment of the star's atmosphere is probably not justified.

Because of the rather coarse surface grid used in modeling the line profiles, and the large $v \sin i$ of HD 64740, there is considerable ripple apparent in the final calculated model profiles. This distortion arises because of the large difference in the projected radial velocities of adjacent rings in the surface grid. Rather than increasing the number of surface area elements (at least twice as many rings, or about 4 times as many area elements would be needed to remove the ripple), we have convolved the profiles with a triangular profile with a FWHM equivalent to one-quarter of the desired $v \sin i$. Tests suggests that this smoothing removes the ripple without seriously affecting the overall shape of the line profile or the equivalent width of the line.

Finally, we have already suggested that the surface magnetic field of HD 64740 will have only a slight effect on the line profiles of the star. For this reason, and for reasons of economy, much of our modeling has employed a simplified version of Landstreet's (1988) program which ignores all effects of the magnetic field, but does allow for nonuniformly distributed surface abundances. In practice, we have used this version to find, by trial and error, a reasonable approximation of the surface abundance distribution of a given element by modeling the line profiles for each observed phase. The magnetic version is then used to determine the actual surface abundances for the final model of the star. For hydrogen and helium line profiles the effects of the surface field are ignored entirely because of the large intrinsic widths of these lines, and hence the negligible effect of the magnetic field.

b) *Modeling*

The effective temperature of HD 64740 has been estimated using the color indices of three photometric systems, corrected for interstellar reddening. It is not practical to use the ionization equilibrium of Si II/Si III/Si IV as a temperature determinant for HD 64740. Because of the star's high $v \sin i$, only the Si III multiplet 2 lines are strong enough to model with any confidence.

Buser and Kurucz (1978) have published theoretical $T_{\rm eff}$ versus *UBV* color curves for early-type stars based on theoretical colors determined from Kurucz's (1979) blanketed model atmospheres. For B stars, the $(U-V)_0$ index is most sensitive to changes in $T_{\rm eff}$. From the observed $(U-V) = -1.16$ (Egret and Jaschek 1981) we find $(U-V)_0 = -1.20$ for HD 64740 using the Q method. Inspection of Buser and Kurucz's (1978) Figure 5 then suggests that the $T_{\rm eff}$ of HD 64740 could range from 24,550 K for $\log g = 3.5$ to 26,300 K for $\log g = 4.5$. In the Geneva photometric system, the photometric index X is related to the effective temperature (Cramer 1984). Using the data of Rufener (1981) we find $T_{\rm eff} = 24{,}360$ K. The theoretical $uvby\beta$ indices of Lester, Gray, and Kurucz (1986) have also been used to estimate the temperature of HD 64740. Using their solar composition results, $\log g = 3.90$ (see below), and $[u-b] = 0.164$ (from Strömgren photometry of Hauck and Mermilliod [1980], and equations in Lester, Gray, and Kurucz [1986]), an approximate temperature of $T_{\rm eff} = 23{,}750$ K is derived. An average effective temperature of $24{,}500 \pm 1000$ K has been adopted for HD 64740.

The next step in the analysis is to determine the relative abundances of helium and hydrogen. The helium singlet λ4437 is most suited for this purpose, being sensitive to $\epsilon_{\rm He}$, free from blends, and relatively insensitive to the surface gravity. Because of their greater natural width, helium lines are also not very sensitive to Zeeman broadening or intensification. Preliminary models of the He I λ4437 profile of HD 64740 suggested that the helium abundance of this star is roughly normal over a large fraction of its surface and nowhere exceeds 3 times the solar abundance.

In determining the hydrogen and helium abundance geometry an inclination of 40° and a magnetic obliquity of 75° was first assumed for HD 64740. This represented a lower limit on i as determined by Bohlender *et al.* (1987) and proved to be an appropriate choice. By trial and error a preliminary abundance distribution for helium was determined which consisted of two helium-rich spots ($\epsilon_{\rm He} \approx 0.30$, radii $\approx 60°$) near the magnetic poles, which fitted the observed λ4437 variations adequately. The $v \sin i$ of the best fit is 140 ± 10 km s^{-1}.

Once $T_{\rm eff}$ and the helium abundance geometry are known, the surface gravity can be estimated by fitting the profiles of the gravity-sensitive lines Hδ and He I λ4471. Using the above helium abundance geometry, the best fit over all phases of both lines was found for a $\log g$ of 4.0. Remembering that the surface gravity is most likely overestimated by a small amount, a value of $\log g = 3.90 \pm 0.15$ has been adopted.

With accurate values for $T_{\rm eff}$ and $\log g$ the mass and radius of HD 64740 can be determined. In Figure 4 the evolutionary tracks of Maeder and Mermilliod (1981) and Maeder (1981) (with mass loss) have been plotted in the $\log g$ versus $\theta_{\rm eff}$ plane ($\theta_{\rm eff} \equiv 5040/T_{\rm eff}$), along with the location of HD 64740. The error box indicates our estimates of the uncertainty in $T_{\rm eff}$ and $\log g$. From the star's position we arrive at a mass of 11.5 ± 2.0 $M_\odot$, and a radius of 6.3 ± 1.8 $R_\odot$. The exact position of the theoretical evolutionary tracks is sensitive to the assumed metal abundance, Z, used in the evolutionary models (Alcock and Paczyński 1981), and we have made an attempt to allow for this in our error analysis.

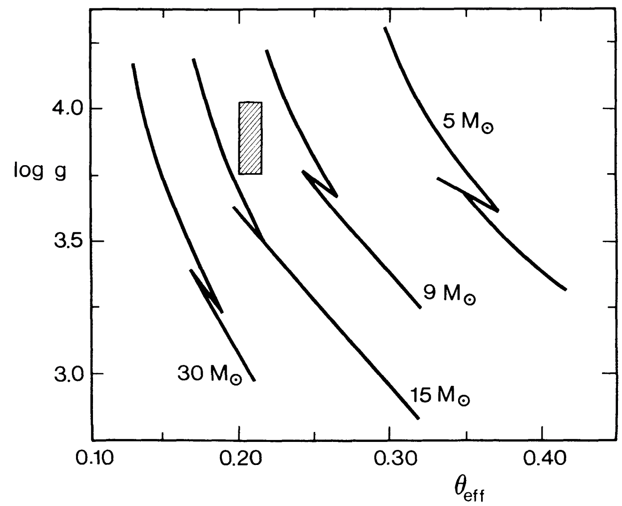

FIG. 4.—Location of HD 64740 in the log g vs. $\theta_{\rm eff}$ plane. The error box gives the estimated uncertainties in log g and $\theta_{\rm eff}$. The labeled curves are the evolutionary models of Maeder and Mermilliod (1981) and Maeder (1981).

This radius and a rotation period of 1$^{\rm d}$33026 gives a value of $i = 36° \pm 15°$ for the inclination of HD 64740's rotation axis to the line of sight. If the oblique rotator model is the correct interpretation of the spectrum and magnetic field variability, and the magnetic field geometry is predominantly dipolar, then the obliquity of the magnetic axis to the rotation axis, β, is given by (Preston 1967)

$$\tan \beta = (1-r)/[(1+r) \tan i] , \quad (2)$$

where r is the ratio of the magnetic extrema given by

$$r \equiv B_e({\rm min})/B_e({\rm max}) = \cos(\beta + i)/\cos(\beta - i) . \quad (3)$$

This argument still holds if higher multipole field components are present, as long as they are of equal or smaller magnitude than the dipole component. Given $r = -0.55$ for HD 64740 (Bohlender *et al.* 1987), equation (3) gives $\beta = 78° \pm 8°$. With this inclination and obliquity a polar field strength of 4000 G is needed to model the effective field variation with a centered dipole. A field of this strength is consistent with the lack of significant differential Zeeman intensification of the Si III lines (see below). This magnetic geometry has been used in the final model of the abundance geometry of HD 64740.

The broken lines in Figures 1 and 2 present the result of the final adopted best-fit models for HD 64740. The derived abundance geometries are given in Table 3, along with the solar abundances of Kurucz (1979). The abundance geometry for helium consists of two spots of enhanced helium near the magnetic poles: one spot with radius 60° centered at a point 20° from the positive pole at magnetic longitude 180° and with $\epsilon_{\rm He} = 0.30$, the other at the negative pole with radius 70°, and $\epsilon_{\rm He} = 0.35$. The helium abundance is normal ($\epsilon_{\rm He} = 0.10$) elsewhere. This surface distribution is illustrated in Figure 5*a* for each of the observed phases. The 20° displacement of one of the helium-rich spots from the magnetic pole is significant: locating both helium-rich spots at the magnetic poles gives a poor fit for the line profile variations. Adjusting the radii of the spots by more than 10°, or changing the helium abundance in the

TABLE 3

HD 64740 ABUNDANCE GEOMETRIES

A. HELIUM SPOT LOCATIONS[a]

$\log \epsilon_{He}$	Colatitude	Longitude	Radius
−0.456..........	0°	0°	70°
−0.523..........	160°	180°	60°

B. NITROGEN SPOT LOCATIONS[b]

$\log \epsilon_{N}$	Colatitude	Longitude	Radius
−4.00...........	140°	0°	70°
−4.70...........	Remainder of surface		

C. SILICON GEOMETRY[c]

Colatitude	0°–110°	110°–140°	140°–180°
$\log \epsilon_{Si}$...........	−4.30	−3.60	−6.00

D. MAGNESIUM GEOMETRY[d]

Colatitude	0°–110°	110°–140°	140°–180°
$\log \epsilon_{Mg}$..........	−4.90	−4.20	−4.90

[a] $\log \epsilon_{He\odot} = -1.0$.
[b] $\log \epsilon_{N\odot} = -3.99$.
[c] $\log \epsilon_{Si\odot} = -4.50$.
[d] $\log \epsilon_{mg\odot} = -4.51$.

spots by more than 0.10 dex also degrades the profile fits significantly. In addition, the helium abundance of the rest of the star's surface can not be varied by more than 0.05 dex without affecting the model fit. It should, however, be pointed out that a significant fraction of the stellar surface remains hidden from view because of the low inclination. Varying the inclination and obliquity between the above limits also has little effect on the resulting abundance geometry.

Figure 2 gives the fit for the Si III λ4567 line. Silicon appears to be overabundant ($\log \epsilon_{Si} = -3.6$) in a band whose boundaries are 40° and 70° from the positive magnetic pole. Most of the remainder of the surface of HD 64740 has an approximately normal abundance of $\log \epsilon_{Si} = -4.4$. However, a very low silicon abundance of $\log \epsilon_{Si} = -6.0$ in a 40° cap at the positive pole leads to an improved fit near $\phi = 0.458$ and is included in our final model. The derived silicon abundance distribution on the visible hemisphere of the star is shown in Figure 5*b*. Si III λ4574 lines are also reproduced very nicely with this abundance geometry and provide no evidence for measurable differential magnetic intensification. However, at such a high value of $v \sin i$, we can probably not rule out a possible surface field as large as 10 kG, so there is still considerable uncertainty about possible higher multipole components to the field of HD 64740.

The Mg II λ4481 profiles in Figure 1 have been modeled with an abundance distribution identical to that adopted for silicon. Inside the magnesium-rich band the abundance is given by $\log \epsilon_{Mg} = -4.2$, while the rest of the surface has $\log \epsilon_{Mg} = -4.9$. This geometry reproduces the profiles reasonably well, except perhaps near $\phi = 0.718$.

Model profiles for N II λ3995 and O II λλ4415 and 4417 are shown in Figure 2. Nitrogen appears to be roughly uniform in abundance, although evidence of a nitrogen-rich patch may be present at $\phi = 0.201$. An abundance of $\log \epsilon_N = -4.70$ is found over most of the surface; a 60° radius spot at the positive magnetic pole with $\log \epsilon_N = -4.0$ improves the fit somewhat and is incorporated in the final model. The oxygen lines appear to vary in strength slightly, being strongest near $\phi = 0.458$, but problems with blends in the wings of the two lines shown in Figure 2 have made it difficult to model the possible variation

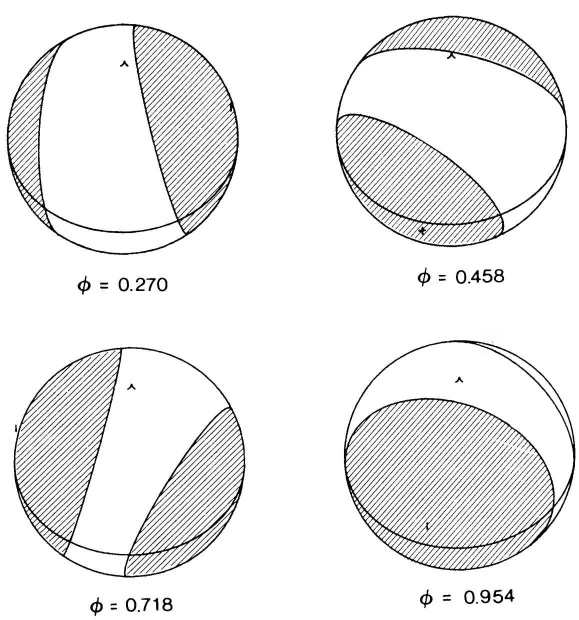

FIG. 5*a*

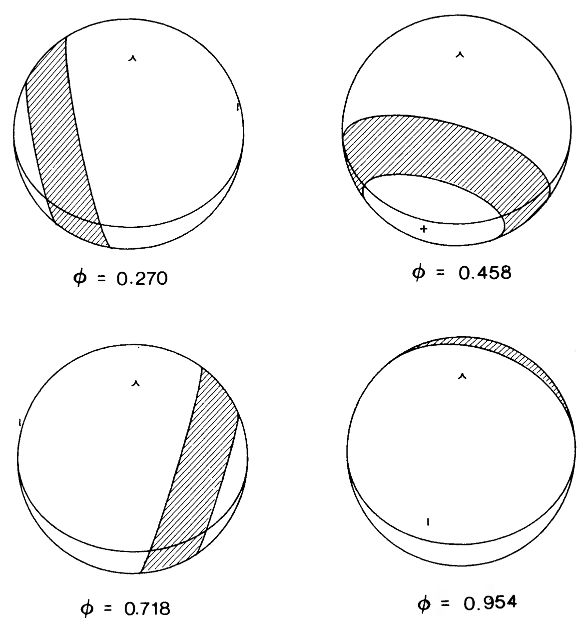

FIG. 5*b*

FIG. 5.—(*a*) Illustration of the helium abundance geometry of HD 64740. The shaded areas represent the locations of the helium-rich regions of the star's surface. The locations and signs of the magnetic poles are indicated by the symbols − and +. The rotational phases are given below each figure. Details of the model are given in the text. (*b*) As for (*a*) but for the silicon abundance geometry.

of these profiles. A uniform abundance of $\log \epsilon_0 = -3.5$ has been used for the fits in Figure 2.

For the metals, the model profile fits are sensitive to changes of 10° or more in the radii of the abundance patches. Altering the metal abundances in Table 2 by greater than approximately 0.30 dex in the spots, or by more than 0.15 dex on the remainder of the surface of the star, again causes a significant degradation of the model fit.

IV. DISCUSSION

The abundance geometries of HD 64740 suggest some possible problems with current theories concerning the helium-strong stars. For example, Shore (1987) predicts that for helium-peculiar stars with dipolar magnetic fields, helium should be enriched at progressively lower magnetic latitudes (where the field lines are horizontal) as the temperatures of the stars increase. Since HD 64740 is one of the hottest helium-strong stars, our observation of helium overabundances near the magnetic poles of this star rather than at the magnetic equator may indicate a breakdown in Shore's (1987) model. Alternatively, this could also be taken as evidence that our magnetic model of HD 64740 omits a large undetected quadrupolar or higher order magnetic component. It may also be significant that the helium peculiarity of HD 64740 is less pronounced than the somewhat cooler helium-strong stars σ Ori E and HD 37776 (Bohlender and Landstreet 1988; Bohlender 1988).

That the band of enhanced silicon (and magnesium) is closer to the positive magnetic pole of HD 64740 may also suggest the presence of a quadrupolar component to the surface field, if we adopt the models of Michaud, Mégessier, and Charland (1981). This pole, however, is never very close to the line of sight, so that it is not feasible to say anything quantitative about the importance of this possible complication to the field. The abundance geometries of the star are approximately axisymmetric with respect to the magnetic axis. The two helium-rich spots are, however, not both situated at the magnetic poles, as modeling the helium-line profiles with the smaller spot moved 20° to the positive pole results in a large deterioration in the fit to the observed profiles.

In HD 64740 the abundances of silicon, oxygen, and nitrogen vary by a factor of approximatly 5 at most over the surface of the star. According to Kamp (1978) the use of LTE in modeling Si III lines at $T_{\rm eff} = 24{,}500$ K will result in an overestimate of the silicon abundance by approximately 0.35 dex. The work of Dufton and Hibbert (1981) suggests an overestimate of 0.20 dex for nitrogen, while the recent study of Brown, Dufton, and Lennon (1988) indicates a larger overestimate in the abundance of oxygen of 0.4 dex. With these corrections allowed for, the overall average surface abundances for HD 64740 would seem to be approximately solar. The relatively low-level abundance variation may be the reason for the lack of photometric variability of the star (Pedersen and Thomsen 1977).

Using the values for the radius and $T_{\rm eff}$ derived above, an estimate can be made of the distance to HD 64740. The temperature and radius give $\log L/L_\odot = 4.1 \pm 0.3$. The bolometric corrections of Code *et al.* (1976) and the observed $E(B-V)$ of 0.02 then leads to $r = 350 \pm 80$ pc. From Maeder's (1981) evolutionary models, we find that HD 64740's properties are consistent with a main-sequence star with an age of approximately 1.1×10^7 yr.

V. CONCLUSION

We have carried out an analysis of the optical spectrum variability of the helium-strong star HD 64740 using an oblique rotator model and spectra obtained with the CFHT coudé spectrograph and Reticon detector at several phases. Models of the variable helium lines suggest that helium is overabundant in a 60° radius spot ($\epsilon_{\rm He} = 0.30$) centered 20° from the positive magnetic pole of the star, and in a second spot of 70° radius ($\epsilon_{\rm He} = 0.35$) centered on the negative pole. The helium abundance is normal on the rest of the surface. Silicon has an abundance of $\log \epsilon_{\rm Si} = -3.6$ in a band between 40° and 70° from the positive magnetic pole. The remainder of the surface has $\log \epsilon_{\rm Si} = -4.3$. Magnesium has a very similar abundance distribution. Nitrogen is approximately uniform in abundance ($\log \epsilon_{\rm N} = -4.7$), except in a 60° radius spot at the positive magnetic pole with $\log \epsilon_{\rm N} = 4.0$. Oxygen also appears to be roughly uniformly distributed with $\log \epsilon_0 = -3.5$.

As we have already noted, several improvements could be made in our model of HD 64740. The most important would be a more consistent treatment of the atmosphere of the star. Most previous detailed analyses of this class of stars have incorporated helium-rich model atmospheres (Hunger and Kaufmann 1973; Wolf 1973; Higginbotham and Lee 1974; Kaufmann, Schönberner, and Rahe 1974; Osmer and Peterson 1974; Kaufmann and Hunger 1975; Lee and O'Brien 1977), but only Groote and Kaufmann (1981) and Groote and Hunger (1982) modeled variations in helium line strengths. They modeled the helium line equivalent width variations by calculating the helium content averaged over the entire visible surface of the star at each phase. Our derived surface gravity and abundances have been found by modeling line profiles in a solar abundance model atmosphere. The inconsistency that this produces in the derived model has been discussed above.

A better approach might be to calculate a separate model atmosphere for each area element on the star's visible surface using a helium abundance appropriate for the local surface abundance. This would enable a definitive determination of the mass (and hence radius, inclination, and magnetic obliquity) of HD 64740. Such a model could also be used to examine the photometric variations of the star by calculating the model fluxes as a function of rotational phase, and comparing these to the observed light variations. The question of the cause of the metal line variations might also be answered with this improved atmospheric treatment. We are currently in the process of modifying our line synthesis program to carry out this procedure for two helium-strong stars for which we have much more complete phase coverage (σ Ori E and HD 37776). We encourage additional spectroscopy of HD 64740 before attempting similar work for this star.

Finally, HD 64740 is currently the hottest main-sequence star known to possess a globally ordered magnetic field. Such fields are known to exist between temperatures of about 8000 K (the SrEuCr Ap stars) and 25,000 K (helium-strong stars). The low-temperature cutoff of the peculiar magnetic stars is thought to be well understood. In low-mass stars diffusion occurs under the surface convection zone, which become very extensive in stars cooler than about F0, and lead to very long diffusion time scales. As a result, abundance anomalies do not have enough time to develop. The surface magnetic field is also believed to become much more complex and localized, as in the active regions on the Sun, and hence, is undetectable by conventional polarimetry.

The apparent high-temperature limit of the magnetic stars is not as well explained. In fact, average field strengths seem to increase with increasing effective temperature (Thompson, Brown, and Landstreet 1987). Stars hotter than 25,000 K have strong stellar winds, which may prevent the formation of extreme spectral peculiarities, so there may be few peculiar O-type analogs of the Ap and Bp stars. These winds, however, should not have a large effect on the magnetic field. We might then expect that a fraction of the OB main-sequence stars should have measurable magnetic fields, unless some other mechanism is acting to remove the field, change its topology, or prevent its formation in the first place. To date, only a small number of hot stars have been searched for magnetic fields (Landstreet 1982; Didelon 1983), but we have begun a large polarimetric survey of early B and O stars. The possibility of detecting magnetic fields in O stars is quite exciting and would be of considerable significance to studies of nonradiative processes in OB and Wolf-Rayet stars. Until such fields are detected, the magnetic helium-strong stars will remain an important laboratory for studies of the interaction of rotation, diffusion, and radiatively driven winds with stellar magnetic fields.

We would like to thank P. K. Barker for the use of his CFHT reduction routines. The staff at CFHT, especially Tom Gregory, Bob McLaren, Bernt Grundseth, and telescope operators Norman Purves and John Hamilton, make observing at 4200 m a pleasure. C. T. Bolton is gratefully acknowledged for providing advice and support throughout the course of this work. The figures were prepared for publication by Mrs. M. Rasche. This work has been supported by the Natural Sciences and Engineering Research Council of Canada and by the Government of Ontario.

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