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DELTA ORIONIS C AND HD 58260: PECULIAR HELIUM-STRONG STARS?

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ABSTRACT

High signal-to-noise Canada-France-Hawaii telescope Reticon spectra are presented for the sharp-lined helium-strong stars δ Ori C and HD 58260. Line profiles of the two stars have been modeled using a line synthesis program that incorporates the effects of a magnetic field and nonuniform abundances on the line profiles of a star. The star δ Ori C displays very peculiar helium line profiles that can be reproduced with two different models: a helium-rich spot ($\epsilon_{He} = 0.50$, radius 45°) on an otherwise extremely helium-poor star ($\log \epsilon_{He} = -3.6$) or a vertical variation in the helium abundance from $\epsilon_{He} = 0.40$ below to $\epsilon_{He} = 0.005$ above $\tau_{4471} = 0.35$. HD 58260 also shows evidence of a similar, but less extreme, peculiarity. Both stars have substantial surface magnetic fields. Differential magnetic intensification of the Si III multiplet 2 lines indicate dipolar field strengths of approximately 9 kG for δ Ori C and 8 kG for HD 58260. HD 58260 appears to be somewhat evolved, and has metal abundances 5–10 times lower than the roughly normal abundances of δ Ori C.

Subject headings: stars: abundances — stars: individual (δ Ori C; HD 58260) — stars: magnetic — stars: peculiar A

I. INTRODUCTION

The helium-peculiar stars of the upper main sequence are generally believed to represent an extension of the peculiar A star phenomena to higher temperatures (Osmer and Peterson 1974). The helium peculiarities range from an apparent overabundance of helium ($N_{He}/N_H \approx 1$, where N is the number density) in the helium-strong stars, with $T_{eff} = 18{,}000$–$25{,}000$ K, to apparent deficiencies ($N_{He}/N_H \approx 0.01$) in the cooler helium-weak stars (these probably include the Ap Si stars, which are believed to have low helium abundances). At temperatures near the dividing line between the two classes of objects there exists a small group of stars which vary from helium-strong to helium-weak in a systematic manner or show a high isotopic abundance of ^{3}He (Hartoog and Cowley 1979). Helium atmospheric abundances thus vary by a factor of about 10 on either side of the solar value ($N_{He}/N_H \approx 0.10$).

The helium-weak and ^{3}He stars can easily be understood to be the result of the gravitational settling of helium in the envelopes of these stars. Because of saturation effects, radiation pressure can only support a very low helium abundance in the line formation region in the absence of other influencing factors (Michaud *et al.* 1979). At suitable temperatures ^{3}He can then replace ^{4}He in the atmosphere because of its lower mass (Vauclair, Michaud, and Charland 1974; Michaud *et al.* 1979). On the other hand, the helium-strong stars for some time defied such a simple explanation. Osmer and Peterson (1974) first suggested that the helium overabundances observed in these stars might be caused by diffusion processes occurring in the presence of a stellar wind. Vauclair (1975) subsequently argued that if a general outflow of material did exist, then helium would accumulate at a depth where the downward diffusion velocity of the element was of equal magnitude the general outward flow velocity, because the diffusive mass flux decreases with depth. For suitable mass-loss rates ($10^{-12}\ M_\odot$ yr^{-1}) and temperatures (20,000 K) this accumulation would occur in the line-forming region for the helium-strong stars, but well below this zone for the cooler helium-weak stars. The ^{3}He stars could also be interpreted using this simple model, since ^{3}He would be pushed into the line-forming region at slightly lower temperatures because of its lower mass. Michaud *et al.* (1987) have recently extended this model by allowing for the possible effects of separation of helium in the envelope or wind of a star. They find that in order to explain the helium enrichment by separation in the atmosphere for a range of effective temperatures, the mass-loss rate must decrease as the effective temperature rises from 20,000 to 25,000 K. At the higher temperature the mass loss allowing separation is $3 \times 10^{-13}\ M_\odot$ yr^{-1}. A maximum mass-loss rate of $2 \times 10^{-12}\ M_\odot$ yr^{-1} still allows separation to occur in the wind, but this is likely to be less observable than separation in the atmosphere. It is also shown that, for these mass-loss rates, downward diffusion of helium in the envelope is too slow to reduce the helium abundance in the atmosphere during the main-sequence lifetime of a helium-strong star.

A major problem with this picture of the helium-strong stars is that the mass-loss rates derived by Vauclair (1975) and Michaud *et al.* (1987) appear to be considerably smaller than the rates determined from *IUE* observations of the C IV and Si IV resonance doublets in the helium-strong stars. For example, Michaud *et al.* (1987) estimate that the helium-strong star HD 184927 loses mass at a rate of more than $5 \times 10^{-12}\ M_\odot$ yr^{-1}, and Shore and Adelman (1981) give a value of $4 \times 10^{-10}\ M_\odot$ yr^{-1} for σ Ori E, HD 37776, and HD 37017. To resolve this difficulty, Michaud *et al.* (1987) suggest that the strong magnetic fields observed in many of the helium-strong and helium-weak stars (e.g., Bohlender *et al.* 1987; Borra, Landstreet, and Thompson 1983) may suppress the mass flux near the magnetic equator, where the field lines are horizontal and thus inhibit the flow of ions. The presence of a magnetic field might also alter the diffusion processes themselves, as has been demonstrated to be the case for silicon at small optical depths, owing to trapping of Si ions on nearly horizontal field lines (Michaud *et al.* 1979; Vauclair, Hardorp, and Peterson

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1979). This is similar to the model developed by Shore (1978, 1987). In his scenario the magnetic field constrains the mass loss to occur in a jet above the magnetic poles. These jets might explain the observed rotational modulation of the UV resonance lines (Shore and Adelman 1981; Barker *et al.* 1982; Shore, Brown, and Sonneborn 1987). Shore suggests that in the hottest helium-strong stars, helium is supported in the line-forming region at the magnetic equator but escapes along with the rest of the atmosphere at the poles. (In the simplest scenario the magnetic field is dipolar, but for a more complicated field geometry helium is expected to accumulate where the field lines are horizontal.) In cooler stars the helium is supported in the line-forming region progressively closer to the poles until, for the coolest helium-strong stars, helium is overabundant at the poles and underabundant near the equator. For still cooler stars the field suppresses motion at the magnetic equator below the region required for upward diffusion of helium, and the wind is too weak to levitate helium at the poles, so that the entire star appears helium-weak.

These models are very sensitive to temperature, magnetic field strength, and geometry, the mass-loss rate, stellar age, and probably rotation. The stars 3 Sco and a Cen present two excellent cases in point. The star 3 Sco has weak helium lines with very broad damping wings, and might be an example of a star in which helium is supported at an intermediate depth in the atmosphere, so that a vertical abundance gradient of helium in the line-forming region causes the peculiar line profiles (Vauclair 1975; Norris and Strittmatter 1975). However, Norris and Strittmatter (1975) have also demonstrated that a patchy surface abundance of helium can explain the peculiar profiles of 3 Sco. They reproduce He I $\lambda\lambda$4026 and 4471 profiles by assuming that two-thirds of the visible surface of the star has no helium, while the remainder of the surface has normal helium abundance. The subsequent discoveries of helium line variations (Pedersen and Thomsen 1977) and a variable magnetic field (Landstreet, Borra, and Fontaine 1979) for 3 Sco indicate that the patchy model is the correct interpretation for this star, and suggest that helium is underabundant at the magnetic poles. This is quite similar to the model proposed for the spectacular helium variable a Cen (Norris and Baschek 1972), except that here helium is overabundant at one magnetic pole (Mihalas 1973; Borra, Landstreet, and Thompson 1983), and the star ranges from helium-rich to helium-poor over its surface. But why should two stars, with roughly the same temperature, have such different surface distributions of helium? An obvious difference between the two is their magnetic field strengths: 3 Sco has a maximum longitudinal field on the order of 8 times stronger than the extrema of a Cen (Landstreet, Borra, and Fontaine 1979; Borra, Landstreet, and Thompson 1983).

Spectroscopic observations of the helium-peculiar stars can give important constraints for theoretical discussions of the diffusion of helium in hot stars. While several objects are known to have nonuniform helium abundances (e.g., discussion above and Pedersen and Thomsen 1977), the actual helium surface distribution geometries have been determined for only a very small sample of stars (e.g., Mihalas 1973; Hensler 1979). The variations and shapes of strong and weak helium line profiles should be examined at high signal-to-noise and high resolution for as large a range of temperatures as possible to determine the strengths and weaknesses of the above models, and the relative importance of the various factors that may influence the atmospheric distribution of helium in these stars. In this paper we present such observations for two helium-strong stars, δ Ori C and HD 58260. Bohlender *et al.* (1987) have recently reviewed the previous studies of these stars and have given a detailed discussion of their magnetic field observations. Both stars have large, constant longitudinal magnetic fields, approximately -3400 G for δ Ori C, and $+2300$ G for HD 58260, and have narrow spectral lines. Neither star appears to be an obvious spectrum variable, although work by Walborn (1983) and Pedersen (1979) may indicate low-level and irregular spectral variations. With temperatures of approximately 19,000 and 20,000 K, respectively, δ Ori C and HD 58260 are two of the coolest stars with anomalously strong helium lines.

II. OBSERVATIONS

Spectra of δ Ori C and HD 58260 (and several other helium-strong and Ap stars) were obtained with the coudé spectrograph of the Canada-France-Hawaii 3.6 m telescope during a six-night observing run in 1986 January. The f/7.4 camera was used with the 600 lines mm^{-1} grating in first order and the 1872 diode Reticon detector (Campbell *et al.* 1981). Used in first order, the 600 lines mm^{-1} grating gives a dispersion of 6.7 Å mm^{-1} (0.101 Å $pixel^{-1}$) and a spectrum about 180 Å long with 0.3 Å resolution. Two spectral windows were observed for each of our program stars and for several comparison standards. The region 4400–4580 Å was observed because it contains the Zeeman-sensitive second multiplet of Si III ($\lambda\lambda$4552, 4567, 4574) as well as a strong and a weak helium line (He I $\lambda\lambda$4471 and 4437). We also observed a region centered on Hδ, extending from 3980 to 4160 Å. This window also contains a Si II multiplet that (combined with the Si III lines) might be used 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 observations is given in Table 1. For each star observed, we give the Julian date of the midpoint of each exposure, the exposure duration in seconds, and the wavelength window observed.

The observations were reduced with a modified version of a reduction package developed for Canada-France-Hawaii telescope (CFHT) Reticon spectra by P. K. Barker. Each spectrum consists of the raw stellar exposure (or comparison lamp or flat field) and eight 1 s baseline exposures to measure the electronic readout noise. The first step in the reduction is the subtraction of the averaged baselines from the raw spectrum. Next, the baseline-subtracted stellar spectrum is divided by the average of four flat-field lamp spectra to correct for the small pixel-to-pixel variations in sensitivity and amplitude gain. (These 10 s long flat-field exposures, giving a signal-to-noise value comparable to that of the stellar exposures, were recorded at the end of each set of observations made at one grating setting.)

To establish the laboratory wavelength scales of the spectra,

TABLE 1

JOURNAL OF CFHT OBSERVATIONS

Star	Julian Date (2,446,000+)	Duration (s)	Wavelength Range (Å)
δ Ori C	452.781	1731	4395–4585
	453.786	1780	3985–4175
	455.002	3600	4395–4585
HD 58260	454.910	3609	3985–4175
	454.958	3600	4395–4585

a 10 s iron-argon comparison lamp spectrum was obtained at the beginning and end of each set of exposures at a given grating setting. The wavelength-pixel relation is determined by fitting a third-order polynomial to the measured pixel numbers of several well-exposed lines in the comparison lamp spectra covering the entire wavelength range. This polynomial fit is used to calculate the wavelength corresponding to each pixel in the observed spectrum. A correction is then applied to this wavelength scale to convert it to a heliocentric frame of reference. The wavelength scales derived from comparisons taken at the start and end of each set of exposures at a particular grating setting differ typically by only 0.02 Å, and, at most, 0.1 Å in the blue wavelength region on a few occasions. This indicates that any flexure of the spectrograph is minimal during each 3 or 4 hr observing period.

The final step in the data reduction is the continuum fitting to remove residual low-amplitude waves introduced into the stellar continuum probably by small wavelength-dependent reflectivity variations in the dielectric coatings of the blue coudé mirror train. Our procedure consists of specifying a number of 1 Å sections of the stellar spectrum that are free of lines and distributed at approximately 10 Å intervals. The intensities in these wavelength regions are averaged, and piecewise-smooth cubic splines are fitted between the averaged continuum points. The stellar spectrum is then divided by this continuum so that the spectrum is normalized to a continuum level of 1.0. The final reduced spectra have not been smoothed in any way.

Time constraints permitted repeated observation of only one of the chosen standard stars in the 4000 Å spectral range, and none in the 4500 Å region. However, δ Ori C was observed twice at the 4500 Å setting. Since this star is presumably a slow rotator with a period much greater than 6 days, or is viewed pole-on, large spectral variations are not expected. Comparison of these spectra suggests that the coudé spectrograph instrumentation and the data reduction techniques are reasonably well behaved and give reproducible spectra.

In Figure 1 the Hδ and He I $\lambda\lambda$4009, 4026, 4143, and 4471 profiles of HD 58260 and δ Ori C are illustrated along with the same lines for the normal B2 IV–V star 22 Ori. The effective temperatures of these stars, as determined from their broadband colors, do not differ by more than 1000 K. The weaker He I $\lambda\lambda$4121, 4168, and 4437 line profiles are shown in Figure 2. From these figures it is immediately apparent that the helium line profiles of δ Ori C are very peculiar, while those of HD 58260 appear anomalously strong. The substantial Stark broadened wings of Hδ for δ Ori C are indicators of a large surface gravity for this star compared with HD 58260.

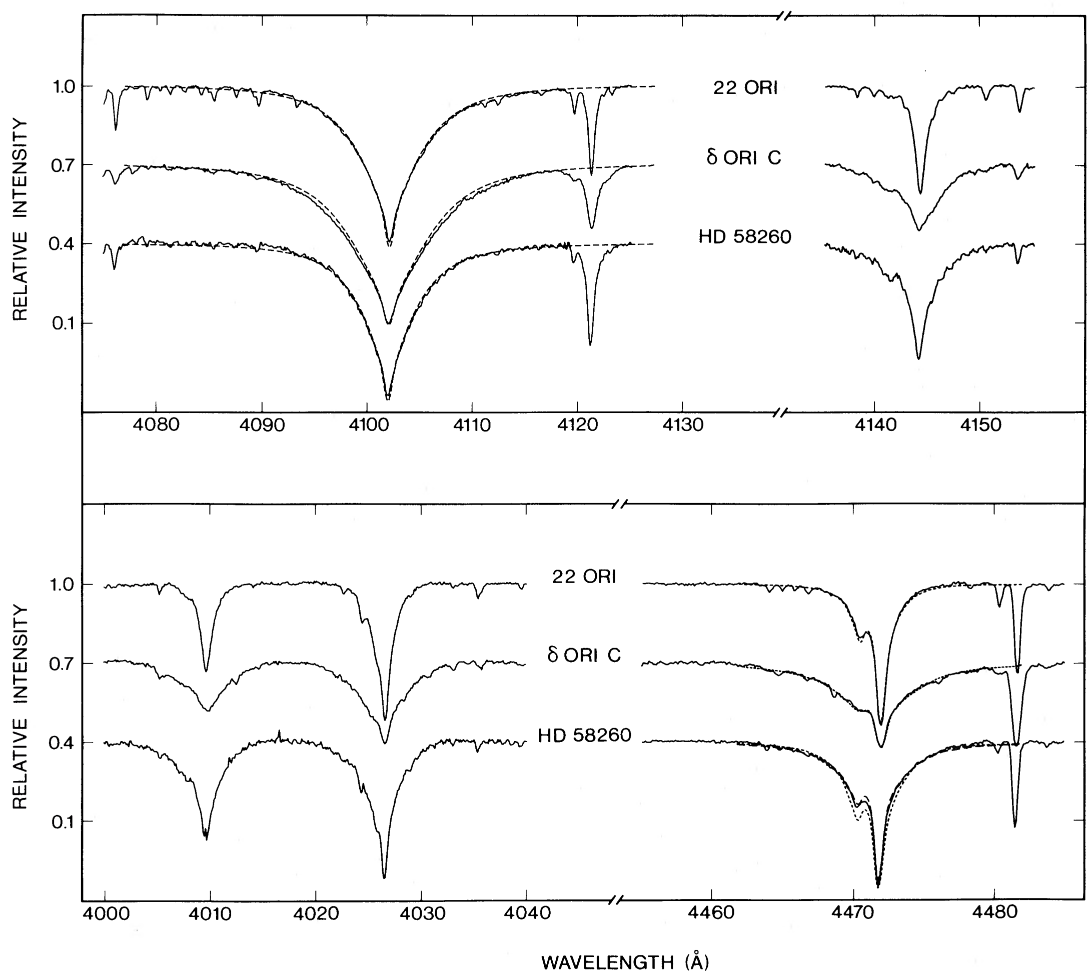

FIG. 1.—Hδ, He I $\lambda\lambda$4009, 4026, 4121, 4143, and 4471, and Mg II line profiles of 22 Ori, δ Ori C, and HD 58260. Solid profiles are CFHT Reticon data. For 22 Ori and δ Ori C the dotted profiles are models discussed in the text. For HD 58260 the dotted profile is the model with a uniform helium abundance, while the dashed profile is the model with a vertical variation in helium abundance. Details of both models are given in the text.

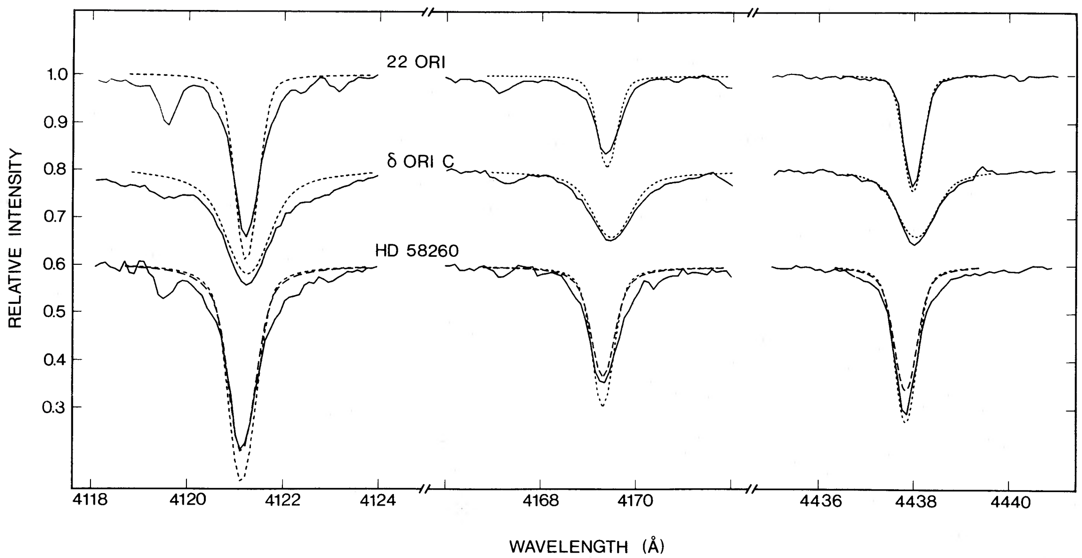

FIG. 2.—As in Fig. 1, but for He I λ4121, 4168, and 4437 line profiles

III. THE LINE SYNTHESIS PROGRAM

We have modeled the spectra of δ Ori C and HD 58260 with a modified version of Landstreet's (1988) spectral line synthesis program, which calculates the integrated intensity and polarization profiles of spectral lines for a star with an assumed model atmosphere, magnetic geometry, and surface abundance distribution. Since Landstreet (1988) has discussed this code in some detail, only a short summary, along with changes made to the program for this work, will be presented here.

Briefly, the line synthesis program divides the visible hemisphere of the star into 60 approximately equal areas. For each area, the local value of the surface magnetic field and the local abundance are found, using the specified magnetic field and abundance geometries. The program then solves the coupled equations of transfer for an atmosphere permeated by a magnetic field, to calculate the local intensity and polarization profiles of all specified spectral lines in a region defined by the user, using the efficient numerical technique of Martin and Wickramasinghe (1979). Once the above calculations have been performed for each sampled disk point, the program sums all of the local components of the Stokes parameters, each weighted according to the fractional area of the total disk which it samples, after giving each component the appropriate Doppler shift determined from a specified value of $v \sin i$. The final profile is broadened with a triangular instrumental profile with a FWHM of 0.3 Å.

In this version of the program, the wavelength window to be modeled is specified by three parameters: the reference wavelength for the spectral region to be modeled, the number of wavelength points to be modeled, and the resolution of the model profile. An adjustable resolution has been added to permit more economical modeling of the Stark-broadened Hδ and He I λ4471 profiles. The wavelength region modeled ranges from 2 Å for isolated metal lines to 50 Å for Hδ. For metals and He I λλ4121, 4168, 4437, the line profiles are modeled at 0.01 Å intervals, while a resolution of 0.1 Å is employed for Hδ and He I λ4471. Using the finer wavelength spacing for the latter lines would have been prohibitively expensive in CPU time. The above wavelength spacings provide sufficient resolution of each element's intrinsic profile at temperatures appropriate for the stars examined in this work (18,000–20,000 K), except perhaps in the cores of Hδ and He I λ4471, where non–LTE effects are likely to be important anyway.

Blending is not as serious a problem for these early B stars as it is for the cooler Ap stars, so in cases where a single, symmetric line is being modeled, the line synthesis program was modified so that only one-half of the *local* profile at each surface element of the star is synthesized, which reduces the computation time by a factor of almost 2. The rest of the local profile is obtained by a suitable reflection around the center of the line: i.e., the Stokes parameters, I, Q, and U, are symmetric around the line center, while V is antisymmetric.

For the line profile calculations, a model atmosphere is needed. We have used published ones. The model atmosphere gives the run of temperature, mass density, and electron number density as a function of standard optical depth, τ_{5000}, for a specified number of depths, usually 30 or 40. The continuum opacity at a reference wavelength in the synthesized window and the Planck function are then calculated at each level in the atmosphere. Landstreet's original code included only electron scattering, bound-free and free-free absorption from neutral hydrogen, and negative hydrogen ions as continuum opacity sources. Because of the higher temperatures of the helium-strong stars, the continuum opacities of neutral and singly and doubly ionized helium have now been added.

Kurucz's (1979) solar abundance model atmospheres have been employed in this work. A simple linear interpolation, first in temperature, and then in log g, has been used to generate atmospheres on a finer grid suitable for estimating the effective temperatures and surface gravities of the program stars. Of course, the anomalous helium abundance of the helium-strong stars makes the use of Kurucz's solar abundance atmospheres somewhat inaccurate. Some use has therefore been made of the helium-rich (but unblanketed) atmospheres of Klinglesmith (1971) in determining the effects of these inconsistencies in helium abundances in the model atmospheres and in the assumed surface abundances of the helium-strong stars considered in this investigation.

The essential difficulty is that Kurucz's (1979) model atmospheres have $\epsilon_H = 0.90$ ($\epsilon_j \equiv N_j/N_{tot}$), where N_j is the number density of the element j), but helium line profiles in the helium-strong stars must be modeled using different, and often nonuniform, abundances. Helium-rich atmospheres have a substantially reduced continuous opacity relative to similar models with solar composition, which results in line profiles being formed deeper in the atmosphere and therefore at higher pressures than in normal atmospheres. However, comparison of Kurucz and Klinglesmith atmospheres at the same $T_{\rm eff}$ and log g shows that $T(\tau)$ is virtually the same in both. Norris (1971) has discussed the problem of determining gravity in the context of the helium-weak stars. In that case, the use of normal atmospheres results in an underestimate of the surface gravity. Here, our tests show that the surface gravity is overestimated by roughly 0.5 dex, if the actual helium abundance is approximately $\epsilon_{\rm He} = 0.50$ and uniformly distributed. Hunger (1975) has also considered these modeling difficulties. An allowance will be made for this error in the surface gravities determined for each star. A future investigation of these stars may incorporate more appropriate helium-rich model atmospheres.

LTE has been assumed in the calculation of line strengths. In modeling the metal line profiles, the radiation damping has been taken into account, using the classical damping constant. It is assumed that the magnetic field suppresses turbulent motions, and so the microturbulence has been set equal to zero. Collisions with neutral hydrogen are treated using the Unsöld approximation for van der Waals broadening (Aller 1963, Art. 7-5) or the results of Deridder and van Rensbergen (1976), depending on which theory gives the larger damping constant. The quadratic Stark effect due to collisions with protons and electrons is calculated using the approximations of Cowley (1971). Oscillator strengths and their sources are given in Table 2.

As already noted, Landstreet's original code has been modified to permit modeling of hydrogen and helium line profiles. Stark broadening of Hδ is calculated using the unified theory of Vidal, Cooper, and Smith (1973). The quadratic Stark effect for the helium lines $\lambda\lambda$4121, 4168, and 4437 has been modeled using the simple theory of Griem *et al.* (1962) or Dimitrijevic and Sahal-Bréchot (1984). These lines can be approximated by shifted dispersion profiles for electron densities below 10^{17} cm^{-3}. The diffuse line λ4471 is treated using the broadening theory of Barnard, Cooper, and Smith (1974). Fine-structure splitting of the 2 ^3P level is ignored. Hydrogen and helium oscillator strengths were taken from Wiese, Smith, and Glennon (1966).

The polarized line-to-continuum opacity ratios η_I, η_Q, and η_V of the I, Q, and V Stokes components, needed for the numerical integration of the Stokes vector through the atmosphere, are calculated as a function of wavelength and depth in the atmosphere. Except for hydrogen, the opacity ratios for each line in the spectral window are calculated using the numerical prescription for the Voigt profile calculation given by Baschek and Scholz (1982), and the damping constants are determined for each line. The interpolated hydrogen Stark broadening profiles have already been convolved with appropriate Voigt functions (Vidal, Cooper, and Smith 1973). The resulting opacity ratios are summed over all lines and Zeeman components to yield the total ratios η_I, η_Q, and η_V as functions of wavelength.

For reasons of economy, in the case of the hydrogen and helium line profiles the effects of the magnetic field are ignored entirely because of the large intrinsic widths of these lines, and hence the negligible effect of the magnetic field. Because of the constant longitudinal components of their magnetic fields, not enough information is available to define a unique magnetic geometry with even two multipole components. For this reason, the field geometries of δ Ori C and HD 58260 are assumed to be simple centered dipoles. Such a dipolar geometry is defined by the obliquity of the magnetic axis to the rotational axis, β, and the polar field strength. One must also specify the inclination, i, of the line of sight to the rotation axis.

IV. RESULTS

a) HD 58260

i) *Effective Temperature*

The temperatures of HD 58260 and δ Ori C have been estimated from the stars' intrinsic *UBV*, *uvby*β, and Geneva photometric indices. The $(U-V)_0$ values were derived from the observed colors (Egret and Jaschek 1981; Hoffleit and Jaschek 1982) with the Q method (e.g., Mihalas and Binney 1981). Strömgren photometry is from Hauck and Mermilliod (1980), and reddening-free $[u-b]$ values were found from the equations given by Lester, Gray, and Kurucz (1986). The Geneva color index, X (Cramer and Maeder 1979; Cramer 1984), for δ Ori C was derived from the photometric data of Rufener (1981). Geneva photometry is not available for HD 58260.

In principle, the Si II/Si III ionization equilibrium could be used as a temperature determinant, but earlier work has indicated that Si II/Si III line ratios do not yield the same $T_{\rm eff}$ as the Si III/Si IV ratio (Peters and Aller 1970; Hardorp and Scholz 1970; Peters 1976). Peters and Aller (1970) suggest that Si II lines form high in the atmospheres of hot stars, where the assumption of LTE, used by the above investigators, could be incorrect. However, the non–LTE analysis of silicon by Kamp (1973, 1978) still does not completely solve the problem. For this reason, Si II/Si III ionization equilibrium will not be employed in this work.

In the *UBV* system, the $(U-V)_0$ index is most sensitive to changes in $T_{\rm eff}$. Interpolating from Buser and Kurucz's (1978) theoretical $T_{\rm eff}$ versus $(U-V)_0$ relation, HD 58260's $(U-V)_0$ of -1.03 leads to a temperature of 20,770 K for log $g = 4.0$, or 20,070 K for log $g = 3.5$. As will soon be seen, the surface gravity of HD 58260 is close to log $g = 3.30$. From the theoretical *uvby*β indices of Lester, Gray, and Kurucz (1986), a temperature of about 19,300 K is estimated from the observed $[u-b]$ index of 0.287 for HD 58260. A $T_{\rm eff}$ of 20,000 K will be assumed for HD 58260. Obviously, this treatment ignores the effects of the peculiar helium abundance on the visible flux of a star, but previous work (e.g., Groote and Hunger 1982) suggests that this leads to only a small error. The uncertainty in $T_{\rm eff}$ is conservatively estimated to be about 1000 K.

ii) *Surface Gravity and Helium Abundance*

The helium abundance and surface gravity of HD 58260 are found by adjusting these two parameters and modeling the profiles of Hδ, He I λ4471, and He I λ4437 until a suitable fit is achieved for each line. Models of He I $\lambda\lambda$4121 and 4168 are then calculated to check for consistency. A uniform abundance of helium is assumed. The effects of the star's surface magnetic field are ignored for this fitting. A v sin i of 16 ± 2 km s^{-1} is determined from the fit of He I λ4437 alone.

The resulting best-fit profiles of Hδ and He I λ4471 for HD 58260 are shown in Figure 1. They were obtained with a surface gravity of log $g = 3.30$ and $\epsilon_{\rm He} = N_{\rm He}/N_{\rm tot} = 0.30$. Allowing for the inherent problem in using solar abundance atmospheres in the above analysis, the final adopted log g is

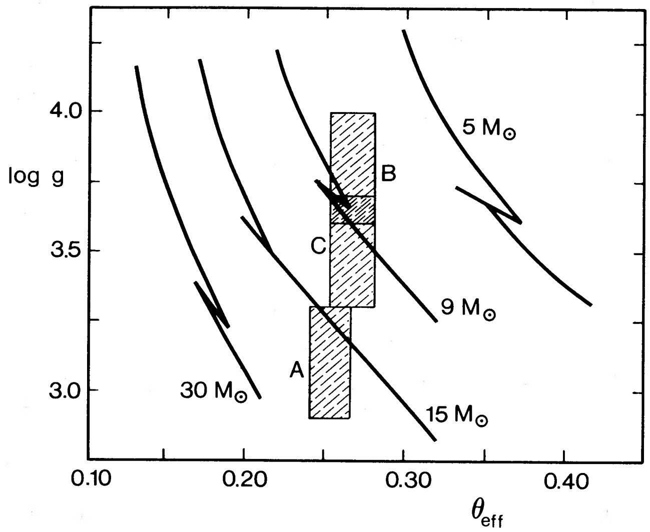

FIG. 3.—Locations of HD 58260 and δ Ori C in the (log g, θ_{eff})-plane. A: error box for HD 58260. B: error box for δ Ori C and spotted helium abundance model. C: error box for δ Ori C and stratified helium abundance model.

3.10 ± 0.20. A discussion of the success of the modeling presented here will be deferred until the next section. For comparison, however, the resulting model line profiles for 22 Ori are also shown in Figure 1, where we have assumed a normal $\epsilon_{He} = 0.10$, $T_{eff} = 19{,}300$ K (again, an average of the T_{eff} values determined from the various color indices of the star), and a log $g = 3.30$.

The location of HD 58260, the evolutionary track of Maeder and Mermilliod (1981) for a 5 $M_\odot$ star, and Maeder's (1981) evolutionary tracks for stars with masses ranging from 9 to 30 $M_\odot$ and with mass loss have been plotted in the (log g, θ_{eff})-plane ($\theta_{eff} = 5040/T_{eff}$) in Figure 3. The error box indicated for the gravity and temperature of HD 58260 has been estimated by including possible errors in the adopted model atmosphere, as well as the sensitivity of the theoretical evolutionary tracks to the assumed metal abundance (Alcock and Paczyński 1981). Interpolating from the theoretical evolutionary tracks, a mass of 18 ± 6 $M_\odot$ is found for HD 58260. This corresponds to a radius of 20 ± 8 $R_\odot$. The above model of HD 58260 suggests that the star is considerably evolved. An estimate of its age can be made from Maeder's (1981) calculations, and is found to be on the order of 1.0×10^7 yr.

iii) *Magnetic Field and Metal Abundances*

An examination of the magnetic sensitivities of unblended multiplets of spectral lines of suitable strength in the spectra of early B stars indicates that the lines of the second multiplet of Si III are the most sensitive indicators of surface magnetic field strengths in the temperature range of the helium-strong stars. The effective Landé g-values (g_{eff}) for these lines are 1.25 (λ4552), 1.75 (λ4567), and 2.0 (λ4574), and they display a wide range in the complexity of their Zeeman patterns. As is well known (Babcock 1949; Preston 1970), a strong surface field has two effects on a line profile: it broadens the line, because of the splitting of the line into its Zeeman components, and, if the line is on the saturated portion of the curve of growth, it can cause a strengthening of the line, if the splitting is large enough to desaturate the line profile. For the relatively sharp-lined stars δ Ori C and HD 58260, the Zeeman broadening of the lines of the program stars may be observable, and the differential magnetic intensification of the Si III lines should be measurable, since both stars have large surface magnetic fields.

In fact, for silicon, the λ4574 line ($g_{eff} = 2.0$) will split first, and it is easy to show that this will occur for a field strength of about 4 kG. The separations of the σ and π components of the lines λλ4567 and 4552 are somewhat smaller, so these lines will begin to strengthen at slightly higher magnetic field values.

The line λ4574 will cease to strengthen when the simple triplet pattern of the line is completely resolved. The other two lines will continue to intensify, however, because of their more complex Zeeman patterns. They will continue to strengthen until the individual components of the separate σ and π groups desaturate. The separation between the individual Zeeman subcomponents approaches the Doppler broadening at a field strength of about 15 kG.

The argument above suggests that differential Zeeman intensification of the silicon lines should be seen in the helium-strong stars, if their surface fields are between about 4 and 15 kG, and this is certainly the case for HD 58260 and δ Ori C. Unfortunately, an application of this effect to the helium-strong stars must be confined to Si III λλ4567 and 4574, since λ4552 is blended with lines of nitrogen and sulfur at these temperatures.

Fitting the profiles of the Zeeman-sensitive lines Si III λλ4567 and 4574 can then yield constraints for the surface magnetic field of HD 58260 and δ Ori C. Unfortunately, because the effective magnetic fields of these stars do not vary, we have only two constraints on the field: the effective field, B_e, and the surface field, B_s, at some unknown viewing angle α to an unknown magnetic field configuration. As a result, only two parameters can be determined with any confidence: the polar field strength of the dipole component of the field, B_d, and α. Since no variation in the field is seen, it is likely that $i \approx 0$ or $\beta \approx 0$. Since $v \sin i$ is small for both stars, we cannot rule out either of these possibilities. For the remainder of this work it will be assumed that $i = \alpha$ ($\beta = 0$).

For HD 58260, the Si III λλ4567 and 4574 line profiles have been modeled for various values of i and B_d, consistent with the observed constant longitudinal magnetic field of +2300 G. The silicon abundance is adjusted to give the best fit for λ4574, and the same model is then used to synthesize the λ4567 profile. It is found that suitable fits can be found simultaneously for both profiles for $10° < i < 50°$. For $i < 10°$ the λ4567 profile is slightly weak, while for $i > 50°$ the same line is too strong, and both line profiles are too broad, even for $v \sin i = 0$, because a large value of i combined with a given observed B_e requires a large B_d and hence a large B_s. An inclination of $i = 40°$ will be assumed for the remainder of the models. This gives a polar field strength of $B_d = 8.1$ kG for HD 58260. From the range of allowed models, B_d is uncertain by as much as 2 kG. Since He I λ4437 may be broadened to a small extent by such a field, this line was remodeled utilizing the derived magnetic geometry. The helium abundance is not affected, but a slightly lower $v \sin i$ is found. Profiles of other helium and metallic lines are modeled in a similar way. Most of the broadening of the metal line profiles appears to be a result of the Zeeman effect. An upper limit to $v \sin i$ is about 12 km s^{-1}, but the majority of the lines suggest a $v \sin i$ near zero. Note, however, that the minimum velocity resolution of the spectrograph is on the order of 10 km s^{-1}, so that little can be said about rotation velocities below this limit. We adopt $v \sin i = 6 \pm 6$ km s^{-1}. If $i \approx 0°$ is adopted, then, from the above considerations, $\beta = 40°$.

TABLE 2

HD 58260 AND δ ORI C ABUNDANCE RESULTS

Ion	Multiplet	λ (Å)	log gf	Reference[a]	log ϵ HD 58260	log ϵ δ Ori C	log ϵ Solar
N II	12	3995	0.28	WSG	−5.0	−4.5	−3.99
O II	5	4415	0.305	WSG	−4.2	−3.4	−3.22
	5	4417	0.044	WSG	−4.2	...	...
Mg II	4	4481	0.97	WM	−4.8	−4.0	−4.51
Al III	3	4529	0.67	WSG	−6.2	−5.6	−5.65
Si II	3	4128	0.31	WSG	−5.4	−5.0	−4.50
		4130	0.46	WSG	−5.5	−5.3	...
Si III	2	4567	−0.07	WM	−5.0	−4.4	...
		4574	−0.41	WM	−5.0	−4.4	...
Fe II	38	4549	−2.14	A	...	−3.0	−4.50
Fe III	4	4419	−2.33	A	−5.3	−4.3	...

[a] WSG = Wiese, Smith, and Glennon 1966; WM = Wiese and Martin 1980; A = Adelman 1988.

The model He I $\lambda\lambda$4121, 4168, and 4437 line profiles are compared with the observations in Figure 2. In each case the fit is quite good, and at least as good as the fit for the normal star 22 Ori. The derived abundances for silicon and some of the other elements seen in the spectra of HD 58260 are summarized in Table 2. Included in the table are the wavelengths of the lines considered, adopted oscillator strengths and their sources, and the derived logarithmic abundances. In all cases, the element in question is assumed to be uniformly distributed over the surface. Solar abundances for each element are also indicated and are adopted from Kurucz (1979). Typically, the adopted abundances are 0.2 dex lower than would be needed if the effects of the strong surface magnetic field were neglected. Effects of non–LTE should be small for both HD 58260 and δ Ori C. It should be pointed out that these abundances may be systematically high because of our use of Kurucz's solar abundance atmospheres. However, since $T(\tau)$ is relatively insensitive to the helium content of the atmosphere, the effect of this error should be small.

b) δ *Ori C = HD 36485 = HR 1851*

i) *Effective Temperature*

For δ Ori C, the Geneva ($X = 0.4723$) and *UBV* [$(U-V)_0 = -0.94$] photometries, and the relations of Cramer (1984) and Buser and Kurucz (1978), yield temperature estimates of 19,000 and 19,050 K, respectively. The $[u-b]$ index of 0.392 gives a temperature of about 18,000 K for a log g near 4.0, appropriate for δ Ori C. A $T_{\rm eff}$ of 19,000 ± 1000 K will be employed throughout the remainder of this work.

ii) *Surface Gravity and Helium Abundance*

The modeling approach for δ Ori C proceeds in much the same manner as for HD 58260, except for the complication added by the peculiar nature of the star's helium profiles: the He I λ4471 line profile cannot be reproduced with a uniform atmospheric abundance of the element. Attempts at modeling this line with a high surface gravity and uniform helium abundance result in reasonable fits to the wings of λ4471, but the core of the line is then much too strong. The Hδ profile also does not support a high surface gravity interpretation.

After extensive trial and error, it has been found that the helium and Hδ profiles of δ Ori C can be reproduced reasonably well if either one of two assumptions is adopted: (1) the surface helium abundance distribution is not uniform, but instead most of the helium is concentrated in only a small portion of the star's surface, or (2) helium is distributed uniformly, but there is a vertical stratification of helium in the line-forming region of the atmosphere of δ Ori C. Neither assumption is unprecedented (see § I). These two models for the helium abundance of δ Ori C will be discussed in turn.

Norris and Strittmatter (1975) have discussed how a decidedly nonuniform helium abundance can produce peculiar line profiles. Because the line λ4471 is strongly saturated in the core, increasing the helium abundance has little effect on the core of the line but does increase the strengths of the line wings, which increase in strength approximately linearly with helium abundance. Now, consider a star in which all of the helium is concentrated in a small portion of the visible disk of a star, say with $\epsilon_{\rm He} = 0.20$. If the region with no helium is f times larger than the region with helium, the resulting profile will then be similar to that of the region with the helium overabundance, but with the absorption reduced by a scale factor of $1 + f$. Hence, the core will be shallower and the wings more pronounced than for a normal star.

A suitable *spotted* model for the helium abundance geometry of δ Ori C was found by first fitting the core of the line λ4471 with a uniform, but low, abundance of helium. Then the wings of the line were fitted by incorporating a spot located at the visible magnetic pole (this also corresponded to the subsolar point, i.e., the inclination of the rotation axis and the obliquity of the magnetic axis were set equal to zero), while using the abundance determined from the fit of the core for the remainder of the star's surface. The size of the spot, the abundances inside and outside of the spot, and the surface gravity were then adjusted until the best fit to the observed λ4471 profile was obtained. The resulting model was then used to produce synthetic profiles of He I λ4437 and Hδ. This procedure was repeated until a satisfactory fit was obtained for all three profiles. Models of He I $\lambda\lambda$4121 and 4168 were then calculated as an additional check.

The adopted spot model consists of a helium-rich spot ($\epsilon_{\rm He} = 0.50$) with radius 45° on an otherwise *extremely* helium-poor surface (log $\epsilon_{\rm He} = -3.6$). A surface gravity of log $g = 4.00$ and a $v \sin i$ of 32 km s^{-1} (found from the He I λ4437 profile with no magnetic field) gives the best results for the model profiles. Simultaneous fitting of Hδ and a strong and weak helium profile provide quite tight constraints on the proposed model. For example, the relative strengths of the core and wings of He I λ4471 are very sensitive to the helium abundance outside the helium-rich spot. Varying the "background" helium abundance by 0.3 dex seriously degrades the model fit for this profile. Changing the size of the helium-rich spot by more than 10° (approximately the surface resolution of the model grid) or altering the helium abundance of the spot results in poor fits to He I λ4437 and the wings of He I λ4471. Hδ gives an additional constraint for the surface gravity of the model.

The *stratified* model of δ Ori C was determined in a similar manner. First, the He I λ4471 line core is fitted with a uniform, unstratified helium abundance. Then, a vertical abundance gradient of helium is incorporated into the model by using a simple step function at a specified optical depth at 4471 Å, τ_s. Since the line wings are formed deep in the atmosphere, where the pressure broadening is large, the helium abundance is increased at optical depths greater than τ_s in an attempt to fit the line wings. A step function for the helium stratification is probably justified when the rapid change in the radiative acceleration of helium with depth is considered. More complicated treatments of the stratification were not considered, because of the lack of a sufficiently well-developed theory of helium stratification in stellar atmospheres, as well as because of the additional free parameters that more sophisticated treatments would introduce. Here, the best-fit model is found by varying τ_s, the helium abundance above and below τ_s, and the surface gravity, until a satisfactory fit is found for Hδ and He I λλ4471 and 4437 simultaneously. The He I λλ4121 and 4168 profiles are again used as an additional test of the model.

The adopted stratified model for the helium abundance of δ Ori C has a surface gravity of log $g = 3.70$ and $\tau_s = 0.35$. Above τ_s, $\epsilon_{He} = 0.005$, and below τ_s, $\epsilon_{He} = 0.40$, a factor of 80 enhancement in helium abundance. The model profiles of Hδ and He I λ4471 calculated with these parameters are shown in Figure 1. The line profiles obtained for the spotted model of the star are essentially identical to those for the stratified model of the star, and are therefore not shown. In each case the model line profiles fit the observations very well.

As was done for HD 58260, the possible positions of δ Ori C in the (log g, θ_{eff})-diagram are indicated in Figure 3, after adjusting the derived gravities by -0.2 dex, because of the inconsistency of using Kurucz's atmospheres. The above models give two possible values of the surface gravity, and hence the mass and radius of the star. The error boxes shown include an additional uncertainty because of metallicity effects. The resulting interpolated masses and radii for δ Ori C are approximately $8 \pm 2\ M_\odot$ and $6 \pm 2\ R_\odot$ for the spotted model, and $11 \pm 3\ M_\odot$ and $10 \pm 4\ R_\odot$ for the stratified model of the star.

iii) *Magnetic Field and Metal Abundances*

As discussed by Bohlender *et al.* (1987), the constant magnetic field of δ Ori C is unlikely to be due to poor spacing of the observations. A $v \sin i$ of 32 km s^{-1} and the above radii give upper limits of 9.5 and 15.8 days, respectively, for the rotation period of the star, and magnetic field observations have been obtained over several years. So either the inclination or the obliquity of the magnetic axis of δ Ori C must be small. A lower limit on i may be obtained by noting that the distribution of rotation velocities of the helium-strong stars is apparently similar to the distribution for normal stars (Walborn 1983; Bohlender *et al.* 1987). δ Ori C should then have a maximum possible v_{eq} of about 400 km s^{-1}, the largest value observed in normal early B stars (Wolff, Edwards, and Preston 1982). Obviously, the inclination of δ Ori C is only slightly constrained and must be greater than about 4°. Once more, β is poorly constrained by the longitudinal magnetic field observations. Proceeding as for HD 58260, modeling of Si III λλ4567 and 4574 then leads to an upper limit on the inclination i (if β is assumed equal to zero) of approximately 40°. The final adopted model has $i = 10°$, and a polar field strength of -9 kG, again with an uncertainty of about 2 kG. The subsequent use of this value of the inclination and field has no effect on the helium abundance models, or on the $v \sin i$ of the star. Model profiles for He I λλ4121, 4168, and 4437 are compared with the observations in Figure 2. Again, the fit is excellent.

Table 2 contains the derived abundances for elements, other than helium, modeled in the spectra of δ Ori C using the above stratified magnetic model (i.e. log $g = 3.7$) and the assumption that the elements have uniform surface abundances. An average $v \sin i$ of 32 km s^{-1} is found from the entire set of profiles. The tabulated abundances are slightly higher if the log $g = 4.0$ spotted magnetic model is adopted. These abundances should also be treated as approximations because of the inconsistencies in our choice of model atmospheres.

V. DISCUSSION AND CONCLUSIONS

Both models of the helium abundance geometry for δ Ori C presented above give very good fits to the Hδ and helium line profiles. The results of the simple uniform abundance model for the He I λ4471 line profile of HD 58260 are reasonably good, but not as good as the agreement between model and observations for the standard star 22 Ori. Also, for HD 58260, the wings of He I λ4437 are too weak in the model profile, while the forbidden component of λ4471 is too strong. The behavior of the λ4471 profile is similar to that of δ Ori C, which suggests that HD 58260 may also have a vertical or horizontal variation in helium abundance.

To investigate this possibility, spot and stratified models of the helium abundance have been attempted for HD 58260 following the procedure outlined above for δ Ori C. We find a considerable improvement in the He I λ4471 profile fit using a 60° radius helium-rich spot ($\epsilon_{He} = 0.50$) at the visible magnetic pole of HD 58260 (log $g = 3.30$ and $T_{eff} = 20,000$ K). The remainder of the surface has $\epsilon_{He} = 0.03$. Alternatively, a stratified model, with $\tau_s = 0.30$, $\epsilon_{He} = 0.10$ above τ_s and $\epsilon_{He} = 0.50$ below τ_s, log $g = 3.30$, and $T_{eff} = 20,000$ K, also works very well. The resulting model profiles for the stratified model are given in Figures 1 and 2 (the profiles for the spot model are similar). For both models, the He I λλ4121 and 4168 model profiles are in better agreement with the observations, while the fit of the λ4437 profile is worse than for the uniform abundance model. While there is still considerable uncertainty, we conclude that HD 58260 does indeed show evidence of vertical or horizontal variations in atmospheric helium abundance.

With the data presently in hand, it is impossible to discriminate between the two models proposed for δ Ori C (and HD 58260). We are currently attempting to obtain high signal-to-noise spectra of He I λλ5876 and 6678 to help solve this problem. Since the continuum opacity at 6678 Å is considerably higher than it is at 4471 Å (where we establish the location of the step function in helium abundance), the above stratified model for δ Ori C should produce a weaker He I 6678 profile than the spot model of the star. This is illustrated in Figure 4, where profiles of He I λ6678 are shown for both cases. Observations of similar quality to those presented here should easily distinguish between these two possibilities.

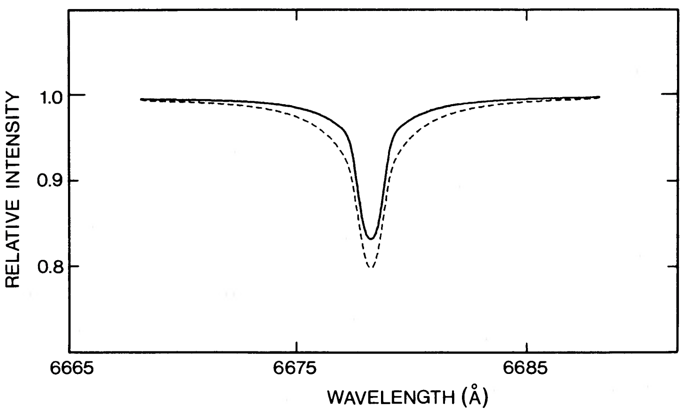

FIG. 4.—Model He I λ6678 line profiles for δ Ori C. *Solid line*: stratified helium abundance model. *Dashed line*: spotted helium abundance model.

Alternatively, Zeeman observations in a helium line (for example, the line λ5876 used by Bohlender *et al.* 1987) could also possibly help in determining which of the models applies to the star. If the longitudinal magnetic field, as derived from a helium line, is significantly different from the roughly constant −3400 G field found from Hβ observations, then the spot model might be preferred for the star, since in this case less than the entire visible disk of the star contributes to the longitudinal field. Unfortunately, models of the Stokes V profiles of the helium line λ4471 seem to indicate that the circular polarization in the wings of this line are similar for both the spot model of the star and the stratified model, so that such an effort might not be rewarded with a positive answer.

Two admittedly weak arguments favoring the spot model of δ Ori C can be made. First of all, Warren and Hesser (1977) suggest that δ Ori C is a member of the Orion OB1 association, so that its distance is on the order of 400 ± 50 pc. The visual magnitude may then be used to estimate the luminosity, and hence the radius, of the star. The distance and apparent magnitude give $M_v = -1.29$. The tables of Code *et al.* (1976) give a bolometric correction of −1.91 using a temperature of 19,000 K. This gives $\log (L/L_\odot) = 3.18$ and a radius of 3.60 $R_\odot$. This independent determination of the radius of δ Ori C would seem to support the spotted helium geometry of the star, although the result depends heavily on the assumption that the star is a member of the Orion association. Obviously, if the star was at a greater distance, the derived radius would be in better agreement with the stratified model for the star derived earlier.

Second, an examination of Table 2 indicates that δ Ori C is more metal-rich than HD 58260 by a factor of between 5 and 10 for the limited sample of elements for which abundances have been determined. HD 58260 is almost certainly metal-deficient. This in itself is an interesting result, since Michaud *et al.* (1987) conclude that the abundances of heavy elements should not be modified by diffusion in the helium-strong stars. Either HD 58260 was formed with a very low metal abundance, or the work of Michaud *et al.* (1987) is incomplete. It seems unlikely that we have underestimated the metal abundances by a factor of 10, either because of the inappropriate choice of model atmosphere or because of a large overestimate of $T_{\rm eff}$. An improved treatment of diffusion in the helium-strong stars which incorporates magnetic fields quantitatively is badly needed. In contrast, relative to the Sun, δ Ori C is overabundant in magnesium. Oxygen and nitrogen are underabundant in the star. Silicon and aluminum have roughly solar abundances. Iron presents an interesting case. The difference in derived abundances between Fe II and Fe III may suggest that the temperature of δ Ori C, as determined from its color indices, has also been overestimated by a substantial amount. The two lines in Table 1 yield an identical abundance of $\log \epsilon_{\rm Fe} = -3.3$ (10 times the solar abundance) for a $T_{\rm eff}$ of 16,500 K, 2500 K lower than the temperature derived above. It is difficult to determine how much weight to give to this ionization equilibrium temperature, given the uncertainties in the oscillator strengths of iron, errors in the outer atmosphere structure, or possible non–LTE effects, but the discrepancy should be investigated further. If the star is indeed this cool, then the abundances given in Table 2 will all be too small, with the exception of magnesium. The star in this case would be metal-rich, and probably more closely related to the helium-weak stars than to the helium-strong class. Indeed, this might be supported by the spotted helium geometry discussed earlier, since the star can be modeled by assuming that it is very helium-weak over much of its surface.

The stars δ Ori C and HD 58260 would seem to be examples of a small group of stars with peculiar helium line profiles, of which 3 Sco and a Cen are members. Another peculiar object is the helium variable HD 49333. Hunger (1986*a*, *b*) shows spectra obtained by Kaufman and Theil for this star which suggest that helium is underabundant above $\tau = 0.4$ ($N_{\rm He}/N_{\rm H} \approx 0.001$) and normal below this level. These peculiar line profiles might also be caused by abundance patches similar to those observed on a Cen, but little is known about the star's variability. These stars all have effective temperatures between approximately 14,000 and 20,000 K, and all appear to have magnetic fields (Bohlender *et al.* 1987; Landstreet, Borra, and Fontaine 1979), although only a few low-significance measurements are available to date for HD 49333 (Borra, Landstreet, and Thompson 1983). (K. Hunger [1988, private communication] has informed the authors that at least three other stars similar to HD 49333 are known.)

Interestingly, in this temperature region there also exists a group of stars classified as "sn," which have *sharp-lined* metallic spectra but *nebulous* or very diffuse helium lines (e.g., Mermilliod 1983). In fact, Abt and Levato (1977) classified δ Ori C as B2 Vsn. Mermilliod shows that essentially all slow rotators in this temperature region are sn stars, which suggests a possible diffusion scenario for their origin, since slow rotation implies small meridional currents and therefore a stable outer envelope necessary for diffusion processes to occur. As discussed earlier, Vauclair (1975) has suggested that these peculiar profiles could be caused by a large abundance gradient in the line-forming region (between $\tau = 0.1$ and $\tau = 1.0$).

Several magnetic helium-weak stars are also classified as sn, and recent observations appear to indicate that the only helium-weak stars that show evidence of stellar winds or magnetospheres in their ultraviolet spectra are those with the sn designation (Shore, Brown, and Sonneborn 1987; Shore *et al.* 1988). These stars are not particularly slow rotators, but their magnetic fields will result in atmospheres that are stable enough for diffusion processes to occur. The strong winds would then seem to be related to the presence of a strong, globally ordered magnetic field. *IUE* spectra of HD 58260 show strong and constant C IV emission (Barker 1986), and indicate that this star also has a magnetosphere or wind. The fact that δ Ori C is a strong nonthermal radio source (Drake *et al.* 1987) would seem to imply the presence of a magnetosphere surrounding this star as well, even though *IUE* spectra show no evidence for either a magnetosphere or a stellar wind (Barker 1986).

It is rather surprising how few of these objects have been observed spectroscopically at reasonably high dispersion. Considering the interesting results we have presented here, it would certainly seem to be worthwhile to observe as many more of the sn, peculiar, and normal stars with T_{eff} between about 14,000 and 20,000 K as possible. These observations could provide important constraints for improved theories of helium diffusion in hot stars and give additional useful information on the roles of the effective temperatures, magnetic fields, and rotation on these diffusion processes.

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