

PHOTOSPHERES OF HOT STARS. II. AN ANALYSIS OF ZETA PUPPIS

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ABSTRACT

High signal-to-noise ratio line profiles of ζ Puppis (O4f) obtained with a CCD camera are compared with theoretical model atmospheres that include radiation scattered back from the stellar wind onto the photosphere, an effect referred to as wind blanketing. Our best-fit wind-blanketed model for the observed mass loss rate of $5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ yields the following properties of ζ Puppis: $T_{\text{effective}} = 42,000 \pm 1500 \text{ K}$, gravity $= 3.5 \pm 0.1 \text{ dex}$, helium abundance by number, $[Y] = 0.17 \pm 0.03$. The effect of wind blanketing for a star with a wind like that in ζ Puppis is to produce helium lines of the same strength as those from an unblanketed model with an effective temperature of 46,500 K. From our atmospheric model, if we assume a distance modulus of $8.2 \pm 0.4 \text{ mag}$, ζ Puppis has a bolometric magnitude of -10.1 ± 0.4 , a radius of $18 \pm 4 R_{\odot}$, and current mass of $36 (+21, -15) M_{\odot}$. The high helium abundance and low gravity are consistent with ζ Puppis as an evolved star very near the end of core hydrogen burning. Comparison with tracks of stellar evolution with mass loss suggests that ζ Puppis was initially a 70–90 $M_{\odot}$ star.

Subject headings: line profiles — stars: atmospheres — stars: early-type — stars: evolution — stars: individual

I. INTRODUCTION

The accurate determination of the effective temperature and surface gravity of a hot star is fundamental to our understanding of massive stars and the environment in which they are found. The bolometric luminosity of the most luminous stars and the global rate at which they input energy, momentum, and mass into the interstellar medium are all sensitive to these parameters. Moreover, such areas as the study of the initial mass function and the observational discrimination among various theories of stellar evolution depend on the accurate knowledge of the stellar parameters of hot luminous stars.

Abbott and Hummer (1985, hereafter Paper I) have demonstrated that accurate values of the effective temperature and surface gravity of hot stars can be determined *only* by an analysis of high-precision line profiles using non-LTE model stellar atmospheres which account for the heating of the photosphere by radiation backscattered by the stellar wind, i.e., the so-called *wind blanketing* first discussed by Hummer (1982). Line profiles are measures of the *surface* temperature, which can be related to the *effective* temperature only by theory; this relationship is sensitive to the wind blanketing. Thus effective temperature, surface gravity, mass-loss rate, and chemical composition are all relevant parameters in modeling the spectra of stars undergoing extensive mass loss. Moreover, a number of technical details must be carefully controlled in order to obtain reliable results.

Of equal importance is the use of line profiles observed with high photometric precision. For stars with effective tem-

peratures of order 40,000 K, the wings of H γ must be determined with a precision of 0.2% in order to obtain gravities with an error of 0.1 dex; to obtain temperatures to within 5%, the core-wing region of the lines must be known to within 1%. Although this precision is not possible with photographic techniques, it can be obtained for even quite faint stars by using currently available electronic detectors capable of operation with linear response and high signal-to-noise ratios. By analyzing a larger number of line profiles instead of the three usually used for photospheric parameters of early O-type stars (H γ , He I 4471 Å, and He II 4542 Å), we are able to overcome some of the effects of unresolved line blends and observational error, as well as to examine the internal consistency of the models.

This series of papers is devoted to the determination of stellar parameters, including the helium abundance, for a variety of O and early B-type stars. Among the goals of this work is the redefinition of the effective temperature sequence for early-type stars. In the present paper we consider ζ Puppis, which, because of its high apparent brightness and low interstellar extinction, offers unique potential for determination of stellar parameters. The stellar parameters of ζ Puppis have a long history of controversy. Continuum and spectroscopic diagnostics yielded values of effective temperature ranging from 32,000 K to 50,000 K, and gravities from 3.2 dex to 4.0 dex (e.g., Conti 1973; Code *et al.* 1976; Underhill *et al.* 1979). Possible explanations for the discrepancy included spherical atmospheres, a stellar wind “halo” of emission, and UV line blanketing (e.g., Heap 1972; Conti 1973; Castor, Abbott, and Klein 1975; Holm and Cassinelli 1977). Recently Kudritzki, Simon, and Hamann (1983) demonstrated that a non-LTE, plane-parallel atmosphere can give a good fit to both the line and the continuum spectra of ζ Puppis if the analysis includes the effect of surface gravity as well as effective temperature. In Paper I, continuum techniques were shown to be unreliable diagnostics of effective temperatures and surface gravity in hot stars because the maximum of the continuum flux is so far in the extreme ultraviolet. A general discussion of the discrep-

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ancies in the parameters determined for ζ Puppis is also given in the review of Kudritzki and Hummer (1986).

In the present paper, we show that high-precision CCD observations of the photospheric spectrum of ζ Puppis can be fitted by wind-blanketed, plane-parallel, model atmospheres, without recourse to micro- or macro-turbulence, nonradiative processes, sphericity, or continuum scattering by a stellar wind. The observations are described in § II, and the atmospheric models are summarized in § III. In § IV we give details of the analysis of the observed spectrum using the model profiles, and finally, in § V, we discuss the nature of ζ Puppis on the basis of our parameters.

II. THE OBSERVATIONS

We observed profiles of 13 lines involving 23 hydrogen and helium transitions between 3900 Å and 6700 Å (see Table 1). These observations were obtained at Kitt Peak National Observatory on the nights of 1984 February 17–22 using the coude feed telescope with the coude spectrograph and RCA CCD camera (KPNO RCA No. 2) at a spectral resolution of 0.59 Å (2 pixels) in the blue and 0.89 Å in the red. The RCA CCD, a thinned, buried-channel device, has 512 rows by 320 columns (pixel size of 0.030 mm², aligned with the long axis of the chip parallel to the dispersion of the grating. We used the RCA CCD at an exposure level not affected by readout noise (approximately 80 electrons per pixel) and where the nonlinearity (0.019% at 87,800 electrons) was a small fraction of the overall noise from photon statistics. In a typical exposure, 120,000 electrons per pixel were counted. This CCD has a peak quantum efficiency of approximately 75% at 6000 Å with a wide spectral range (70% efficiency at 4000 Å and 55% at 7100 Å).

At the coude spectrograph, the photometric precision of a CCD is limited by calibration of fringing effects, not by the number of photons counted. Apparently the CCD in the coude spectrograph is not illuminated in the same fashion by the flat-field lamp as by the starlight. This effect is generally more severe in the red than in the blue. In addition we found that ζ Puppis, always observed at large zenith distances, and consequently always under poor seeing conditions, had much worse uncorrected fringing than other stars in our program. To minimize residual fringing, we added together spectra taken at

slightly different grating settings (flat-field calibrations were always taken at the same setting as the stellar exposures). The last column of Table 1 shows the number of spectra added together to produce the observed line profiles of ζ Puppis. In the red, we were never able to achieve our goal of less than 0.5% noise because of residual fringing; in the blue, noise levels as low as 0.25% were reached. However, the photometric noise level measured in the blue is still roughly 70% higher than that expected from the statistics of the total electron count.

Raw CCD pictures were reduced with the KPNO Mountain Reduction Program to trim, subtract bias, apply flat-fielding, and extract and sum the CCD columns that contain the spectrum. The Kitt Peak version of the Tololo-Vienna Interactive Image Processing System was used at the University of Colorado to linearize the spectrum to a wavelength scale and to normalize line profiles for comparison with profiles with the model atmospheres (see § IV).

The Tololo-Vienna Program (TV) consists of a series of interactive programs that include routines to set the continuum and to determine the wavelength scale by measuring the positions of comparison lines. We defined the continuum as the average level of regions that appeared at our resolution to be free of spectral lines or other features (see below). Since the spectral response of the grating and the CCD, both relatively smooth functions of wavelength, are the primary contributors to the shape of the apparent continuum, a polynomial of order three could be used to interpolate between the continuum points. Typically, 10–15 continuum points were used. The wavelength scale was determined by measuring the positions of comparison lines, fitting a polynomial of given order (usually third), and linearizing the spectrum. The final wavelength scale was shifted to account to the observed radial velocity of ζ Puppis (assumed to be -24 km s^{-1}).

The residual fringing introduced some uncertainty into the determination of the continuum. Bumps wider than stellar lines and spikes narrower than stellar lines, but wider than the instrumental resolution, occasionally appear above the noise level of the stellar spectrum (for example, in Fig. 1 there is a bump redward of He I 4026 Å that is not of stellar origin). The source of these features is unknown. We suspect they arise in the flat-fielding calibration and in some cases may be attributed to the effects of seeing and atmospheric dispersion that

TABLE 1
STATISTICS OF CCD SPECTRA OF ZETA PUPPIS

SPECTRAL FEATURES	$S/R_{(\text{observed})}$	Noise _(observed)	$S/R_{(\text{expected})}$	NUMBER OF SPECTRA ^a	EQUIVALENT WIDTH	
					Observed	Theory
He II 6681 Å + He I 6678 Å	82	1.2	640	4(3)	0.604	0.652
H α 6563 Å + He II 6560 Å	82	1.2	640	4(3)	...	...
He II 6527 Å	82	1.2	640	4(3)	1.084	0.549
He I 5876 Å	192	0.5	794	2(1)	0.482	0.472
He II 5411 Å	136	0.7	679	2(1)	1.075	0.972
He II 4542 Å	665	0.2	675	3(3)	0.936	0.737
He I 4471 Å	665	0.2	675	3(3)	0.248	0.218
H γ 4340 Å + He II 4339 Å	384	0.3	699	3(3)	1.792	1.672
He II 4200 Å	408	0.2	707	4(3)	0.689	0.611
H δ 4101 Å + He II 4100 Å	408	0.2	707	4(3)	1.849	1.543
He II 4026 Å	347	0.3	764	5(2)	0.436	0.376
He I 3970 Å + He II 3962 Å	347	0.3	764	5(2)	1.354	1.418
He II 3923 Å	347	0.3	764	5(2)	0.401	0.361

^a The number of independent spectra co-added to form the final line profile. The number in parenthesis is the number of spectra taken at different grating settings to minimize the effect of residual fringing.

cause the detector to be illuminated differently by the starlight and by the flat-field calibration lamp. Features of stellar width or slightly narrower were especially troublesome in defining the continuum as one did not know if these were weak stellar lines, telluric lines, or uncorrected fringes.

Baade (1985) reported line profile variations in C IV 5801, 5812 Å that he attributed to nonradial oscillations. At our level of resolution and signal-to-noise ratio, we did not see night-to-night variations in the hydrogen and helium line profiles.

The photometric precision for each line profile in Table 1 is based upon direct measurement of the root mean square variations of the continuum. We feel that they represent conservative measures of the precision of our observations as they include any uncorrected fringing. This estimate does not include effects of continuum setting and so represents the internal error rather than the external error. The nonlinearity of the RCA CCD is still significantly less than our estimated precision. The expected signal-to-noise ratios listed in Table 1 are computed from the square root of the total electron counts in the extracted spectrum (i.e., Poisson statistics). The noise observed is the reciprocal of the observed signal-to-noise ratio expressed in percent.

III. THE THEORETICAL MODEL ATMOSPHERE

The model atmospheres used in our analysis are described in Paper I. These models are based upon assumptions of radiative and hydrostatic equilibrium, plane-parallel atmospheres, non-LTE statistical equilibrium, contain only hydrogen and helium, and account for the scattering of radiation by the stellar wind back onto the photosphere. In the star-plus-wind model, the upper layers of the photosphere emit radiation that provides the lower boundary condition for the wind; radiation backscattered from the wind determines the upper boundary conditions for the photosphere.

The model atmosphere code is essentially that of Mihalas (1972). Departures from LTE are allowed for five levels of hydrogen, two of He I, and two of He II. The usual upper boundary of no incident radiation has been replaced by radiation backscattered by the wind as represented by a wavelength-dependent albedo. The albedo has been calculated by Abbott and Lucy (1985) using a Monte Carlo solution of the transfer equation in the wind that accounts for approximately 10^4 lines with wavelengths between 200 Å and 10,000 Å. Multiscattering of photons by overlapping lines and by electron scattering is included. The wind velocity field was parameterized in the form $V = V_\infty[1 - (r_*/r)]^\beta$, where $v_\infty = 2600$ km s⁻¹ as observed for ζ Puppis (Abbott 1978) and the parameter β was set to 1.0. Test cases are illustrated in Paper I justifying this method for calculating the albedo and the choice of the parameter β.

The hydrogen line profiles were calculated using the line-broadening theory described by Mihalas (1972) from hydrogen level populations obtained in the model atmosphere calculations. The He I line profiles were computed as described by Auer and Mihalas (1973), supplemented by line-broadening data from Mihalas *et al.* (1974). For He II line profiles, we used a model atom with 10 non-LTE levels, treating explicitly 16 transitions among levels 2–7 (Auer and Mihalas 1972). The line profiles were rotationally broadened with center-to-limb variations taken into account using the method of Stoeckley and Mihalas (1973). In all cases no “microturbulence” was assumed, i.e., the Doppler broadening in the line profile calcu-

lation is from thermal motions at the local electron temperature.

IV. ANALYSIS OF LINE PROFILES IN ZETA PUPPIS

The observed line profiles (§ II) were compared with line profiles calculated from model atmospheres both with and without the effects of wind blanketing (§ III) to determine atmospheric parameters appropriate to ζ Puppis. From the wind-blanketed analysis, the observed line profiles are best-fitted by an atmosphere with $T_{\text{eff}} = 42,000 \pm 1500$ K, $\log g = 3.5 \pm 0.1$, and number fraction of helium, $[Y] = 0.17 \pm 0.03$ (Fig. 1). By comparison, an unblanketed model would fit the same observations with $T_{\text{eff}} = 46,500 \pm 1500$ K, $\log g = 3.6 \pm 0.1$, and $[Y] = 0.16 \pm 0.03$. Thus for ζ Puppis, the wind-blanketed analysis yields an effective temperature 4500 K cooler than that from an unblanketed atmosphere.

At our level of photometric precision, every line is contaminated to some extent by blends and by uncertainty in setting the continuum. By averaging over several lines of each species, we were able to minimize these effects. In Figure 1, the line profiles from our CCD spectra are plotted with line profiles from our best-fit atmosphere. While certain lines were given a larger weight in determining specific parameters, we considered the fit of all the lines. In some cases we fitted only part of a line because of blends. We chose not to use a numerical fitting procedure, but rather adjusted the model parameters until a best fit by eye was achieved. We feel that the goodness-of-fit is within the uncertainty in the physics of our model and the photometric errors in our line profiles.

The assumed parameters for ζ Puppis used in our model atmospheres are given in Table 2. In all wind-blanketed models the wavelength-dependent albedo of a wind with a mass-loss rate of $5 \times 10^{-6} M_\odot \text{ yr}^{-1}$ (Abbott and Lucy 1985) is used. While we calculated models with a range of rotational velocities, our adopted rotational velocity of 210 km s⁻¹ is the same as that measured by Conti and Ebbetts (1977). We find no evidence to support a rotational velocity as high as 350 km s⁻¹ (e.g., Barnes, Lambert, and Potter 1974).

The input parameters, T_{eff} , $\log g$, and $[Y]$, were used in an iterative scheme to arrive at a best fit of the theoretical line profiles to the observed. The wings of the hydrogen lines were used to determine the gravity (Fig. 2a). The effective temperature was found primarily by fitting the He I lines (Figs. 2b and 2c). The fractional abundance of helium $[Y]$, was set by the sum of the equivalent widths of both neutral and ionized helium (Fig. 3). We first fixed the gravity, then the effective temperature, and finally $[Y]$. Before adopting the final values, the fits to all the lines were examined. Had the fits not been satisfactory, the process would have been repeated until a good fit was achieved. For this analysis of ζ Puppis, we did not have to iterate because we had a well-chosen set of initial parameters and because of the relative insensitivity in ζ Puppis of the hydrogen lines to T_{eff} and $[Y]$. To estimate the uncertainties in the final parameters we determine the changes in the final parameters that would make the adopted model not fit the line profiles to within our observational error.

After best-fit model parameters were determined through comparison of the observed and theoretical line profiles, a final self-consistency check was made for the values of effective temperature and helium number fraction. Plots of the sum of equivalent widths of He I and He II versus effective temperature (Fig. 3) were made from models which bracketed the best-fit

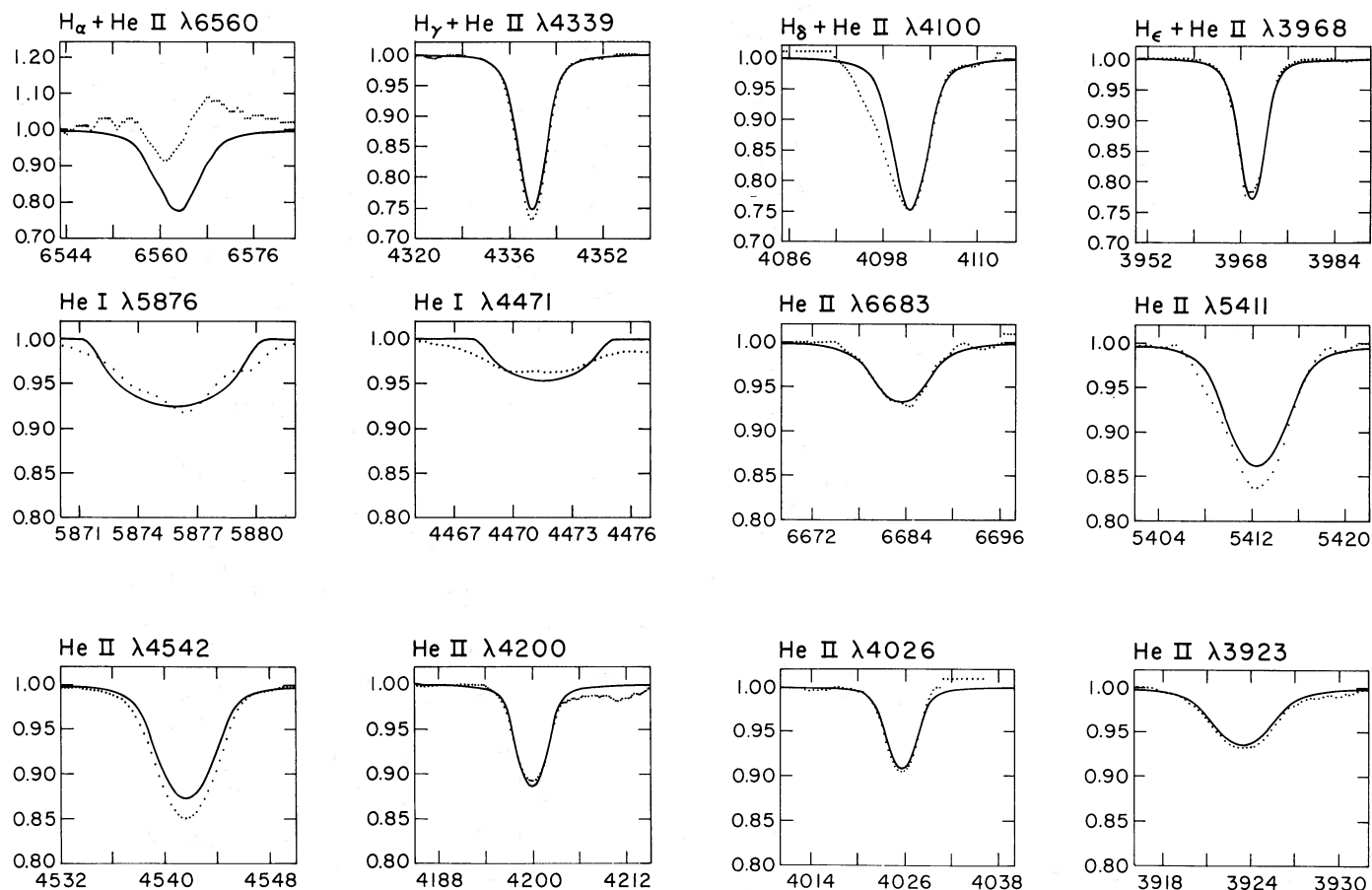


FIG. 1.—A comparison of observed line profiles of ζ Puppis (dots) with those from our best-fit model atmosphere (solid lines) for $T_{\text{eff}} = 42,000$ K, $\log g = 3.5$, and $[Y] = 0.17$.

model. Each plot indicates a set of effective temperature and helium fraction values that are valid for each stage of helium ionization. The overlap of these two sets suggests an atmosphere with $T_{\text{eff}} = 41,500$ K and $[Y] = 0.17$ from the helium lines alone. A model with these parameters is consistent with our best-fit model. We did not change the temperatures because this result is well within our errors and because of problems in modeling He II 4542 Å and 5411 Å.

Some comment on specific lines in Figure 1 is appropriate to illustrate our confidence in the atmospheric parameters that we have determined. Except for H α 6563 Å, the fit to hydrogen

lines is excellent. Since our model does not include the effect of radiation emitted in the wind, H α 6563 Å, which shows a P Cygni-like profile, could not be used for this analysis. H γ 4340 Å, the red wing of H δ 4101 Å, and H ϵ 3970 Å all are well fitted by the model. The blue wing of H δ 4101 Å was excluded because of a blend with N III 4097 Å. The neutral helium lines, 4471 Å and 5876 Å, are quite weak in a star as hot as ζ Puppis. The observed profile for He I 4471 Å is flatter in both the core and in the wings than the model suggests. Several of the ionized helium lines are contaminated on their red wing. We fitted only the blue wing of He II 4200 Å and 4026 Å. As explained in § II, the bump redward of He II 4026 Å is attributed to an artifact of the flat-field calibration process of the CCD. The two remaining ionized helium lines, 4542 Å and 5411 Å, could not be fitted consistently with other lines as well as we would expect. The result of changing atmospheric parameters to get a good fit to these two lines was to produce a line profile of all other lines that was clearly incorrect. As these lines are strongest lines in the Pickering series which we have observed, and consequently are formed higher in the atmosphere (Fig. 4), it is likely that their cores are formed in the superficial layer in which non-LTE line blanketing, as discussed recently by Anderson (1985), causes the local temperatures to be distinctly lower than in the non-line-blanketed models. We therefore gave the He II transitions 4542 Å and 5411 Å very low weight in this analysis despite their relative strength and generally high quality of the observations. On the

TABLE 2
ADOPTED PROPERTIES OF ZETA PUPPIS

Property	Value	Reference
Mass-loss rate	$5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$	1
Terminal velocity	2600 km s^{-1}	2
V	2.25	3
$B - V$	-0.26	3
Reddening, E_{B-V}	0.04 ± 0.02	3
Distance	$450 \pm 100 \text{ pc}$	4
True distance modulus	8.2 ± 0.4	4
M_V (distance and reddening)	-6.0 ± 0.4	4
Angular diameter	$4''.0 \times 10^{-4}$	5

REFERENCES.—(1) Abbott and Lucy 1985. (2) Abbott 1978. (3) Bright Star Catalog. (4) Brandt *et al.* 1971. (5) Hanbury Brown *et al.* 1974.

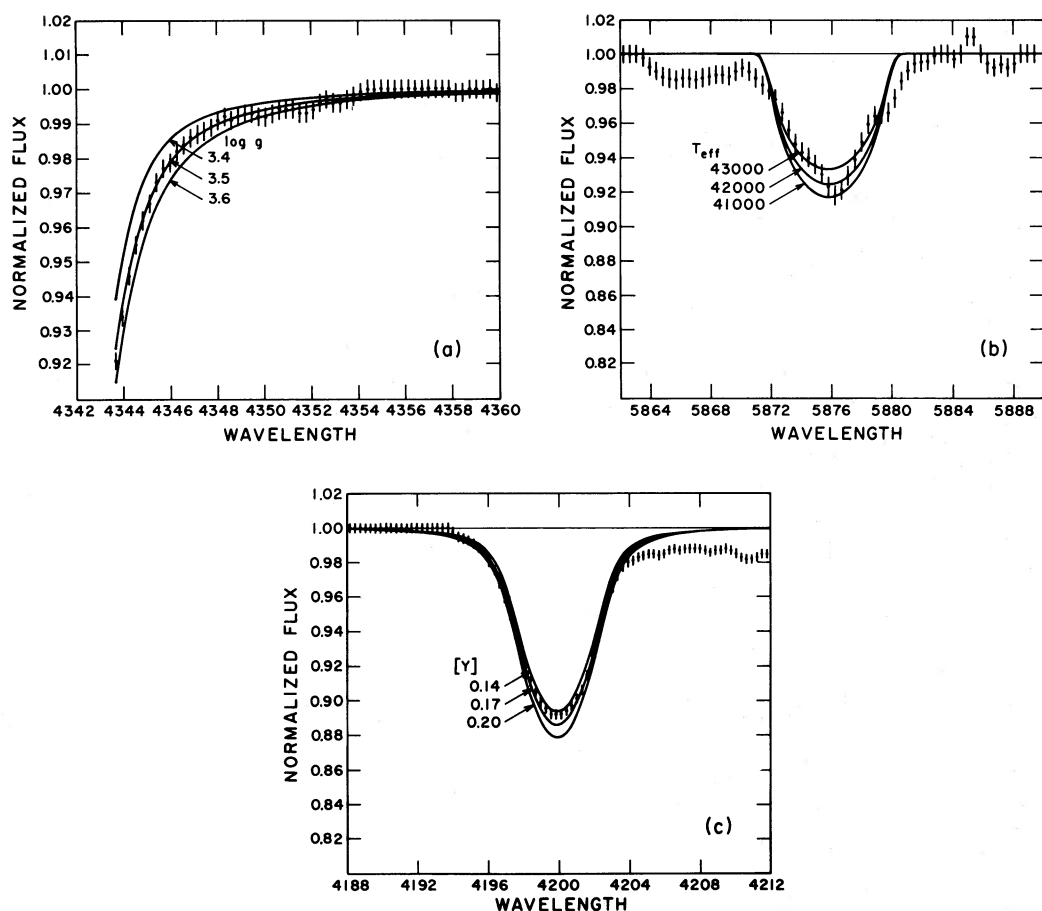


FIG. 2.—An illustration of the goodness of fit for various lines for variations in the model parameters. (a) The effect of gravity on the red wing of H γ 4340 Å for $T_{\text{eff}} = 42,000$ K and $[Y] = 0.17$. (b) The effect of effective temperature on He I 5876 Å for $\log g = 3.5$ and $T_{\text{eff}} = 42,000$ K. For all models the rotational velocity was set to 210 km s^{-1} , and the mass-loss rate was $5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. The vertical bars indicate the measured error in the observed spectra.

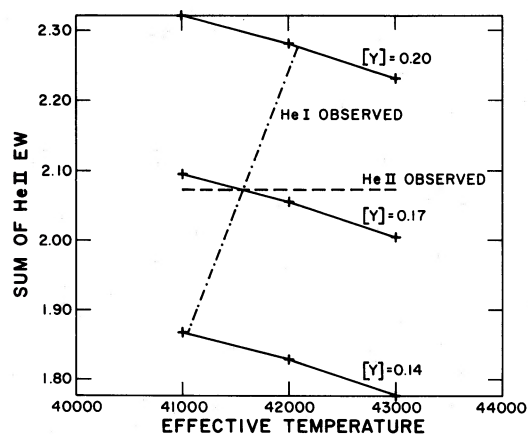


FIG. 3a

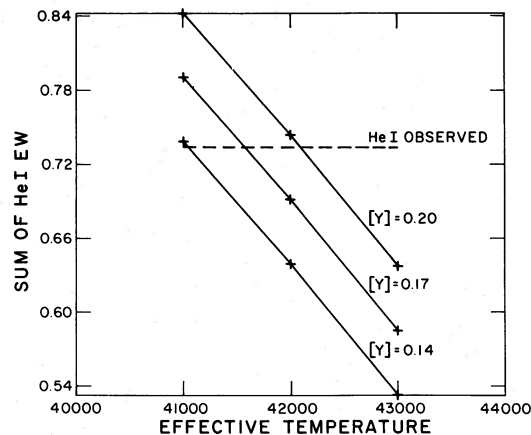


FIG. 3b

FIG. 3.—A check of the self-consistency of the best-fit of the model effective temperature and helium fraction. (a) The sum of equivalent widths of He II 3923 Å, 4026 Å, 4200 Å, and 6683 Å as a function of effective temperature for models with varying helium abundance. The observed sum of equivalent widths (dashed line) indicates possible combinations of effective temperature and helium fraction. (b) The analogous plot for the sum of equivalent widths of He I 4471 Å and 5876 Å. A self-consistent model is then one with an effective temperature and helium fraction common to both plots. We indicate such a model by the intersection of the observed sum of He II equivalent widths with the dash-dot line on (a) which is the He I observed line from (b) plotted at the appropriate temperature and helium fraction points in (a). The intersection suggests an effective temperature of 41,500 K and $[Y] = 0.17$ consistent with our best-fit model. For all models in these plots, $\log g = 3.5$ and $V_{\text{rotational}} = 210 \text{ km s}^{-1}$ were used.

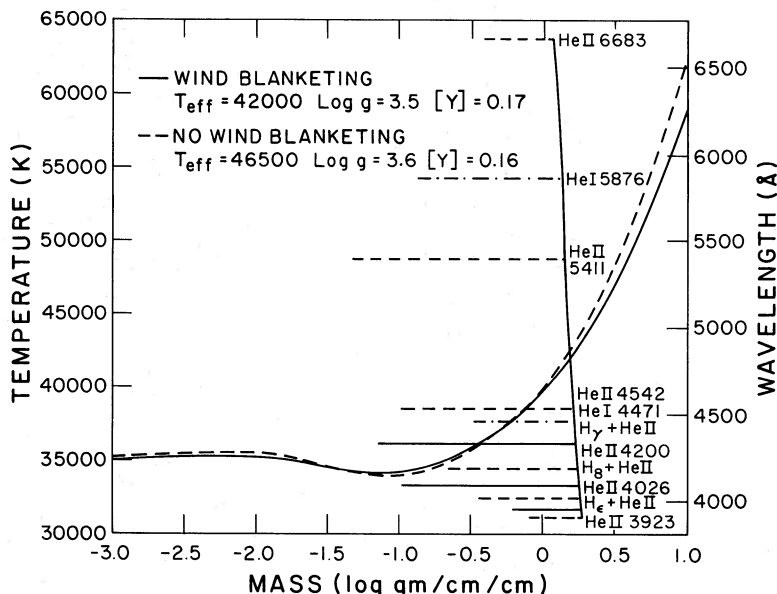


FIG. 4.—Temperature vs. depth in the atmosphere for the wind-blanketed and unblanketed calculations which best fit the observed line profiles for ζ Puppis. The horizontal lines show the region of formation for the indicated spectral features, and the nearly vertical curve represents the location of unit optical depth in the continuum.

other hand, there is little reason to distrust the weaker lines except, perhaps, the increasing uncertainty in line blanketing theory for the higher lines.

From our wind-blanketed study we determined the same effective temperature for ζ Puppis as did Kudritzki, Simon, and Hamann (1983) from their unblanketed analysis. Yet, from our blanketed and unblanketed results we would expect roughly a 4500 K difference. The explanation for the similar effective temperature is a 0.15 Å difference in the equivalent width of He I 4471 Å between our CCD observations and the photographically determined line profiles of Kudritzki, Simon, and Hamann, who digitally combined line profiles recorded on Kodak type IIIa-J spectroscopic plates to achieve signal-to-noise ratios sufficiently high to measure the gravity of ζ Puppis. This difference alone accounts almost entirely for the 4000 K difference between their analysis and our results with unblanketed models. It is not unexpected that there might be larger photometric calibration errors of the photographically determined line profiles than their estimated signal-to-noise ratios of 100:1. On the other hand, the measured linearity of the RCA CCD at the exposure level used in our observations is 0.2%, much smaller than our measured noise levels. As He I 4471 Å is very weak in ζ Puppis and has a very chopped-up appearance even in our CCD spectra (Fig. 2) it is easy to see how this difference could arise. This circumstance illustrates the importance of using several lines of one species to fit the model atmosphere.

V. DISCUSSION

The effective temperature of ζ Puppis is changed from earlier spectroscopic analysis (e.g., Conti and Frost 1977) because of the following three factors: (1) including the effect of wind blanketing caused a roughly 4500 K decrease in T_{eff} ; (2) correctly accounting for the low gravity of ζ Pup caused a roughly 8000 K decrease in T_{eff} ; and (3) using CCD observations with high signal-to-noise ratio caused a roughly 4000 K increase in T_{eff} . These three factors combine to give an effective tem-

perature of 42,000 K for spectral type O4f, which is roughly 8000 K cooler than earlier spectroscopic calibrations (e.g., Conti 1973). Errors of this magnitude have profound effect upon the fundamental parameters of massive stars and their environment. For example, at the effective temperature of ζ Puppis (42,000 K), an error of only $\pm 10\%$ in temperature corresponds to an uncertainty of $\pm 50\%$ in the derived value of the bolometric luminosity and the total number of hydrogen ionizing photons. Both of these quantities are critical to the determination of the initial mass function of our Galaxy and that of other galaxies, to the study of the rate of stellar heating and ionization of the interstellar medium, for comparisons between theory of stellar structure and evolution, and for the observed location in the Hertzsprung-Russell diagram. Accurate models of photospheric spectra are necessary before an analysis of atmospheric chemical abundances is possible. In addition, efforts to derive the properties of stellar winds require measures of the ionizing flux, and of the radius and temperature of the photosphere.

Although the effective temperatures of wind-blanketed and unblanketed atmospheres differ by 4500 K, their surface temperatures and helium ionization populations are nearly identical (Fig. 4), and hence the predicted emergent spectrum is nearly the same. Because the two atmospheric structures are nearly identical, there is no observational diagnostic from the photosphere which can be unambiguously associated with the presence of wind blanketing.

The radius and mass of ζ Puppis can be calculated from our atmospheric parameters (Table 2) through the equations $L = 4\pi R^2 \sigma T_{\text{eff}}^4$ and $g = GM/R^2$ by using the observed distance and the reddening. The bolometric correction calculated from our best-fit model atmosphere is -4.0 . The bolometric magnitude of ζ Puppis is then -10.1 ± 0.4 , where most of the uncertainty comes from the uncertainty in the distance modulus (equivalent luminosity; $\log L/L_{\odot} = 5.94 \pm 0.18$). The radius of ζ Puppis calculated from the luminosity and temperature is $18 (-3, +5) R_{\odot}$. The mass of ζ Puppis calculated from the gravity

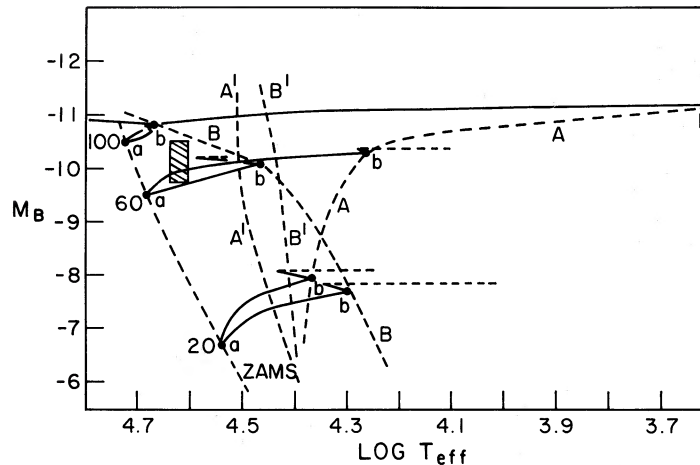


FIG. 5.—The location of ζ Puppis in the Hertzsprung-Russell diagram. The hatched rectangle represents the location of ζ Puppis determined from wind-blanketed model atmosphere analysis. Theoretical tracks of stellar evolution from Bresson, Bertelli, and Chiosi (1981). The vertical dashed lines indicate the temperature at the end of core hydrogen burning for different models: A, constant mass, convective overshooting; A', constant mass, standard core; B, mass loss due to stellar wind, convective overshooting; B', mass loss due to stellar wind, standard core.

as determined from the wind blanketed photospheric analysis and a radius of $18 R_{\odot}$ is $36 M_{\odot}$ (+21, -15). A comparison of our observed temperature and luminosity of ζ Puppis with tracks of theoretical stellar evolution of Bresson, Bertelli, and Chiosi (1981) suggests that ζ Puppis was formed as a 70–90 $M_{\odot}$ star (Fig. 5). The stellar properties that we found from our photospheric analysis or otherwise calculated for ζ Puppis are given in Table 3.

Our derived helium number fraction, $[Y] = 0.17$, is significantly higher than that commonly assumed (e.g., Davidson and Kinman 1985 measure a primordial helium abundance of $[Y] = 0.063 \pm 0.007$ for 1 Zw 18; Peimbert, Serrano, and Torres-Peimbert 1984 state that all well-observed H II regions in our Galaxy and other galaxies show $0.065 < [Y] < 0.100$). Kudritzki, Simon, and Hamman (1983) from their unblanketed study also find a high helium abundance, although their value of $[Y] = 0.14$ is lower than ours because of an unresolved discrepancy between their He II statistical equilibrium code and that of Auer and Mihalas (1972) which we have used. There might be an additional 10% systematic uncertainty in our derived $[Y]$ which is not represented in our estimated error. Nevertheless, there is no question that helium is overabundant in ζ Puppis despite these known uncertainties. We note that Conti and Frost (1977) have already argued for an overabundance of helium in ζ Puppis based upon examination of photographic spectra.

TABLE 3
STELLAR PARAMETERS OF ZETA PUPPIS (O4f)
FROM A WIND-BLANKETED ANALYSIS

Parameter	Value
Effective temperature	$42,000 \pm 1500$ K
Gravity	3.5 ± 0.1
Helium abundance	0.17 ± 0.03
Rotational velocity	210 km s^{-1}
Log luminosity	5.94 ± 0.18
M_{bol}	-10.1 ± 0.4
Bolometric correction	-4.0 ± 0.1
M_V	-6.1 ± 0.4
Radius	$18 (+5, -3) R_{\odot}$
Mass	$38 (+22, -14) M_{\odot}$

The high helium abundance is not surprising given the evolved nature of ζ Puppis as evident from its lower than main sequence gravity, 3.5 dex. What can the helium abundance of ζ Puppis tell us about stellar structure and evolution? Two mechanisms bring helium formed in the nuclear-burning core to the surface: mass loss in a stellar wind removes mass from the surface; mixing or convective overshooting brings processed material from the core toward the surface. Interior models are well constrained in the rate that mass is removed from the surface by direct observations of mass loss rates (e.g., Abbott, Bieging, and Churchwell 1981; Garmany and Conti 1984).

The stellar evolution codes must be consistent with the observations of ζ Puppis (i.e., $4 \times 10^{-6} < \dot{M} < 7 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ for $\log L/L_{\odot} = 6.00$ and $T_{\text{eff}} = 42,000$ K). Models without mixing (e.g., Chiosi, Nasi, and Sreenivasan 1978; Maeder 1981; Stothers and Chin 1977) do not show a change in the surface composition of helium, in direct conflict with our measurement. On the other hand, models with mixing do show at least a qualitative agreement. For example, from the models of Bresson, Bertelli, and Chiosi (1981), a star with an initial mass of $60 M_{\odot}$ has the following parameters at the end of the core hydrogen burning: $\log L/L_{\odot} = 5.95$, $M/M_{\odot} = 41$, $T_{\text{eff}} = 28,800$ K, $[X]_{\text{surface}} = 0.50$ (by mass). This model over its hydrogen-burning lifetime has a time-averaged mass-loss rate of $6 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. Models with a slightly higher initial mass will have a considerably higher effective temperature at the point when surface helium enhancements occur. These parameters are strikingly similar to those that we determine for ζ Puppis, except for the effective temperature which is much lower than that found here for ζ Puppis. With an overshooting parameter of $\lambda = 1$ and a mass-loss formulation reasonably in agreement with that measured for ζ Puppis, the evolution tracks by Bresson, Bertelli, and Chiosi (1981) are in agreement with these observations (Fig. 5). ζ Puppis is a highly evolved star in the final quarter of its hydrogen-burning lifetime.

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