A NON-LTE ANALYSIS OF THE $\zeta$ AURIGAE B-TYPE SECONDARY. I. DETERMINATION 
OF THE FUNDAMENTAL STELLAR PARAMETERS

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ABSTRACT

We present a non-LTE model atmosphere analysis of the B star secondary of $\zeta$ Aurigae (B5 V + K4 Ib) and determine its stellar parameters. A grid of model atmospheres and synthetic spectra were computed for stellar parameters typical of mid-B stars, using the TLUSTY and SYNSPEC codes of Hubeny with the lines and continua of H and He calculated in non-LTE. We observed $\zeta$ Aur with the Goddard High Resolution Spectrograph (GRHS) of the Hubble Space Telescope (HST) at several epochs near the 1993 eclipse. By carefully removing the circumstellar wind features at the two epochs furthest from eclipse, we recovered the intrinsic photospheric spectrum of the B star. The photospheric spectrum of $\zeta$ Aur B is compared to the grid of synthetic spectra, and the best fit is determined using a least-squares technique. We find $T_{\text{eff}} = 15,400 \pm 300$ K, $\log g = 3.9 \pm 0.1$, and $v \sin i = 200 \pm 15$ km s$^{-1}$. The corresponding spectral type, using the effective temperature scale of Underhill et al., is B5 V.

The C I UV 5, 6, 7, and 9 resonance multiplets (1277–1281 Å) and the Si II UV 4 (1260–1265 Å) and UV 5 (1190–1197 Å) resonance multiplets are observed to be much weaker than our models predict. We empirically determine departure coefficients of C I and Si II by varying the oscillator strengths of transitions of each of these ions until a good match with the GRHS spectra is obtained. For C I, we provide theoretical confirmation of these empirically determined departure coefficients by computing a more detailed model atmosphere including levels and transitions of C I, C II, and C III treated in non-LTE. The synthetic spectra computed from this model are in good agreement with the GRHS observations, and the C I ground-state departure coefficient is consistent with the empirically determined value.

We examine several possible causes of the weakness of the Si II lines and conclude that an underabundance due to non-LTE effects is the probable explanation. Previous model atmospheres including Si II computed in non-LTE show that the Si II resonance lines are formed essentially in LTE. We suggest that autoionization of Si II (neglected in previous modeling) may shift the silicon ionization balance enough to account for the weakness of the Si II lines.

Subject headings: stars: early-type — stars: fundamental parameters — stars: individual ($\zeta$ Aurigae) — ultraviolet: stars

I. INTRODUCTION

Analysis of the ultraviolet spectra of the eclipsing binary system $\zeta$ Aurigae at different orbital phases provides an excellent opportunity to probe the outer atmosphere of the evolved primary star using the light of its early-type companion. In the ultraviolet shortward of 3000 Å, the K supergiant primary contributes negligible flux and the observed spectrum is purely that of the main-sequence B star with superimposed interstellar and circumstellar lines from the outer atmosphere of the K supergiant. These circumstellar lines sample varying lines of sight as the B star proceeds into and out of eclipse behind the K supergiant, providing a rare opportunity to obtain spatially resolved information about the structure of the primary star's chromosphere and wind. We have obtained Hubble Space Telescope (HST) Goddard High Resolution Spectrograph (GRHS) spectra of $\zeta$ Aurigae at six epochs around the 1993 eclipse. The GRHS data have a spectral resolution of $R = \lambda/\Delta \lambda \sim 20,000$ (grating G160M) to 40,000 (Echelle-B), with a typical signal-to-noise ratio (S/N) of 50. These resolutions allow, for the first time, a clear separation of the circumstellar and interstellar absorption components. The overall quality of these data demands a proper treatment of the line radiative transfer and statistical equilibrium of the important ions observed in the ultraviolet spectrum. The first step in the modeling procedure is to ensure that our “light probe”—the B star secondary—has well determined stellar parameters and a well characterized ultraviolet radiation field.

Despite many years of observation, the spectral type of the secondary star, $\zeta$ Aur B, remains poorly determined. Wright (1970) reviewed the early optical photometry and spectroscopy and concluded the spectral type was about B6–B7 IV–V. Faraggiana & Hack (1980) modeled the continuous spectrum of $\zeta$ Aur B, observed with IUE, with Kurucz (1979) LTE atmospheres, obtained a good match for $T_{\text{eff}} = 12,000$ K, and adopted a spectral type of B7. An effective temperature of $T_{\text{eff}} = 12,000$ K corresponds to a spectral type of about B8 on the Underhill et al. (1979) temperature scale. Che, Hempe, & Reimers (1983) also used low resolution IUE spectra and Kurucz models to estimate an effective temperature of 13,000 K and a spectral type of B8; the Underhill et al. (1979) cali-
ibration gives a spectral type of B7. Griffin et al. (1990) concluded, from a study of the optical spectrum of the secondary (obtained by subtracting a total eclipse spectrum from the composite spectrum far from eclipse), that the spectral type was B6.5. In summary, the analyses to date imply a spectral type in the range B6–B8 for ζ Aur B, but the effective temperatures remain poorly determined. The early optical determinations of the companion’s spectral type suffered from severe contamination by the K star flux, which dominates for λ > 4000 Å. Since the slope of the ultraviolet continuum longward of the flux peak is insensitive to the effective temperature, temperatures determined by model fits to this continuum will also be poorly constrained. Given the lack of a model atmosphere analysis, and the importance of a well determined B star effective temperature and radiation field for the modeling of the circumstellar environment of the ζ Aur system, we have undertaken a full model atmosphere analysis of ζ Aur B using the TLUSTY code of Hubeny (1988).

The aims of this study are twofold. We seek to provide a better determination of the fundamental stellar parameters (effective temperature, gravity, and rotational velocity) of the B star. Additionally, we need to accurately reproduce the spectrum of the B star in order that the K star wind lines may be reliably separated from the underlying stellar spectrum.

2. OBSERVATIONS AND REDUCTIONS

We have obtained GHRS spectra of selected spectral regions from 1170 to 3140 Å at six epochs near the 1993 eclipse of ζ Aurigae (Table 1). The orbit of the eclipsing binary ζ Aurigae, and the phases of our GHRS observation epochs, are shown in Figure 1. For details of the design and capabilities of the GHRS see Duncan (1992). The small science aperture (SSA) was employed with the medium resolution G160M grating for the exposures with λ < 1700 Å, and the large science aperture (LSA) was used with the echelle-B grating for λ > 1700 Å. The G160M spectra have a resolution R = λ/Δλ ≈ 20,000 and the echelle spectra have an R ≈ 43,500. For each spectral region, four sets of four exposures each were co-added and pixel-shifted (the FPSPLIT-4 procedure) to reduce fixed-pattern noise. The S/N of the resulting spectra is typically ~50. A complete description of the data set can be found in Brown et al. (1995).

For this paper, we are mainly concerned with the 1172–1209 Å and 1245–1285 Å spectral regions where strong lines of C III, Si II, and Si III dominate the photospheric spectrum of the B star. For the purposes of spectral classification, the 1172–1209 Å region is the more useful, since the Si II and C III multiplets have opposite temperature dependencies for mid-B stars. In principle, this behavior should make the Si II and C III lines effective temperature indicators.

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* Calculated using the ephemeris of Wood et al. 1980.

The present analysis uses GHRS observations obtained at epochs 1 and 6 (Table 1) when the two stars were well separated and the B star photospheric spectrum was relatively uncontaminated by circumstellar absorption lines. Each set of exposures was acquired during a 2 hour period. The co-added and wavelength-calibrated GHRS spectrum for the 1172–1209 Å spectral interval is shown in Figure 2a, and for the 1245–1285 Å region is shown in Figure 3a.

An optical spectrum of ζ Aur B was kindly supplied by R. E. M. Griffin. This spectrum (Fig. 4a of Griffin et al. 1990) was obtained by subtraction of the 1987 total eclipse spectrum (of ζ Aur A) from a composite light spectrum. We used the region of the He I 3970 Å and the He I 4026 Å lines of the Griffin spectrum to confirm that our models are consistent with the optical spectra. This region of the Griffin spectrum is shown in our Figure 4a. We also reproduce the Griffin spectrum in the region of the Balmer series limit as Figure 4b. No radial velocity correction has been applied to these data.

The angular separation of the components of the ζ Aurigae system at epochs 1 and 6 were the largest in our data set. Nevertheless, these spectra still contain numerous circumstellar and interstellar lines superimposed upon the photospheric spectrum of the B star. Since the B star has a rotational velocity of v sin i ~ 200 km s⁻¹ (Griffin et al. 1990), the intrinsic photospheric lines are broad and readily distinguished from the narrower features of circumstellar and interstellar origin. The pixels corresponding to the circumstellar and interstellar lines are readily identified and deleted, leaving a pure photospheric spectrum (with gaps) of the B star. Finally, the radial velocity of the B star, calculated using the orbital elements of Wright (1970), has been corrected to zero in the heliocentric frame. The B star radial velocities were v₁ = +32.0 km s⁻¹ at epoch 1 and v₂ = -28.0 km s⁻¹ at epoch 6.

The “intrinsic photospheric” spectra of ζ Aur B obtained in this manner are highly oversampled. The composite GHRS spectra, obtained by co-adding four individual exposures, have a pixel spacing (≈1/2 diode width) of 18 mÅ (=4.5 km s⁻¹) for the 1172–1209 and 1245–1285 Å regions. By contrast, the full
width of a rotationally broadened line is 1.6 Å (corresponding to ±200 km s\(^{-1}\)), or ~90 pixels. Since the data are highly oversampled, we have reduced the photon noise by smoothing the observed spectra in the following manner. A low-order (usually cubic) polynomial was used to smoothly interpolate across the gaps in the spectrum left after removal of the wind lines. This is necessary since the Fourier transform requires that the input spectrum consist of equally spaced data points. The smoothing procedure is insensitive to the choice of interpolating function as long as the function and its slope are smoothly varying (discontinuities in these quantities could introduce artifacts outside the region of the wind line gaps, since the Fourier transform of a step function has power at all frequencies). Next, a parabola passing through the endpoints of the spectrum, and roughly following the trend of the spectrum elsewhere, was subtracted from the spectrum. The resulting detrended (= original − parabola) spectrum, which is zero at both endpoints, was fast Fourier transformed and filtered in the Fourier domain with a cosine bell filter (Gray 1992) to 7.3% of the Nyquist frequency. This cutoff frequency corresponds to a spatial resolution of 13.7 pixels. The filtered Fourier spectrum was then inverse transformed, and the parabolic trend added back to produce the final smoothed data spectrum. The filtered spectra have seven independent data points within each rotationally broadened line profile. Inspection of the power spectra of the original data showed only white noise above the spatial frequency cutoff of the cosine bell filter. Similarly, inspection of the smoothed spectra in the wavelength domain showed that the B star photospheric features were faithfully reproduced. We plot these smoothed photospheric spectra (interpolated across the wind line gaps) superimposed on the original GHRS spectra (with the wind lines removed) for the 1172–1209 and 1245–1285 Å regions in Figures 2b and 3b, respectively. In these figures the principal absorption features have been identified. For the elements C, N, O, S, and Si, the labeled multiplet structure is essentially
complete, but this is not true for Fe. There are many weak Fe II lines not shown in Figures 2b and 3b: we have chosen to show only those Fe II lines with equivalent widths (as calculated in the final model synthetic spectrum) greater than 15 mÅ.

We followed a similar smoothing procedure for the Griffin spectrum, except these data were smoothed to 4.2% of the Nyquist frequency. The smoothed Griffin spectrum in the region of the He and He I 4026 Å lines is shown superimposed on the original spectrum in Figure 4a. The analogous plot in the region of the Balmer series limit, 3650–3950 Å, is shown in Figure 4b.

One expects a reduction in the noise (when photon counting statistics are valid) which is proportional to the square root of the number of pixels smoothed (here, $13.71^{1/2} \approx 3.7$). To verify this, we conducted numerical experiments in which Poisson noise was smoothed by the previously described Fourier filter. The standard deviations of the original and smoothed data sets were compared, and were found to be well described by a function of the form

$$\frac{\sigma_{\text{GHR}}}{{\sigma}_{\text{sm}}} = 1.10 f_{\text{Nq}}^{-1/2} + 0.14,$$

where $f_{\text{Nq}}$ is the cosine bell filter cutoff frequency expressed as a fraction of the Nyquist frequency, and the $\sigma$ variables represent the respective standard deviations. We used equation (1) to calculate the standard error ($\sigma_{\text{sm}}$) and S/N of the smoothed spectra from the error estimates of the original GHRs data ($\sigma_{\text{GHRs}}$). The statistical error of the GHRs data were calculated by the standard HST reduction software assuming Poisson statistics. The error estimates of the smoothed data are used to estimate the standard errors in the model parameters $T_{\text{eff}}$, log $g$, and $v \sin i$ determined by least-squares fitting.

3. MODELS

We have computed nonlocal thermodynamic equilibrium (non-LTE) model atmospheres of $\zeta$ Aur B using the TLUSTY code of Hubeny (1988), updated as described in Hubeny & Lanz (1992). Synthetic spectra were produced for converged models using the SYNSPEC code kindly supplied by I. Hubeny. We used the atomic line list of Kurucz (1990) for the computation of our synthetic spectra. The models computed in this initial investigation treated the continua of hydrogen and helium in non-LTE, but with the lines of H and He assumed to be in detailed radiative balance (non-LTE/C H-He models). The accuracy of these models was verified by computing a small number of models with the lines of hydrogen and neutral helium taken explicitly in non-LTE (non-LTE/L H-He models). We also examined the effect of metal bound-free edges on the spectrum by computing a non-LTE/C H-He, LTE C-Mg-Si-S-Ca model for the best-fit stellar parameters of $T_{\text{eff}} = 15,400$ K, and log $g = 3.9$. Finally, we computed a more elaborate non-LTE H-He-C model for these stellar parameters in order to examine more closely the non-LTE effects present in the spectrum of neutral carbon.

The default specifications in TLUSTY were generally used for the atomic data for hydrogen and helium. In particular, the bound-free and free-free cross sections of hydrogen were calculated using the exact expression with the exact Gaunt factors. The corresponding He I cross sections were based on cubic fits to Opacity Project results. Collisional rates for H and He I were calculated from the approximate expressions of Mihalas, Auer, & Heasley (1975). Other specifications were input as the default options as described in Hubeny (1988). Line blanketing due to atomic (mainly Fe) lines in the ultraviolet was not included in the model computations, although these lines were included in the subsequent synthetic spectrum calculations.

The non-LTE/C H-He models were computed for $T_{\text{eff}} = 13,000$ to $17,000$ K in increments of $500$ K and from $17,000$ to $22,000$ K in increments of $1000$ K, for a range of gravities from log $g = 2.7$ to $4.6$ (cgs) in increments of $0.3$, and a microturbulent velocity of $v = 0$ km s$^{-1}$. These models were computed with the bound-free continua of the first 5 levels of H and 14 levels of He I treated explicitly in non-LTE. Spectral lines were assumed to be in detailed radiative balance. The standard Holtmark profile was used to calculate the Lyman $\alpha$ profile. Solar metallicities were adopted throughout. In particular, for the key elements C and Si, we used C/H $= 3.68 \times 10^{-4}$ and Si/H $= 3.51 \times 10^{-5}$. For each value of $T_{\text{eff}}$ and log $g$ we first computed an LTE model, which was then used as a starting estimate to compute the non-LTE/C H-He models. The B star spectrum is broadened by rotation; we
The effective temperature determination used the epoch 1 spectrum at 1172–1209 Å and the epoch 6 exposure at 1245–1285 Å, where the spectrum is dominated by photospheric absorption in the B star, and not by wind lines from intervening circumstellar material. The B star spectrum in these regions is dominated by the resonance lines of Si II at 1190–1197 Å (UV 5) and 1260–1265 Å (UV 4), the resonance line of Si III at 1206 Å (UV 2) and the C III multiplet at 1175 Å (UV 4). The resonance lines of S III at 1201–1202 Å are also seen in the photospheric spectrum, although much weaker than the C and Si multiplets. For the mid through late B stars, the Si II lines weaken while the C III lines strengthen with increasing temperature. In principle, this behavior should make the Si II (Massa 1989) and C III lines excellent temperature indicators. The strong UV Si II lines are generally considered insensitive to non-LTE effects, unlike the optical silicon lines (Kamp 1978; Massa 1989). Recently, Singh & Castelli (1992) have demonstrated the utility of the autoionizing lines of the UV multiplet 13.04 of Si II (1305–1309 Å) for the determination of the effective temperature. Unfortunately, these lines were not included in the spectral regions observed.

The synthetic spectrum calculated from the non-LTE/C H-He models for each effective temperature was compared to the reduced GRS spectrum (after removal of wind lines and Fourier smoothing). A stackplot of these spectra for the 1127–1209 Å spectral region is shown in Figure 5a, and the corresponding plot for the 1245–1285 Å region is shown in Figure 5b. The comparison of the models with the Griffin spectrum for the 3940–4060 Å region is shown in Figure 5c. The effective temperature, \( T_{\text{eff}} \), was then determined by selecting the model effective temperature which gave the best fit in a least-squares sense.

The fitting was done in a systematic manner by calculating an overall residual, or root-mean-square deviation, \( \epsilon \), between the observed and computed spectra for each model temperature. We define \( \epsilon \) as

\[
\epsilon^2 = \frac{1}{N} \sum_{i=1}^{N} w_i [(F_i - \epsilon F_i) - s F_i^\text{obs}]^2 ,
\]

where \( N \) is the number of data points considered (the model fluxes are interpolated to the data wavelengths), \( w_i = 1/\sigma_i^2 \) are the assigned weights, \( F_i^\text{obs} \) are the fluxes observed by the GRS, \( F_i^\text{mod} \) are the model fluxes (calculated at the stellar surface) and interpolated to the wavelengths of the GRS pixels, and \( s \) is the scale factor relating the observed and computed fluxes (\( s \) depends upon the stellar angular diameter and the interstellar extinction). The error estimates \( \sigma_i \) are the errors obtained from equation (1) for the Fourier-smoothed GRS data. The value of \( s \) was determined by a least-squares fit. The Griffin's optical data is normalized to the continuum and, in this case, we calculated the residual by

\[
\epsilon^2 = \frac{1}{N} \sum_{i=1}^{N} w_i [(F_i^\text{obs} - (s + \lambda_i t) F_i^\text{mod})^2 ,
\]

where the parameters \( s \) and \( t \) are determined by a least-squares fit of \( F_i^\text{mod} \) to \( F_i^\text{obs} \) (here the Griffin spectrum), and \( \lambda_i \) is the wavelength of the \( i \)th data point. This transforms the fluxed model spectrum with a sloping continuum to match the Griffin data, which have been rectified to a flat continuum. A parabola was then fitted through the residuals as a function of model temperature, and the location of the minimum was taken to be the effective temperature.

A good match of the synthetic and observed spectra could not be obtained for any single value of model effective temperature \( T_{\text{eff}} \). Fits to the Si II UV 4 (1260–1265 Å) and UV 5 (1190–1197 Å) resonance multiplets yielded consistently higher values of \( T_{\text{eff}} \) than did fits to other spectral features. We display the residual \( \epsilon \), calculated over the vicinity of the C III 1175 Å line, the Si III 1206 Å line, and the He and H II 4026 Å lines, as a function of effective temperature in Figure 6a. The residuals for the Si II UV 4 and 5 multiplets are plotted as a function of effective temperature in Figure 6b. The effective temperatures weaken while the C III lines strengthen with increasing temperature. In principle, this behavior should make the Si II (Massa 1989) and C III lines excellent temperature indicators. The strong UV Si II lines are generally considered insensitive to non-LTE effects, unlike the optical silicon lines (Kamp 1978; Massa 1989). Recently, Singh & Castelli (1992) have demonstrated the utility of the autoionizing lines of the UV multiplet 13.04 of Si II (1305–1309 Å) for the determination of the effective temperature. Unfortunately, these lines were not included in the spectral regions observed.

The synthetic spectrum calculated from the non-LTE/C H-He models for each effective temperature was compared to the reduced GRS spectrum (after removal of wind lines and Fourier smoothing). A stackplot of these spectra for the 1172–1209 Å spectral region is shown in Figure 5a, and the corresponding plot for the 1245–1285 Å region is shown in Figure 5b. The comparison of the models with the Griffin spectrum for the 3940–4060 Å region is shown in Figure 5c. The effective temperature, \( T_{\text{eff}} \), was then determined by selecting the model effective temperature which gave the best fit in a least-squares sense.

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\]

where \( N \) is the number of data points considered (the model fluxes are interpolated to the data wavelengths), \( w_i = 1/\sigma_i^2 \) are the assigned weights, \( F_i^\text{obs} \) are the fluxes observed by the GRS, \( F_i^\text{mod} \) are the model fluxes (calculated at the stellar surface) and interpolated to the wavelengths of the GRS pixels, and \( s \) is the scale factor relating the observed and computed fluxes (\( s \) depends upon the stellar angular diameter and the interstellar extinction). The error estimates \( \sigma_i \) are the standard errors \( \sigma_i \) obtained from equation (1) for the Fourier-smoothed GRS data. The value of \( s \) was determined by a least-squares fit. The Griffin's optical data is normalized to the continuum and, in this case, we calculated the residual by

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\epsilon^2 = \frac{1}{N} \sum_{i=1}^{N} w_i [(F_i^\text{obs} - (s + \lambda_i t) F_i^\text{mod})^2 ,
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where the parameters \( s \) and \( t \) are determined by a least-squares fit of \( F_i^\text{mod} \) to \( F_i^\text{obs} \) (here the Griffin spectrum), and \( \lambda_i \) is the wavelength of the \( i \)th data point. This transforms the fluxed model spectrum with a sloping continuum to match the Griffin data, which have been rectified to a flat continuum. A parabola was then fitted through the residuals as a function of model temperature, and the location of the minimum was taken to be the effective temperature.

A good match of the synthetic and observed spectra could not be obtained for any single value of model effective temperature \( T_{\text{eff}} \). Fits to the Si II UV 4 (1260–1265 Å) and UV 5 (1190–1197 Å) resonance multiplets yielded consistently higher values of \( T_{\text{eff}} \) than did fits to other spectral features. We display the residual \( \epsilon \), calculated over the vicinity of the C III 1175 Å line, the Si III 1206 Å line, and the He and H II 4026 Å lines, as a function of effective temperature in Figure 6a. The residuals for the Si II UV 4 and 5 multiplets are plotted as a function of effective temperature in Figure 6b. The effective temperatures weaken while the C III lines strengthen with increasing temperature. In principle, this behavior should make the Si II (Massa 1989) and C III lines excellent temperature indicators. The strong UV Si II lines are generally considered insensitive to non-LTE effects, unlike the optical silicon lines (Kamp 1978; Massa 1989). Recently, Singh & Castelli (1992) have demonstrated the utility of the autoionizing lines of the UV multiplet 13.04 of Si II (1305–1309 Å) for the determination of the effective temperature. Unfortunately, these lines were not included in the spectral regions observed.

The synthetic spectrum calculated from the non-LTE/C H-He models for each effective temperature was compared to the reduced GRS spectrum (after removal of wind lines and Fourier smoothing). A stackplot of these spectra for the 1172–1209 Å spectral region is shown in Figure 5a, and the corresponding plot for the 1245–1285 Å region is shown in Figure 5b. The comparison of the models with the Griffin spectrum for the 3940–4060 Å region is shown in Figure 5c. The effective temperature, \( T_{\text{eff}} \), was then determined by selecting the model effective temperature which gave the best fit in a least-squares sense.

The fitting was done in a systematic manner by calculating an overall residual, or root-mean-square deviation, \( \epsilon \), between the observed and computed spectra for each model temperature. We define \( \epsilon \) as

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\epsilon^2 = \frac{1}{N} \sum_{i=1}^{N} w_i [(F_i^\text{obs} - s F_i^\text{mod})^2 ,
\]

where \( N \) is the number of data points considered (the model fluxes are interpolated to the data wavelengths), \( w_i = 1/\sigma_i^2 \) are the assigned weights, \( F_i^\text{obs} \) are the fluxes observed by the GRS, \( F_i^\text{mod} \) are the model fluxes (calculated at the stellar surface) and interpolated to the wavelengths of the GRS pixels, and \( s \) is the scale factor relating the observed and computed fluxes (\( s \) depends upon the stellar angular diameter and the interstellar extinction). The error estimates \( \sigma_i \) are the standard errors \( \sigma_i \) obtained from equation (1) for the Fourier-smoothed GRS data. The value of \( s \) was determined by a least-squares fit. The Griffin's optical data is normalized to the continuum and, in this case, we calculated the residual by

\[
\epsilon^2 = \frac{1}{N} \sum_{i=1}^{N} w_i [(F_i^\text{obs} - (s + \lambda_i t) F_i^\text{mod})^2 ,
\]
obtained from the model fits to these lines are summarized in Table 2.

At higher temperatures, the model C III lines become unacceptably strong, while for cooler temperatures the same is true for the Si II resonance lines. It is thus impossible to reproduce the correct line strengths for both C III and Si II simultaneously with the current models. From Table 2, we see that the effective temperature inferred from the Si II lines ($T_{\text{eff}} \approx 20,000$ K) is ~4500 K hotter than that derived from the other spectral features ($T_{\text{eff}} \approx 15,400$ K).

This is suggestive of a departure from LTE in the Si II level populations, and in § 4.3 we empirically determine a departure coefficient for the Si II ground state consistent with the effective temperatures derived from the other spectral lines. Therefore, we exclude the Si II lines from consideration and adopt as the effective temperature the weighted mean of the estimates found by fitting the other spectral lines to the models. We find $T_{\text{eff}} = 15,400 \pm 300$ K for $\zeta$ Aurigae. Using the effective temperature calibration of Underhill et al. (1979), we obtain a spectral type of B5.

4.2. C I Lines

It is apparent from Figure 5b that the C I resonance lines at 1277–1281 Å (UV multiplets 5, 6, and 7) are much weaker in the observed spectrum than predicted by the models. This is

Fig. 5.—(a) Stackplot of model spectra as a function of $T_{\text{eff}}$ for the 1172–1209 Å region. The observed photospheric spectrum of $\zeta$ Aur is also shown. (b) Stackplot of model spectra as a function of $T_{\text{eff}}$ for the 1245–1285 Å region. The observed photospheric spectrum of $\zeta$ Aur is also shown. (c) Stackplot of model spectra as a function of $T_{\text{eff}}$ for the 3940–4060 Å region. The observed photospheric spectrum of $\zeta$ Aur is also shown.
not due to a nonsolar carbon abundance since the C III 1175 Å multiplet is well fitted by the present models. The weakness of these lines almost certainly results from a classical non-LTE effect described by Snijders (1977) in his non-LTE models of C i. The shift in ionization balance toward C ii is driven by radiative ionization directly from the 3 P ground state with a photoionization threshold at 1101 Å, and from the low-lying 1 D and 1 S metastable states, with thresholds at 1240 and 1445 Å, respectively. Snijders showed that C i is always underabundant in B main-sequence stars compared to LTE; he found typical departure coefficients for the 3 P ground-state populations of log b = −1.5 to −2 in the line-forming region. In our discussion of departure coefficients, we use the definition

\[ b \equiv n_i / n_i^* , \]

where \( n_i \) is the population of the level \( i \), and \( n_i^* \) is the corresponding level population calculated assuming LTE, relative to the population of the ground level of the next highest ionization stage.

**Fig. 6b**

(a) Plot of fit residual (rms deviation between model and observed spectrum) as a function of effective temperature \( T_{\text{eff}} \), calculated in the neighborhood of various absorption lines (excluding Si ii). Left panel: the C iii 1175 Å multiplet. Center panel: the Si iii (UV 2) 1206 Å line. Right panel: the He i 3970 Å and He i 4026 Å lines. Points plotted as crosses were not included in the least-squares parabola fit. The positions of the residual minima, giving the best-fit value of \( T_{\text{eff}} \) for each line, are labeled.

(b) Plot of fit residual (rms deviation between model and observed spectrum) as a function of effective temperature \( T_{\text{eff}} \), calculated in the neighborhood of the Si ii resonance lines. Left panel: the Si ii (UV 5) 1190–97 Å multiplet. Right panel: the Si ii (UV 4) 1260–65 Å multiplet. Points plotted as crosses were not included in the least-squares parabola fit. The positions of the residual minima, giving the best-fit value of \( T_{\text{eff}} \) for each line, are labeled.
TABLE 2

<table>
<thead>
<tr>
<th>Spectral Line(s) Fitted</th>
<th>( T_{eff} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C ii 1175 Å</td>
<td>15675 ± 162</td>
</tr>
<tr>
<td>Si ii (UV 5) 1190–1197 Å</td>
<td>20945 ± 185</td>
</tr>
<tr>
<td>Si ii (UV 4) 1260–1265 Å</td>
<td>19603 ± 98</td>
</tr>
<tr>
<td>Si ii 1206 Å</td>
<td>14632 ± 345</td>
</tr>
<tr>
<td>He, He i 4026 Å</td>
<td>15286 ± 447</td>
</tr>
<tr>
<td>Weighted mean</td>
<td>15467 ± 139</td>
</tr>
<tr>
<td>Adopted value</td>
<td>15400 ± 300</td>
</tr>
</tbody>
</table>

TABLE 3

<table>
<thead>
<tr>
<th>Spectral Line(s) Fitted</th>
<th>( \log b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C ii 1277–1281 Å</td>
<td>1.84 ± 0.11</td>
</tr>
<tr>
<td>Si ii (UV 5) 1190–1197 Å</td>
<td>1.26 ± 0.05</td>
</tr>
<tr>
<td>Si ii (UV 4) 1260–1265 Å</td>
<td>0.85 ± 0.04</td>
</tr>
<tr>
<td>Si ii 1206 Å</td>
<td>0.63 ± 0.19</td>
</tr>
<tr>
<td>Weighted mean C ii</td>
<td>1.84 ± 0.11</td>
</tr>
<tr>
<td>Weighted mean Si ii</td>
<td>1.00 ± 0.03</td>
</tr>
<tr>
<td>Adopted value C ii</td>
<td>1.84 ± 0.11</td>
</tr>
<tr>
<td>Adopted value Si ii</td>
<td>1.00 ± 0.20</td>
</tr>
<tr>
<td>Adopted value Si iii</td>
<td>0.15 ± 0.10</td>
</tr>
</tbody>
</table>

We have empirically determined departure coefficients for the C ii ground state by matching the computed synthetic spectrum to the observed GHRS spectrum in the 1277–1281 Å region. A least-squares fitting technique analogous to that used for the effective temperature determination was used. We mimicked the presence of a non-LTE departure coefficient (i.e., differing from unity) by scaling the oscillator strengths of all spectral lines from transitions belonging to that ionization stage. Since the same correction is applied to all lines of a given ionization stage, the procedure is equivalent to assuming the departure coefficients of all levels of the ion are equal. This will not be true in general since the high-lying levels become collisionally coupled to the continuum for large values of the principal quantum number \( n \). However, it will approximate the behavior of low-lying levels coupled to the ground state of an ion for which photoionization is important, as is the case for neutral carbon.

In Figure 7a we show the observed GHRS spectrum of the 1245–1285 Å region containing the C ii 1277–1281 Å lines, and synthetic spectra calculated for various empirical C ii departure coefficients. A plot of the fit residual as a function of the C ii departure coefficient for the 1277–1281 Å multiplets appears in Figure 7c. From the minimum of the residual, we determine the departure coefficient to be \( \log b = 1.84 ± 0.11 \) (see Table 3), a result consistent with the non-LTE study of Snijders (1977).

To understand why this empirical method of determining departure coefficients works, we consider the non-LTE line formation process. The line absorption coefficient for a transition \( \kappa_\lambda \) from lower level \( i \) to upper level \( j \) is (Mihalas 1978)

\[
\kappa_\lambda(v) = n_i B_{ij} \frac{h \nu_{ij}}{4\pi} \phi_v \left( 1 - \frac{n_j}{n_i} \frac{g_i}{g_j} \right),
\]

where \( \phi_v \) is the line profile, \( g_i, g_j \) are the statistical weights and \( B_{ij} \) is the Einstein coefficient. Using the definitions of equation (4) and the Boltzmann distribution to describe the LTE populations \( n_i^*, n_j^* \), we obtain

\[
\kappa_\lambda(v) = b_i \frac{n_i^* B_{ij} \nu_{ij}}{4\pi} \phi_v \left( 1 - \frac{b_j}{b_i} \exp \left( - \frac{h \nu_{ij}}{kT} \right) \right)
\approx b_i \frac{n_i^* B_{ij} \nu_{ij}}{4\pi} \phi_v.
\]

The above approximation follows since the exponential term (the stimulated emission term) is extremely small in the Wien regime (\( h \nu_{ij}/kT \gg 1 \)). Then, the non-LTE line absorption coefficient is proportional to the product of the LTE value and the departure coefficient of the lower (in this case, ground) state.

The non-LTE line source function assuming complete redistribution (CRD) is

\[
S_i = \frac{2h \nu_{ij}^2}{c^2} \left[ \frac{b_j}{b_i} \exp \left( \frac{h \nu_{ij}}{kT} \right) - 1 \right]^{-1} = \frac{b_j}{b_i} B_i,
\]

where the approximation holds in the Wien limit (\( B_i \) is the Planck function). In our empirical approximation, \( b_j/b_i = 1 \) for all transitions and there is no change from the LTE source function. The emergent flux can be approximated by means of an Eddington-Barbier relation (cf. Gray 1992) as \( F_\lambda(v = 0) \approx S_\lambda(v = \tau_1) \), where \( \tau_1 \) is of order unity. Let \( m_i \) and \( m_j \) denote the formation depth in column-mass units of the non-LTE line and continuum, respectively. Then, the line profile (or ratio of line to continuum flux)

\[
F_\lambda \approx \frac{S_\lambda(v = \tau_1)}{S_\lambda(v = \tau_1) \approx \frac{b_j}{b_i} B_i(m_j)},
\]

where we assume the continuum source function \( S_\lambda = B_i(m_j) \). Switching from LTE to non-LTE radiative transfer changes the line profile in two ways: (1) the line opacity, and therefore formation depth, varies as \( b_j \) (eq. [6]), and (2) the source function varies as \( b_j/b_i \) (eq. [7]). Our empirical procedure correctly accounts for the first effect, but ignores the second. In fact, the first effect dominates in the formation of the C ii 1280 Å lines, since \( B_i(m_j) \approx B_i(11,000 \text{ K}) \) while \( B_j(m_j) \approx B_j(17,000 \text{ K}) \), and therefore \( B_i(11,000 \text{ K})/B_j(17,000 \text{ K}) \approx 0.01. \) By contrast, the ratio of departure coefficients \( b_j/b_i \approx 5 \) (Fig. 7d) in the line-forming region. The dominant effect is therefore the weakening of the lines (by about a factor of 20) due to the increased depth of formation as a result of reduced absorption from the ground state. Our empirical method of analysis is able to mimic this effect quite well.

Finally, we confirm the validity of our empirical approach by comparing the empirically determined departure coefficients with those computed from the non-LTE H-He-C model. We show the computed departure coefficients of the C ii 2p-3p ground state and the 4s3p4p state (the upper level of the UV 5 multiplet at 1280 Å) as a function of depth in Figure 7d. The computed value of \( \log b \) for both is about 1.8 in the line-forming region (at a column mass of log \( m = -1.6 \), in good agreement with the empirical value. A comparison of the observed GHRS spectrum, the spectrum computed from the non-LTE/C H-He, LTE C model with empirically determined departure coefficients, and the synthetic spectrum computed from the non-LTE H-He-C model is shown below in Figure 16. All are in good agreement.
Fig. 7a.—(a) Stackplot of model spectra as a function of empirical C i departure coefficient for the 1245–1285 Å region. The observed photospheric spectrum of ζ Aur is also shown. (b) Stackplot of model spectra as a function of empirical Si iii departure coefficient for the 1172–1209 Å region. The observed photospheric spectrum of ζ Aur is also shown. (c) Plot of fit residual (rms deviation between model and observed spectrum) as a function of empirical departure coefficients. Left panel: b(C i) for the UV 5, 6, and 7 (1277–81 Å) multiplets. Right panel: b(Si iii) for the UV 2 1206 Å line. Points plotted as crosses were not included in the least-squares parabola fit. The position of the residual minima, giving the best-fit values of the departure coefficients, are labeled. (d) Plot showing the theoretical C ideparture coefficients, computed from the non-LTE H-He-C model described in the text, for the 2p^3 P ground state and the 4s^3 P^o state. The transitions connecting these levels form UV multiplet 5 near 1280 Å. The depths of formation of the 1280 Å lines and of the continuum are also indicated.
4.3. Si II Lines

We have shown that the predicted LTE Si II line profiles computed for a non-LTE H-He atmosphere can not reproduce the observed ζ Aur Si II resonance line profiles. Unlike C II however, the observed weakness of Si II is much more troublesome. The spectral lines of Si II are one of the major diagnostics (the lines of Fe II being the other important diagnostic) in our study of the circumstellar environment of ζ Aur. It is essential that the photospheric spectrum be well understood since this spectrum serves as a boundary condition to the radiative transfer problem in the wind lines. Our current models do not include line blanketing in the calculation of the atmospheric structure, although the computed synthetic spectra do include a reasonably complete line list. Line-blanketed models should have lower photoionization rates that would tend to counter non-LTE effects. Although future models should include line blanketing, it seems unlikely that this omission can explain the apparent weakness of Si II. Therefore, we turn to other possible causes of the weakness of the Si II lines and examine each in turn.

4.3.1. Anomalous Abundance

The only definitely observed line of Si III (UV 2 at 1206 Å) appears to be well fitted by LTE-Si models of solar abundance. We have computed synthetic spectra of the 1170–1210 Å region with the Si III abundance varied to simulate possible abundance or non-LTE effects. For this study, the Si II abundance was held fixed at the empirically determined value of log b(Si II) = −1.00 required to bring the model spectrum into agreement with observation (see § 4.3.4). Synthetic spectra computed as a function of the empirical Si III departure coefficient, along with the observed GHRS spectrum of ζ Aur, are shown in Figure 7b. The root-mean-square deviation, or residual, of the synthetic spectrum from the observed GHRS spectrum was calculated for each value of the Si III abundance. A plot of this residual versus Si III abundance (presented as a departure coefficient from the LTE abundance) appears in Figure 7c. The abundance for which the residual is minimized is taken to be the empirically determined Si III abundance. We find log b(Si III) = +0.15.

If the weakness of the Si II lines was due solely to an abundance effect, then we would expect the Si III lines to show a similar behavior. Instead, we find the Si III abundance to be a factor of 15 (=1.15 dex) greater than the Si II abundance. Thus, we can eliminate abundance effects as the source of the anomalous Si II line strengths. This is consistent with observational evidence that the silicon abundance of normal B stars is solar (e.g., Kamp 1978, 1982), and consistent with theoretical expectations that the atmospheric abundance of silicon in normal B stars should remain constant through their main-sequence lifetimes.

We show below in § 4.3.4 that the Si III anomaly is best explained as a non-LTE effect, in which Si III has been overionized compared to LTE. The Si III abundance determined from the 1206 Å line supports the non-LTE origin of the Si II anomaly, since this mechanism would predict an enhancement of Si III relative to LTE solar abundances, which is exactly what is observed. However, we must first consider (and exclude) other possible causes.

4.3.2. Circumstellar Emission

It is possible that diffuse circumstellar emission from resonance scattering in the circumstellar wind could produce a broad component as well as the observed narrow P Cygni wind features. For example, the UV 1 and UV 3 resonance multiplets of Fe II observed by the GHRS at epochs 1 and 6 show pronounced emission humps with a velocity dispersion of ~60 km s⁻¹ superimposed on relatively narrow (Doppler width ~15 km s⁻¹) absorption cores. We show the GHRS observations of the Fe II UV 3 lines in Figure 8. The corresponding Fe II photospheric features are quite weak, and it is this lack of an intrinsic stellar feature that makes the circumstellar emission visible.

By contrast, the photospheric Si II resonance lines are strong features, upon which are superimposed interstellar and narrow (≤12 km s⁻¹) circumstellar absorption cores which sometimes show an associated P Cygni emission feature (see Figs. 2a and 3a). In order to compare the observed spectra with the computed models, the circumstellar and interstellar features have been removed as described in § 2. Nevertheless, broad circumstellar emission, as observed for the Fe II resonance lines, could not easily be distinguished from the underlying stellar feature. The resulting profile might appear stellar, but weaker than expected due to infilling of the profile by the circumstellar emission.

However, we do not believe that infilling of the photospheric profiles by resonance scattering in the wind is significant for Si II. We later examine the possibility that the weakness of

![Graphs showing spectral profiles and wavelengths](https://example.com/graphs.png)

**Fig. 8.** Plot showing the spectrum of ζ Aur observed with the GHRS in the region of the Fe II UV 3 resonance lines at several observation epochs (for dates see Table 1). Wavelengths are in vacuum.
the Si \( \pi \) lines is an non-LTE effect, as is the case for C \( \pi \). When we fit a departure coefficient for the Si \( \pi \) ionization fraction (see § 4.3.4), in the same way as was done for C \( \pi \), the synthetic spectra computed from the non-LTE/C H-He models with empirically scaled Si \( \pi \) abundances are found to be in good agreement with the observed GHRS spectra. In the determination of \( \nu \) sin \( i \) (see § 4.4), the stellar lines are fitted to a rotationally broadened model profile; the same value of \( \nu \) sin \( i \) was found whether the Si \( \pi \) resonance lines were included or excluded from the profile fitting. This would not be the case if these lines were significantly infilled by wind scattering, since it is improbable that the circumstellar emission profile would match the rotationally broadened stellar profile. Therefore, the broad component of the Si \( \pi \) lines, as opposed to the obvious narrow P Cygni feature due to resonance line scattering in the circumstellar wind, is almost certainly an intrinsic photospheric feature.

Additional confirmation that diffuse circumstellar Si \( \pi \) emission is unimportant is provided by the stellar absorption features observed at 1247 and 1250 Å. The first feature is a blend of the C \( \pi \) UV 9 line at 1247.38 Å and the weaker Si \( \pi \) UV 8 multiplet transitions at 1246.74 and 1248.43 Å (Fig. 3b). The second feature is a blend of the two lines of the weakly autoionizing Si \( \pi \) multiplet UV 13.05 at 1250.09 and 1250.43 Å, the remaining line of Si \( \pi \) UV 8 at 1251.16 Å, and a weaker line of the S \( \pi \) resonance multiplet UV 1 at 1250.50 Å. The circumstellar wind lines overlying the photospheric feature are due to this latter Si \( \pi \) line. However, the contribution of this Si \( \pi \) line at 1250.50 (the 3/2 – 3/2 component) to the photospheric spectrum is small, since this line has only the half intrinsic strength of the unblended 3/2 – 3/2 component seen weakly in the photospheric spectrum at 1253.79 Å. The S \( \pi \) lines cannot make a significant contribution to any diffuse circumstellar emission either, because then a broad emission feature would be expected at 1254 Å (instead of the narrow emission peak observed). All of the Si \( \pi \) lines contributing to the stellar 1247 and 1250 Å blends come from transitions with lower levels above the ground state, and this is also true of the C \( \pi \) line. Since these excited levels have very small populations in the circumstellar environment, wind scattering in these lines should be negligible. We conclude that line scattering by the circumstellar wind in the 1247 and 1250 Å lines contributes negligibly to the observed photospheric features.

Nevertheless, the observed absorption features at 1247 and 1250 Å are considerably weaker than the non-LTE/C-H-He model predictions, although this weakening is less than that observed for the Si \( \pi \) resonance lines. When the Si \( \pi \) departure coefficient, empirically determined in § 4.3.4 from the UV 4 and 5 resonance multiplets, is used to compute synthetic spectra from the non-LTE/C H-He synthetic spectrum, the resulting 1247 and 1250 Å line profiles are found to be in reasonable agreement with the observed spectrum, although these lines were not included in the determination of the departure coefficients. The weakness of the 1247 and 1250 Å lines suggests a general underpopulation of the levels of Si \( \pi \) is present. This is exactly the result to be expected if Si \( \pi \) were overionized with respect to LTE, and for these two lines (1247, 1250 Å) at least, this result can not be explained in terms of circumstellar emission.

On the basis of the preceding arguments, we conclude that the observed profiles of the Si \( \pi \) resonance lines (after the removal of the obvious P Cygni wind lines), and the blended but predominantly Si \( \pi \) lines at 1247 and 1250 Å, are intrinsically photospheric features.

4.3.3. Continuous Opacity

Another possible cause of line weakening would be the use of an incorrect or incomplete continuous opacity in our models. The great width of resonance lines is due to the slow decay of the Lorentzian damping wings with distance from line center. A reduction in the continuous opacity means that the spectrum is formed in the damping wings at greater displacements from line center. Conversely, a high continuous opacity means that the continuum will dominate closer to line center, and the line profiles will appear narrower. If the continuous opacity is sufficiently high compared to the line strength, the depth of spectrum formation in the damping wings will lie below the continuum everywhere and only the narrow Doppler core of the line will be observed. The Doppler line width is very nearly independent of the line optical depth, and therefore, the observed equivalent width of lines of moderate strength will be insensitive to the assumed value of the continuous opacity. The equivalent width of strong lines, by contrast, is sensitive to the continuous opacity.

The continuous opacity of B stars in the ultraviolet is dominated by the Balmer continuum of hydrogen. However, this opacity falls steadily with decreasing wavelength until the Lyman limit at 912 Å is reached. Bound-free opacities from metals generally increase with decreasing wavelength as more low-lying levels become accessible for photoionization. Since the non-LTE/C H-He models include only the bound-free opacity of H and He, it is possible that we systematically underestimate the actual continuous opacity due to the lack of metals. An omission of continuous opacity would result in an apparent increase in the equivalent widths of strong lines. This effect could conceivably account for the observed strength of the Si \( \pi \) resonance lines, especially for the UV 5 multiplet at 1190–1197 Å.

To address these concerns, we first computed the non-LTE H-He, LTE C-Mg-Si-S-Ca model described previously. This model showed that including these metals resulted in an increase in the continuous opacity at 1200 Å, mostly due to C \( \pi \), although the Balmer continuum still dominates. The resulting synthetic spectrum, although showing weaker Si \( \pi \) lines, was not in good agreement with the observations. The Lyman \( \alpha \) profile also weakened considerably, and if correct, would result in a conflict with the Balmer profiles, and the C \( \pi \) profile (well fitted by the models without metals) varied as well. The most serious omission in this model is Fe \( \pi \). Although Fe \( \pi \) has a large number of bound-free edges in the far ultraviolet, most lie shortward of 1150 Å and do not directly affect the synthetic spectra in our regions of interest.

However, as discussed in § 4.2, we expect non-LTE effects to considerably reduce the importance of neutral carbon, both in formation of the line spectrum and of the bound-free continuum. We confirmed this conclusion by examining the more detailed non-LTE H-He-C model described previously in § 3. From this model, we find that the major sources of continuous opacity at 1220 Å were the H Balmer continuum (accounting for 62% of the total continuous opacity), electron scattering (19%), the H Paschen continuum (4.7%), and the C \( \pi \) 1 \( D \) continuum (1.9%). Shortward of the 1101 Å edge (outside of the spectral region observed by the GHRS), the C \( \pi \) 3 \( P \) ground state accounts for 14% of the continuous opacity. These computations rule out missing continuous opacity as the cause of the weakness of the Si \( \pi \) lines.

Missing opacity would affect not only Si \( \pi \) but also other lines of moderate strength such as Si \( \pi \), which is not observed.
to be weakened relative to the model predictions. Furthermore, we are able to obtain synthetic spectra which are in excellent agreement with observations by varying the Si II abundance alone. This suggests the problem lies directly with the formation of the Si II lines.

4.3.4. Non-LTE Effects

Non-LTE model studies of silicon in B stars (Kamp 1978; Lennon et al. 1986; Grigsby 1991) show that the Si II resonance lines are formed essentially in LTE. Photoionization is less important for Si II since the thresholds for the thermally populated lower levels lie in the Lyman continuum where the stellar flux is orders of magnitude smaller than at 1200 Å. The threshold for photoionization from the \(2p^2\) ground state is 759 Å, a region of little stellar flux. The metastable \(2p^1\) state lies 5.33 eV above the ground state and would have a population only 1.4% of that of the ground state in LTE at 12,400 K (=0.78 T_eff). The \(2p^1\) state ionizes to the metastable \(2p^2\) state of Si III, with a photoionization threshold at 705 Å. The next lowest states, \(3p^2D\) and \(4s^2S\), have thresholds at 1307 and 1507 Å where the stellar flux is significant and are the lowest states for which photoionization may be important.

We therefore examine some possible non-LTE effects that have not been considered in the previous model studies. One possibility may be autoionization in Rydberg states, lying above the Si III \(3s^23S\) continuum, that converge to the Si III \(3s3p^23P^0\) level. These quasi-bound states appear as resonances in the photoionization cross section (cf. Shore 1969). Transitions to low-lying autoionizing states almost always result in ionization since for the competing processes out of these states, the transition rate for autoionization \(\lambda_{\text{ai}} \approx 10^{10}-10^{14}\) is usually much greater than the comparable rate for radiative de-excitation \(\lambda_{\text{R}} \approx 10^8\). The rate of the inverse process of dielectronic recombination depends on the rate of capture of thermal electrons into the autoionizing states. This means that dielectronic recombination, in general, will not proceed efficiently at low temperatures (except into very low lying autoionizing states), since the thermal energy available is insufficient to efficiently populate the intermediate states. Then the Si II photoionization rate, including autoionization, may be considerably enhanced over the direct photoionization rate alone, while the recombination rate increases less rapidly. This might explain a shift in ionization balance toward Si III. We know of no non-LTE model atmosphere studies that have included a proper treatment of the Si II autoionizing resonances. Kamp (1976) considered autoionization and dielectronic recombination in his models, although in an approximate manner, and he found autoionization insignificant compared to photoionization. Grigsby (1991) did not include autoionization or dielectronic recombination in his models.

The effects of the autoionizing resonances on the cross section may be large. In some cases the peak cross section may be increased by factors of \(10^3 - 10^5\) above the photoionization continuum. An example is provided by the photoionization cross section from the Si II \(4s2S\) state (Mendoza et al. 1995). This cross section, acquired using the TOPBASE interface (Cunto & Mendoza 1993), exhibits a strong resonance with a broad peak of 1300 Mb (1 Mb = 10^{-18} cm^2) near 1205 Å. By contrast, Baade (1986) used a continuum cross section of 0.355 Mb at threshold in his Si II model.

Autoionizing transitions of Si II are unquestionably significant in the spectra of B stars. The strong absorption at 1250 Å in our GHRS spectra is primarily due to the Si II UV 13.05 multiplet (blended with a weaker S II resonance line). The upper level of this transition is the autoionization state \(3p^22D^0\). The Si II UV 13.04 multiplet at 1305-1309 Å is anomalously strong in the spectra of mid-B stars. The great strength of this line is due to autoionization of the \(3d^2P^0\) upper state, as first proposed by Underhill (1981) and confirmed by Castelli & Singh (1990). The broad depression of the spectrum near 1400 Å seen in Ap-Si stars was explained by Artru (1986) as arising from the autoionizing transition \(3d^2P^1 - 3s3p^1(P)3d^2P^0\) of Si II. The question remains as to whether autoionization is sufficiently important so as to significantly affect the Si II ionization balance. On the basis of the good agreement between the observed Si II resonance lines and the LTE models (Grigsby 1991), the answer would appear to be no. LTE synthetic spectra of \(\iota\) Her (B3 IV) have been computed by Castelli & Bonifacio (1990) and of \(\pi\) Cet (B7 V) and \(\nu\) Cap (B9.5 V) by Artru, Borsenberger, & Lanz (1989) and reproduce the observed spectra remarkably well.

Although photoionization is the most probable cause of a shift in ionization balance between Si II and III, other effects such as charge transfer may be significant. Baliunas & Butler (1980) note the importance of the charge transfer reaction

\[
\text{Si}^+ + \text{H}^+ \rightarrow \text{Si}^{+2} + \text{H} - 2.74 \text{ eV}
\]

(9)

in astrophysical plasmas, particularly in the interpretation of lower transition region diagnostics such as the Si III 1892 Å line. At solar transition region densities at 30,000 K, this reaction rate is \(\sim 25\) times that of the (electron) collisional ionization rate. The inclusion of this reaction in the rate equations of statistical equilibrium can substantially shift the ionization balance toward Si III. Charge transfer should be included in future non-LTE models of Si II and III.

We are left with ambiguous conclusions about the prospects for significant non-LTE effects in the formation of the Si II resonance lines. A definitive answer will require more extensive non-LTE models of the Si II and III atoms that include the potentially important process of autoionization and dielectronic recombination. For the remainder of the analyses in this study, we will treat the weakness of the Si II resonance lines as due to an overionization of Si II because of an undetermined non-LTE effect, in the same manner as was done for the C I lines.

We emphasize that we have not computed self-consistent models with silicon calculated in non-LTE. Instead, we have empirically determined factors (the departure coefficients) to bring the synthetic spectrum, computed from the non-LTE/C H-He models, in the region of the Si II UV 4 (1260-1265 Å) and UV 5 (1190-1197 Å) resonance multiplets into agreement with the observed GHRS spectrum. In Figure 9a we show the observed GHRS spectrum of the 1172-1209 Å region and synthetic spectra calculated for various empirical values of the Si II departure coefficient. In Figure 9b we show the corresponding information for the 1245-1285 Å spectral region. Note that the synthetic spectra for these figures are calculated assuming that the C I ionization fraction also departs from LTE by the value given in Table 3. A plot of the fit residual as a function of the Si II departure coefficient for the Si II UV 4 and 5 multiplets is shown in Figure 10. We determine the departure coefficient for each multiplet to be that value which minimizes the residual, using an approach analogous to that followed in the determination of the effective temperature (see § 4.1). The values of
log \( b (\text{Si II}) \) obtained and their standard errors are summarized in Table 3. Taking the weighted mean of the values found from the Si II UV 4 and 5 resonance multiplets, we obtain an departure coefficient of \( \log b (\text{Si II}) = -1.00 \). The standard error of the weighted mean obtained is 0.030. However, the individual \( \log b \) values then lie at 4–5 \( \sigma \) from the weighted mean, a clearly significant amount. This disagreement is probably real, since our empirically obtained estimates of the departure coefficients reflect an average over the line-forming region and will differ somewhat for the two multiplets. Therefore, we take the average difference of the individual \( \log b \) values from the weighted mean as our real standard deviation and adopt \( \sigma (\log b) = 0.20 \) for the Si II lines.

4.4. Rotational Velocity

The model analyses so far have assumed a rotational velocity of 200 km s\(^{-1}\), an estimate inferred by inspection of the broad photospheric lines of the secondary star (Griffin et al. 1990). We now proceed to determine the projected rotational velocity by a least-squares fitting method. A series of synthetic spectra were computed from the non-LTE/C H-He models,

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Fig. 10.—Plot of fit residual (rms deviation between model and observed spectrum) as a function of Si II departure coefficient \( b (\text{Si II}) \). Left panel: the Si II (UV 5) 1190–97 Å multiplet. Right panel: the Si II (UV 4) 1260–1265 Å multiplet. Points plotted as crosses were not included in the least-squares parabola fit. The positions of the residual minima, giving the best fit values of \( b (\text{Si II}) \), are labeled.
with the empirically determined C i and Si ii departure coefficients applied, for a range of rotational velocities. These spectra, and the GHRS observations of the 1172–1209 Å and 1245–1285 Å regions, are shown in Figures 11a and 11b, respectively. Residuals of the synthetic spectra from the GHRS observations were calculated and the results plotted in Figure 12a. The residual plots for the same spectral regions, but with the Si ii lines excluded from the fit, are shown in Figure 12b. The rotational velocities derived and their standard errors are summarized in Table 4. The weighted mean rotational velocity is 199 km s\(^{-1}\). We adopt the rounded value of \(v \sin i = 200 \pm 15\) km s\(^{-1}\) as the projected rotational velocity of ζ Aur B. This value confirms the Griffin et al. (1990) estimate.

### 4.5. Surface Gravity

We also seek a spectroscopic determination of the stellar gravity. The main spectral sensitivity to this parameter is the width of the Stark-broadened hydrogen lines. However, a fundamental ambiguity in the determination of the surface gravity arises from possible confusion between the intrinsic Stark-broadened stellar Lyman α profile, for which the opacity in the far wings is given by the Holtsmark profile with a \(\Delta \lambda \sim 2.5\) dependence, and Rayleigh scattering by circumstellar neutral hydrogen. The Rayleigh scattering, which is dominated by resonance scattering in the far wings of Lyman α, has a \(\Delta \lambda^{-2}\) dependence for \(\lambda \sim \lambda_0 = 1215.67\) Å, but goes over to the steeper \(\Delta \lambda^{-4}\) dependence for \(\lambda \gg \lambda_0\). The GHRS observations used in this analysis were acquired when the ζ Aur components were well separated, and the circumstellar H column is expected to be small with negligible Rayleigh scattering contribution to the observed spectrum. However, the possibility of a significant Rayleigh scattering contribution to the observed Lyman α profile, particularly in the 1172–1209 Å region, cannot be ruled out on the basis of our single observation.

To confirm that the observed Lyman α profile is totally photospheric in origin, we also examined the 3940–4060 Å region containing He and the He i 4026 Å line, and the 3650–3950 Å region of the Balmer series limit (Griffin et al. 1990, their Fig. 4a). Rayleigh scattering from hydrogen is negligible in this region, and the Balmer line profiles are intrinsically photospheric. A comparison of the observed spectrum of ζ Aur B with model spectra of varying gravity is shown in Figure 13b for the spectral region 3940–4060 Å. A plot of the fit residual

<table>
<thead>
<tr>
<th>Spectral Regions Fitted</th>
<th>(v \sin i) (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1172–1209 Å region</td>
<td>194 ± 17</td>
</tr>
<tr>
<td>1245–1285 Å region</td>
<td>219 ± 32</td>
</tr>
<tr>
<td>1172–1209 Å (excluding Si ii UV 5)</td>
<td>220 ± 42</td>
</tr>
<tr>
<td>1245–1285 Å (excluding Si ii UV 4)</td>
<td>196 ± 16</td>
</tr>
<tr>
<td>Weighted mean (including Si ii lines)</td>
<td>200 ± 15</td>
</tr>
<tr>
<td>Weighted mean (excluding Si ii lines)</td>
<td>199 ± 15</td>
</tr>
<tr>
<td>Adopted value</td>
<td>200 ± 15</td>
</tr>
</tbody>
</table>
for the 3940–4060 Å region appears in Figure 14, and the value of the gravity found is $\log g = 4.00$, which confirms the usual designation of luminosity class V.

We also display the region of the Balmer series limit, 3650–3950 Å, for a series of model spectra with varying gravity and the observed Griffin spectrum of ζ Aur B in Figure 13c. The Griffin spectrum in this region proved to be unsuitable for fitting to synthetic spectra, because normalizing to the continuum is a fundamentally ambiguous operation when the continuum flux varies over a small wavelength interval, as occurs in the region of the Balmer limit. For example, the region around 3815 Å appears as a continuum point on the Griffin spectrum, while our model spectra show the peak flux in this region to be only $\approx 0.9$ of the true continuum flux longward of this region. Nevertheless, the 3650–3950 Å region does provide a useful independent gravity calibration derived from the Inglis-Teller relation. The number of distinct Balmer lines present depends sensitively on the stellar gravity (Underhill & Doazan 1982). In the Griffin spectrum the Balmer lines are visible up to H16 (their Fig. 4), which is typical for a main-sequence B star and further confirms the luminosity classification.

In Figure 13a we show comparisons between synthetic spectra computed from non-LTE/C H-He models for varying gravity, using empirically determined C i and Si ii departure coefficients, and our GHRs data for the spectral region 1172–1209 Å. The 1245–1285 Å region is insensitive to the gravity. The fit residuals for the 1172–1209 Å region are also shown in Figure 14. Since the value of $\log g = 3.81$ obtained by fitting the Lyman $\alpha$ profile in the 1172–1209 Å region is actually slightly less than the value derived from the Balmer lines, it is unlikely that our GHRs spectra are contaminated by Rayleigh scattering (which would tend to mimic additional stellar hydrogen broadening, and so result in an artificially higher value of $\log g$ in the 1172–1209 Å spectrum). We conclude that Rayleigh scattering is unimportant in our GHRs (epochs 1 and 6) spectra, and confirm that ζ Aur B is a main-sequence star. From a weighted mean of the Lyman $\alpha$ profile fits and the fit to He i, we obtain our adopted value of $\log g = 3.9 \pm 0.1$. The $\log g$ values obtained from the individual fits and their standard errors are summarized in Table 5.

### 5. CONCLUSIONS

We have determined the fundamental stellar parameters $T_{\text{eff}}$ and $\log g$ for the B-type secondary of ζ Aurigae by comparing observed GHRs spectra, with the wind lines removed, and synthetic spectra obtained from models computed on a grid of $T_{\text{eff}}$ and $\log g$. A grid of non-LTE/C H-He models were com-

<table>
<thead>
<tr>
<th>Spectral Regions Fitted</th>
<th>$\log g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1172–1209 Å region</td>
<td>3.81 $\pm$ 0.06</td>
</tr>
<tr>
<td>1245–1285 Å region</td>
<td>4.61 $\pm$ 1.29</td>
</tr>
<tr>
<td>3940–4060 Å region</td>
<td>4.00 $\pm$ 0.09</td>
</tr>
<tr>
<td>Weighted mean</td>
<td>3.9 $\pm$ 0.05</td>
</tr>
<tr>
<td>Adopted value</td>
<td>3.9 $\pm$ 0.1</td>
</tr>
</tbody>
</table>
computed using the TLUSTY code of Hubeny (1988) and considered 21 levels of hydrogen and neutral helium, and 19 bound-free transitions between these levels, to be in non-LTE. The bound-bound transitions between these levels were assumed to be in detailed balance. We additionally computed a limited number of non-LTE/L H-He models with the same 19 non-LTE levels of H and He as for the non-LTE/C case, but with 29 bound-bound transitions also explicitly treated in non-LTE. No significant differences in the synthetic spectra were found between the non-LTE/C and non-LTE/L models.

We have also determined the projected rotational velocity, $v \sin i$, by comparing the GHRS spectra with the grid of rotationally broadened synthetic spectra computed from non-LTE/C H-He models. The final values of $T_{\text{eff}}$, log $g$, and $v \sin i$ were found by minimizing the root-mean-square deviation, or residual, of the computed synthetic spectra from the observed GHRS spectra. For ζ Aurigae B, we obtain $T_{\text{eff}} = 15,400 \pm 300$ K, log $g = 3.9 \pm 0.1$, and $v \sin i = 200 \pm 15$ km s$^{-1}$, corresponding to a spectral type of B5 V.

The observed C I resonance lines are much weaker than the LTE model predictions, and we initially determined empirical departure coefficients for the C I ground state by matching the

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**Fig. 13**—(a) Stackplot of model spectra as a function of the stellar gravity log $g$ for the 1172–1260 Å region. The observed photospheric spectrum of ζ Aur is also shown. (b) Stackplot of model spectra as a function of the stellar gravity log $g$ for the 3940–4060 Å region. The observed photospheric spectrum of ζ Aur is also shown. (c) Stackplot of model spectra as a function of the stellar gravity log $g$ for the 3650–3950 Å region. The observed photospheric spectrum of ζ Aur is also shown.
synthetic spectra in the region of the C I lines (1277–1281 Å) to the observed G HRS spectra. The empirically determined departure coefficient for C I is \( \log b(\text{C I}) = -1.84 \pm 0.10 \), a value consistent with the departure coefficients found by Snijders (1977). We also computed a more detailed non-LTE H-He-C model for \( T_{\text{eff}} = 15,400 \) K and \( \log g = 3.9 \), with 46 levels of H, He I, and C I, C II, and C III, and 48 bound-free and bound-bound transitions between these levels, treated explicitly in non-LTE. The resulting synthetic spectrum is in reasonable agreement with the observed G HRS spectrum in the region of the C I lines near 1280 Å (resonance multiplets UV 5, 6, 7, and 9). The departure coefficients of the C I ground state computed from the non-LTE H-He-C model are consistent with the empirically determined departure coefficients of the 1280 Å C I lines. The non-LTE H-He-C model also shows that the contribution of neutral carbon to the bound-free opacity is negligible toward the ground-state bound-free edge at 1101 Å. For example, at 1220 Å, the H Balmer continuum accounts for 62% of the total continuous opacity, electron scattering accounts for 19%, the H Paschen continuum for 4.7%, while the C I 1D continuum accounts for just 1.9% of the total.

The Si II resonance lines, and the blended Si II and C III 1247 and 1250 Å lines, are all observed to be weaker than the non-LTE/C H-He model predictions by a roughly similar amount.

The simplest explanation of the weakness of the Si II lines in our G HRS spectra is that Si II is overionized relative to LTE, although other causes cannot be ruled out. We suggest that the process responsible may be photoexcitation to autionizing levels of the Si II 3s3p (3P) core from thermally populated lower (but not ground) levels. Assuming a non-LTE cause for the anomalous behavior of the Si II lines, we empirically determined the Si II departure coefficient by varying this value until the synthetic spectrum matched the observations. The value obtained for the Si II departure coefficient is \( \log b(\text{Si II}) = -1.00 \pm 0.20 \), determined by fitting synthetic spectra to the observed Si II UV 4 and UV 5 resonance multiplets. The resulting synthetic spectra are in excellent agreement with the observed G HRS spectra.

The values of the stellar parameters determined in this study are summarized in Table 6. In Figure 15, the observed G HRS spectrum from 1172–1209 Å with the wind lines removed is compared to the synthetic spectrum computed from the non-LTE/C H-He model for \( T_{\text{eff}} = 15,400 \) K, \( \log g = 3.9 \), \( v \sin i = 200 \) km s\(^{-1}\), with the departure coefficients for C I and Si II (Table 6) applied. The analogous comparison for the 1245–1285 Å region is shown in Figure 16, except now the additional synthetic spectrum computed from the non-LTE H-He-C model is also shown. The C I lines appearing in the non-LTE H-He-C synthetic spectrum have been calculated in non-LTE, and the empirical C I departure coefficient applied in the non-LTE H-He-C models (which are LTE carbon) has not been applied here. However, the empirically determined departure coefficient for Si II has been applied in the calculation of the non-LTE H-He-C synthetic spectra since these models still considered silicon to be in LTE. Finally, the comparison between the Griffin spectrum and the computed non-LTE/C H-He synthetic spectrum for the 3940–4060 Å region is shown in Figure 17. It is evident that these synthetic spectra provide a very good match to the observations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Adopted Value</th>
</tr>
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<tbody>
<tr>
<td>( T_{\text{eff}} )</td>
<td>15400 ± 300 K</td>
</tr>
<tr>
<td>( \log g )</td>
<td>3.9 ± 0.1</td>
</tr>
<tr>
<td>( v \sin i )</td>
<td>200 ± 15 km s(^{-1})</td>
</tr>
<tr>
<td>( \log b(\text{C I}) )</td>
<td>-1.84 ± 0.11</td>
</tr>
<tr>
<td>( \log b(\text{Si II}) )</td>
<td>-1.00 ± 0.20</td>
</tr>
<tr>
<td>( \log b(\text{Si III}) )</td>
<td>+0.15 ± 0.10</td>
</tr>
</tbody>
</table>
We emphasize that despite the problems in modeling the Si II lines, the computed synthetic spectra are otherwise in excellent agreement with the observations. We intend to continue studies of the ultraviolet spectra of B stars with more sophisticated models, in order to understand the anomalous behavior of Si II. However, we do not believe the uncertainties in modeling the Si II profiles compromise the results of this analysis.

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