HST STIS Observations of ζ Aurigae A’s Irradiated Atmosphere

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Abstract

The details of the processes responsible for heating the chromospheres of evolved cool stars remain uncertain. While most spectroscopic diagnostics measure spatially-integrated emission, here we examine diagnostics sensitive to localized atmospheric regions that are specific to cool evolved stars in binary systems with hot main-sequence companions: emission from Si I and C I resulting from the ultraviolet irradiation of the evolved star’s atmosphere. HST Space Telescope Imaging Spectrograph (STIS) high-spectral-resolution near-ultraviolet observations of ζ Aurigae A+B (K4 Ib + B5 V) were obtained at three orbital phases, including total eclipse, to search for Si I and the corresponding C I line emission. Si I 2987.645 Å emission was detected at phases φ = .010 and .448 (from periapsis) in-line with predictions from a previous study of optical Si I 3905 Å and Si I 4102 Å emission lines. No other Si I line emission is apparent, and the analogous C I lines at 2478.561 Å and 2582.901 Å also are not detected. High-spectral-resolution HST STIS and Goddard High Resolution Spectrograph spectra confirm the results of a previous study that showed that the intrinsic chromospheric fluxes on the visible hemisphere of ζ Aur, observed during total eclipse, are representative of the single K4 Ib supergiant λ Vel. Furthermore, the HST spectra show that the chromospheric turbulent velocities are very close to those in this spectral-type proxy. These combined results highlight the importance of detailed spatially-resolved chromospheric models of ζ Aur systems, based on sequences of atmospheric eclipse spectra, to help constrain the poorly understood mechanisms that heat the atmospheres and drive stellar winds in cool evolved stars.

Unified Astronomy Thesaurus concepts: Stellar atmospheres (1584); Ultraviolet astronomy (1736); Stellar chromospheres (230); Hubble Space Telescope (761); Radiative processes (2055); Eclipsing binary stars (444)

1. Introduction

The mechanism(s) responsible for heating the chromospheres and extended atmospheres of cool evolved stars are thought to be related to acoustic shocks and magnetic waves driven by subphotospheric convective motions; however, the details remain uncertain. Spectroscopic diagnostics of these stars typically suffer from the disadvantage of low spatial resolution: the information contained in these diagnostics is spatially integrated over the entire line-forming region on the visible hemisphere of the star. It is advantageous to use spectroscopic diagnostics of cool evolved stars that are sensitive to more localized atmospheric regions. One such diagnostic is the focus of this paper: emission lines from radiative decays of the $4s^1 P^0$ and $4s^3 P^0$ levels of Si I observed in binary systems with a hot main-sequence companion. These levels have too high an excitation energy, ~5 eV, to have significant collisional excitation in the chromospheres of cool evolved stars, instead, those levels are expected to be populated mainly by recombination of Si II. This process only occurs with significant strength for cool evolved stars in binaries near the substellar point of a hot companion where the companion’s far-ultraviolet radiation field ionizes Si I. As the stars orbit each other the substellar patch moves over the evolved star. For these cool evolved stars to serve as good proxies for single stars of similar spectral type, their atmospheres must be otherwise (mostly) unaffected by the presence of hot companions at and during secondary eclipse. We present new observations that support this constraint.

Composite-spectrum eclipsing binary systems with a cool evolved star and a hotter main-sequence companion provide natural laboratories to study the temperature and density structure of cool-star chromospheres (for recent reviews see Ake & Griffin 2015). Most cool-star semiempirical chromospheric models have been constructed for single stars from spatially unresolved observations (Linsky 2017, and references therein), with the notable exception of the eclipsing ζ Aurigae binary systems where a hot main-sequence star orbits a more massive cool evolved star, typically a bright giant or supergiant (e.g., Eaton 1993; Marshall 1996). During atmospheric (chromospheric) eclipses, constraints on the column densities, excitation temperature, ionization balance, and turbulence can be obtained at spatial resolutions as high as the gas pressure scale height. In this paper we focus our attention on the eponymous ζ Aurigae A+B (K4 Ib + B5 V) system, where, during the total eclipse of the B star companion, the chromosphere on the visible hemisphere of the red supergiant does not appear to be significantly influenced by the binary nature of the system (Eaton 1992): the chromospheric cooling rates, and thus heating rates, reflects those of single cool supergiant stars. Outside of eclipse, illumination by the B star’s ultraviolet (UV) bright photospheric spectrum can alter the ionization balance in the cool star’s chromosphere (Schröder 1986), deposit energy, and photoexcite atoms and ions.

A notable and interesting case of photoexcitation is that of Si I 3905 Å and 4102 Å emission in ζ Aurigae A+B which was rediscovered by R. E. M. Griffin and R. F. Griffin, having been
originally reported in (Christie & Wilson 1935, footnote on p. 432) and attributed to W.S. Adams (see Harper et al. 2016 for details). While most observations of ζ Aur systems have been made near the chromospheric eclipse phases, observations made well outside of eclipse when the substellar patch irradiated by the B star is visible can reveal strong Si I 3905 Å emission. Si I 4102 Å emission is present too, but blended with the redward side of Hβ. This emission has also been detected in HR 2030 (K1 II + B8.5 V) and 32 Cyg (K5 Ib + B6 V) (Griffin & Griffin 2000). Other chromospheric irradiation-driven emission that has been detected in ζ Aur are Ca II H & K (Walter 1937) and Fe II (Harper et al. 2016), see also Eaton et al. (2008). Since the photospheric spectrum of ζ Aur’s B star has been accurately constrained by a combination of UV flux-calibrated spectra and synthetic spectra from photospheric models (Bennett et al. 1995), and the orbital elements (Griffin 2005; Eaton et al. 2008) and stellar parameters (Bennett et al. 1996) are well known, ζ Aur A is a prime target for quantitative spectroscopy of cool stellar atmospheres. The Si I 3905 Å and 4102 Å line emission becomes particularly strong as the B star comes in front of the K4 Ib star after periastron—a result of the favorable viewing angle of the phase-dependent irradiation of the K supergiant’s deep chromosphere/upper photosphere by the B star at this orbital phase. These Si I transitions, together with the analogous C I system, which has the same lower-term structure but shifted to higher energies and with transitions shifted to shorter wavelengths, provide good spectroscopic diagnostics and constraints of K-supergiant atmospheres. This study provides new empirical constraints on irradiation-driven photoexcitation, and in particular on the Si I emission line formation.

A detailed empirical study of Si I 3905 Å and 4102 Å emission was presented by Harper et al. (2016), and Figure 1 shows the Si I 3905 Å emission equivalent width (EEW) data (red circles) and a theoretical relative isotropic emissivity curve (gold) from that paper. The EEWs are the additional K-star emission measured with respect to the B star’s photospheric spectrum as a function of orbital phase, as measured from periastron. All phases in this work are measured from periastron, and we use the radial-velocity orbital solution of Griffin (2005), which is in close agreement with Eaton et al. (2008). Figure 1 shows there is a good agreement between the orbital phase variation of the Si I 3905 Å EEWs and the efficiency of the Eddington reflection effect (see Eddington 1926; Sobolev 1975). The Eddington reflection effect is reemission from the K supergiant of the illuminating B-star radiation that changes in intensity as the distance between the stars changes, and with the observer’s viewing angle of the irradiated part of the K star’s surface. Here the reemission is assumed to be isotropic. Despite the overall good agreement there is a difference between the observations and predictions near phase \( \phi = 0.7 \), whose origin has not yet been established but may relate to the details of line formation. The green curve is a simple fit to the EEWs that deviate from the Eddington reflection effect.

The Harper et al. (2016) study also found that the intrinsic Si I 3905 Å line width (turbulent most probable velocity, hereafter \( \text{mpv} \)) to be \( v_{\text{mpv}} = 6 \text{ km s}^{-1} \). The Doppler shifts of the narrow profiles during the orbit also revealed a \( v \sin i = 5.7 \pm 1 \text{ km s}^{-1} \), assuming isotropic emission. The low turbulent velocity places the Si I emission source deep in the chromosphere or in the upper photosphere, and not in the more turbulent upper chromosphere or stellar wind.

Only a small (~2%) fraction of the B star’s photospheric flux impinges on the K supergiant’s chromosphere, but that flux of hot-star ultraviolet photons suffices to ionize Si I, which is a dominant source of bound-free opacity shortward of 1521 Å, down to \( \sim 1100 \text{ Å} \), where C I bound-free opacity becomes significant. Subsequent radiative recombination from Si II into the Si I singlet and triplet terms leads to a cascade down toward the lower energy levels; see Figure 2 for the Si I and analogous C I partial Grotrian diagrams. At the Si I column densities where the bound-free continuum becomes optically thick, i.e., where the B star photon flux rapidly becomes attenuated, the strong bound-bound transitions in the UV1 (2506.8–2528.5 Å) and UV2 (2438.7–2452.1 Å) multiplets, which connect to the ground term, are optically thick. These UV1 and UV2 photons scatter repeatedly and radiative transitions from their upper levels preferentially escape into lower optical depth lines, e.g., RMT1 (2987.645 Å), RMT2 (4102.936 Å), and RMT3 (3905.523 Å). See Table 1 for details of the transitions shown in Figure 2.

Since the solution of the full line-formation problem, where the B-star irradiation of overlapping continua of neutral species and hydrogen Rayleigh scattering combined with a large Si I atomic model is nontrivial, a simple angle-averaged escape probability photon-counting model was developed. The predictions from this analysis (Harper et al. 2016) are summarized in Figure 3. The salient features are: (1) the flux ratio of Si I 4102 Å to Si I 3905 Å line is less than 1.4; (2) the 2987.6/3905 flux ratio will be less than \( \sim 1.5 \); and (3) the 2881.6 Å emission will be negligible unless the column density of formation is very much smaller than expected. Furthermore, there is an analogous system for C I which has strong bound-free continuum cross sections toward shorter FUV
permission from Harper et al. 2016 irradiation of the singlet and triplet terms, and potential transitions enhanced during the system.

\[ \text{Table 1} \]

| No. | Upper Level | Lower Level | Si I Wave (Å) | Si I Mult. | C I Wave (Å) |
|-----|-------------|-------------|---------------|------------|--------------|
| 1   | (n + 1)S 1P0 | np2 3P3      | 2452.118      | UV2        | 1641.507     |
| 2   | (n + 1)S 1P0 | np2 3P1      | 2443.365      | UV2        | 1613.803     |
| 3   | (n + 1)S 1P0 | np2 3P0      | 2438.768      | UV2        | 1613.376     |
| 4   | (n + 1)S 1P0 | np2 1D2      | 2881.579      | UV43       | 1930.905     |
| 5   | (n + 1)S 1P0 | np2 1S0      | 3905.523      | RMT3       | 2478.561     |
| 6   | (n + 1)S 1P0 | np2 3P3      | 2516.112      | UV1        | 1657.008     |
| 7   | (n + 1)S 1P0 | np2 3P1      | 2506.897      | UV1        | 1656.227     |
| 8   | (n + 1)S 1P0 | np2 3P2      | 2528.508      | UV1        | 1656.267     |
| 9   | (n + 1)S 1P0 | np2 3P1      | 2519.202      | UV1        | 1657.907     |
| 10  | (n + 1)S 1P0 | np2 3P0      | 2514.316      | UV1        | 1657.380     |
| 11  | (n + 1)S 1P0 | np2 3P1      | 2524.108      | UV1        | 1657.907     |
| 12  | (n + 1)S 1P0 | np2 1D2      | 2987.645      | RMT1       | 1993.627     |
| 13  | (n + 1)S 1P0 | np2 1S0      | 4102.936      | RMT2       | 2582.901     |

Note. \( n = 2 \) for C I, and \( n = 3 \) for Si I. Wavelengths are given in air for \( \lambda > 2000 \) Å, and in vacuum for \( \lambda < 2000 \). Multiplet numbers are only given for Si I.

Figure 2. Partial Grotrian diagrams for Si I and C I showing the energy levels of the singlet and triplet terms, and potential transitions enhanced during irradiation of \( \zeta \) Aur A by the B star’s FUV photospheric UV spectrum. The lowest energy levels are shown; the upper levels are odd parity. The lines indicate transitions from the \( J = 1 \) upper levels only. Top: Si I (reproduced with permission from Harper et al. 2016 Figure 2). Bottom: The analogous C I system.

Figure 3. The predicted relative Si I line fluxes based on a simple angle-averaged escape probability model for a line-forming region with a gas temperature of \( T_{\text{ex}} = 3000 \) K, representative of the classical temperature minimum region. The fluxes are normalized to Si I 3905 Å. The line-formation region is expected to be throughout and behind the hashed area as the cross-section for bound-free absorption changes with wavelength.

wavelengths, \( \leq 1240 \) Å, whose yield is expected to be sensitive to the amount of B-star radiation scattered back off the K star’s chromosphere by H I Ly\( \alpha \) and Rayleigh scattering.

In order to test these predictions and provide new constraints on the chromospheric structure and velocity fields of \( \zeta \) Aur, we proposed new observations with the high-spectral-resolution HST Space Telescope Imaging Spectrograph (STIS) at three orbital phases: the first during total eclipse, the second phase close to the time of the peak of the expected emission brightness, and third at a later phase where the Si I 3905 Å fluxes are somewhat anomalous for isotropic emission. These spectra were designed to test predictions from the line-formation model; namely, to measure the emission in the 2987.645 Å and 2881.579 Å lines, respectively, and search for analogous C I emission.

The structure of this paper is as follows. In Section 2 the new HST-STIS observations of \( \zeta \) Aur are described along with archival HST Goddard High Resolution Spectrograph (GHRS) eclipse spectra. In Section 3 the HST-STIS out-of-eclipse spectra are discussed, and in Section 4 we examine the total-eclipse spectra with HST spectra of the spectral-type proxy \( \lambda \) Vel. The discussion and conclusions are presented in Sections 5 and 6, respectively.

2. Observations

In this section, we first describe the new HST-STIS observations from Programs 14731 and 15251 (PI: G. Harper); we then describe earlier HST-GHRS total-eclipse observations as they provide additional context regarding how representative \( \zeta \) Aur A may be of single K supergiants.

For the three different binary orbital phases we observed two near-ultraviolet (NUV) wavelength settings with single orbit Visits. The orbital positions of the two stars at these phases are shown in Figure 4. The STIS settings covered the wavelength ranges of 2329–2606 Å (E230H-2463) and 2772–3047 Å (E230H-2912). For each of the three HST Visits, the target acquisition was followed by two exposures of each of the two
wavelength settings. The observations are described in Table 2. Each wavelength region had two exposures, which were cross correlated and coadded. The exposure taken closest to the WAVECAL observation was used to define the absolute wavelength calibration. The biggest wavelength offset between the six pairs of exposures was $0.46 \text{ km s}^{-1}$; most offsets were much smaller. Two different STIS apertures were used; the total-eclipse spectra were obtained through the $0''.2 \times 0''.09$ aperture, which gives a spectral resolution of $R = 114,000$ with a velocity full width half maximum (FWHM) of $\Delta V_{\text{FWHM}} = 2.6 \text{ km s}^{-1}$, and the out-of-eclipse spectra used the $31'' \times 0''.05$ aperture with the NDA neutral density filter (ND = 0.4) to limit the total MAMA detector count rate from the NUV bright B-star companion. These spectra will have similar spectral resolutions.

Initial inspection of the spectra revealed that the observations from Visit 2 had count rates a factor of 3.34 and 3.95 lower than expected for E230H-2463 and E230H-2912, respectively. This may have been a result of miscentering of the star in the very narrow $0''.05$ aperture, and/or due to telescope defocusing. The fluxes for Visit 3 were close to those expected based on previous HST-GHRS observations (Baade et al. 1996). In the following, we have applied corrections to the Visit 2 fluxes to put them on the same flux scale as Visit 3.

### 2.1. GHRS

HST eclipse observations of $\zeta$ Aur were previously obtained using the GHRS (Brandt et al. 1994) on 1995 November 24 at phase $\phi = .923$ (Program 6069; PI: A. Brown), which was seven days before mideclipse. Four HST orbits were used to obtain a mix of echelle and medium-resolution spectra. Echelle ECH-B ($R \sim 80,000$) observations centered at 1787, 1859, 2329, and $2669 \text{ Å}$ were made through the Small Science Aperture (SSA—$0''.22$ square). Medium-resolution ($R \sim 25,000$) spectra were obtained through the photometric Large Science Aperture (LSA—$1''.74$ square) using G160M at 1265, 1538, and $1670 \text{ Å}$, G200M at 1909 Å, and G270M at 2335 Å. The instrument performance at the time of these observations is described by Robinson et al. (1998).

All observations used four FP-SPLIT wavelength settings and standard spectral step-patterns to alleviate the effects of fixed pattern detector noise. The spectra were background-corrected, combined, flux- and wavelength-calibrated (including Doppler and heliocentric velocity corrections) and corrected for scattered light using an IDL version of the CALHRS software package (as described in Keyes 1997, Chapters 34–36).

### 3. Irradiation-driven K-supergiant Line Emission

Phase $\phi = .101$ (Visit 2) is very close to the time of the peak reemission expected from $\zeta$ Aur A’s chromosphere/photosphere. The NUV spectra collected at this phase contain contributions from the intrinsic K star, B-star photons scattered in the stellar outflow, and the B star’s photosphere, in addition to the irradiation-driven emission from the K supergiant’s atmosphere. We can partially correct for the intrinsic K star spectra and wind-scattered B star photons by subtracting the total-eclipse spectra obtained at $\phi = .933$ (Visit 1) either allowing for the different radial velocities of the K star or the radial velocity of the wind-scattered emission which is close to the projected line-of-sight radial velocity of the wind at the B star’s location. In the following analysis we have subtracted the eclipse spectra for both cases. However, this is not a big concern because we are searching for narrow stellar emission ($\text{FWHM} \sim 10 \text{ km s}^{-1}$), and the wind-scattered emission is much broader ($\text{FWHM} \sim 70 \text{ km s}^{-1}$). The following plots are shown in the rest frame of the K star, so that any chromospheric emission features will be close to zero velocity.

Figure 5 shows the Si I 2987.645 Å emission at $\phi = .101$ and .448. In this figure, and the following ones, the wavelength of each spectrum has been Doppler shifted to the $\zeta$ Aur A’s

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8 STIS spectra are calibrated in vacuum wavelengths, but here we show all spectra in air wavelengths.
6.9 km s$^{-1}$ wavelengths are $<0.1$ km s$^{-1}$, which—when corrected for the E230H-2912 line-spread function—corresponds to an intrinsic $mpv$ turbulent velocity of 6.9 km s$^{-1}$, in excellent agreement with that found from optical spectra by Harper et al. (2016). The accuracy of the SiI wavelengths are $<0.1$ km s$^{-1}$ (Radziemski & Andrew 1965); the STIS absolute wavelength calibration is good at the sub 0.2 km s$^{-1}$ level. The line Doppler shifts at the two epochs are $\Delta V = -3.6 \pm 0.2$ km s$^{-1}$, and $\Delta V = +0.2 \pm 0.6$ km s$^{-1}$, where the $1\sigma$ uncertainties are formal fit errors. Unfortunately, these two new Doppler-shift values do not further constrain the previous value for $\nu \sin i$, because they lie at the edge of the scattered distribution of the optical SiI 3905 Å values shown in Figure 8 of Harper et al. (2016).

Figure 6 shows the SiI 2881.579 Å spectra for the same phases. The feature near the line center at $\phi = 0.101$ cannot be claimed as a detection because other features of similar strength are also present, and the wavelength is redshifted from its expected position. In the higher signal-to-noise ratio (S/N) $\phi = 0.448$ spectrum, there is no feature present.

To examine line flux ratios involving the SiI 3905 Å line, we first need to convert the EEWs (shown in Figure 1), which are measured with respect to the B star’s photospheric spectrum, into fluxes. Bennett et al. (1995, 1996) have determined the fundamental stellar parameters of the B star including both UV and optical spectra. For $\zeta$ Aur B they derived $T_{\text{eff}} = 15,200 \pm 200$ K, $\log g_B = 3.82 \pm 0.04$, $\nu \sin i = 200 \pm 15$ km s$^{-1}$, the B star’s angular diameter $\theta_B = 0.16 \pm 0.01$ mas, and interstellar extinction of $A_V = 0.25 \pm 0.03$. We adopt those parameters here, and used a synthetic spectrum computed using the TLUSTY code of Hubeny & Lanz (1995) to model the observed UV flux of the B star. This yields the apparent fluxes of the synthetic photospheric spectrum at selected wavelengths, which are given in Table 3. The model underestimates the HST fluxes by $\approx 20\%$ at the shorter wavelengths.

At $\phi = 0.101$, the measured profile, assuming a Gaussian profile with isotropic turbulence, has an $mpv$ of 7.1 km s$^{-1}$, which—when corrected for the E230H-2912 line-spread function—corresponds to an intrinsic $mpv$ turbulent velocity of 6.9 km s$^{-1}$, in excellent agreement with that found from optical spectra by Harper et al. (2016). The accuracy of the SiI wavelengths are $<0.1$ km s$^{-1}$ (Radziemski & Andrew 1965); the STIS absolute wavelength calibration is good at the sub 0.2 km s$^{-1}$ level. The line Doppler shifts at the two epochs are $\Delta V = -3.6 \pm 0.2$ km s$^{-1}$, and $\Delta V = +0.2 \pm 0.6$ km s$^{-1}$, where the $1\sigma$ uncertainties are formal fit errors. Unfortunately, these two new Doppler-shift values do not further constrain the previous value for $\nu \sin i$, because they lie at the edge of the scattered distribution of the optical SiI 3905 Å values shown in Figure 8 of Harper et al. (2016).

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Table 2

| Dataset | UTC Start (YYYY-MM-DD hh:mm) | $T(\text{exp})$ (s) | Aperture ($\arcsec \times \arcsec$) | Grating-CENWAVE 

| ODSP01010 | 2017-03-21 09:13 | 396 | 0.2 $\times$ 0.09 | E230H-2463 |
| ODSP01020 | 2017-03-21 09:23 | 396 | 0.2 $\times$ 0.09 | E230H-2463 |
| ODSP01030 | 2017-03-21 09:30 | 396 | 0.2 $\times$ 0.09 | E230H-2912 |
| ODSP01040 | 2017-03-21 09:37 | 396 | 0.2 $\times$ 0.09 | E230H-2912 |
| ODGD01010 | 2018-08-03 18:13 | 394 | 31 $\times$ 0.05NDA | E230H-2463 |
| ODGD02010 | 2018-08-03 18:23 | 394 | 31 $\times$ 0.05NDA | E230H-2463 |
| ODGD02030 | 2018-08-03 18:31 | 399 | 31 $\times$ 0.05NDA | E230H-2912 |
| ODGD02040 | 2018-08-03 18:39 | 358 | 31 $\times$ 0.05NDA | E230H-2912 |

The SiI 3905 Å EEWs at phases $\phi = 0.101$ and $\phi = 0.448$ are $\approx 195$ mÅ and $\approx 35$ mÅ, respectively. The predicted B-star fluxes in Table 3 give the SiI 3905 Å fluxes at the Earth of $\approx 7.0 \times 10^{-12}$

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erg cm\(^{-2}\) s\(^{-1}\) and \(\approx 1.3 \times 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\), respectively. The reddening-corrected flux ratios for 2987/3905 Å for \(\phi = 0.1\) and .45, are then \(\approx 0.18\) and \(\approx 0.60\), respectively. The photon-counting model predicts an angle-averaged flux ratio of <1.5 (Figure 3) if the line formation occurs when the SiI bound-free continuum is optically thick, as we expect it to be. The theoretical ratio increases rapidly toward lower SiI column densities. The absence of 2881 Å emission is in agreement with that scenario. If the emission is isotropic then the increase in the ratio at \(\phi = 0.45\) suggests that the line-forming region has shifted to a lower column density (by 0.5 dex); however, angle-dependent emission must be explored before drawing any further conclusions. Such effects are hinted at by the fact that the SiI 3905 Å measurements fall below the isotropic reflection-effect curve, while the relative fluxes for 2987 Å lie above the curve. The escape probability photon-counting model assumed an angle-averaged and frequency-averaged single-flight escape probability (Hummer 1981) and did not include angle-dependent effects from the incident irradiation on the K-supergiant atmosphere to the subsequent line of sight photon reemission.

Figure 7 shows the C I emission lines analogous to Si I 3905 Å and 4102 Å at \(\phi = 0.101\). Top: C I 2478.561 Å analogous to Si I 3905 Å. Bottom: C I 2582.901 Å analogous to Si I 4102 Å. The lower blue curves are the total-eclipse spectra that have been subtracted from the \(\phi = 0.448\) spectrum; each resulting spectrum is shown in gold. The red vertical markers indicate the rest wavelengths. Both lines are nondetections. The very narrow feature near 2582.35 Å is probably a noise artifact.
features. No features were cleanly detected above the noise and wind-scattered emission. (A couple of broad features were observed and not identified, and are not discussed further here).

4. Surface Fluxes of ζ Aur A and Those of λ Vel

We now compare the HST STIS and GHRS total-eclipse spectra of ζ Aur A with those from the single-star spectral-type proxy λ Vel (K4 Ib) that has been observed previously with HST GHRS (Carpenter et al. 1999). Such a comparison enables us to evaluate further how representative the chromosphere of ζ Aur A may be of single stars of similar spectral-types (see Eaton 1992 for a detailed discussion), and how useful the detailed chromospheric structures derived from eclipse spectra are to helping us understand the nature of cool evolved star chromospheres (Schröder 1986; Schröder et al. 1988). That in turn will help us to understand the nature of the mechanism(s) that heat the extended atmospheres, be they acoustic or magnetic (Schrijver & Zwaan 2008). It is worth noting that most of the sample of K and M red-giant, bright-giant, and supergiant stars, including λ Vel, in Eaton (1992; Table 2) have surface Mg II & k fluxes that are ∼2× that of the basal flux limit proposed by (Pérez Martínez et al. 2011, Equation (7)). This suggests that the detailed comparison of ζ Aur A and λ Vel will have broader application to other cool evolved stars with different luminosities.

To compare the two stars directly, we converted the observed fluxes to observed stellar surface fluxes using measured angular diameters, and then dereddened the spectra to obtain the intrinsic surface fluxes. For the angular diameter of λ Vel we took the value measured with the VLTI-AMBER instrument, i.e., 11.75 ± 0.26 mas (as described in the Appendix). The visual extinction for ζ Aur A is taken to be A_V = 0.25, based on the 2175 Å interstellar medium (ISM) absorption feature seen against the B-star companion’s photospheric spectrum, and the extinction law of Cardelli et al. (1989). If we assume a typical Galactic value of R_V = 3.09, that then implies a reddening of E(B − V) = 0.08. λ Vel is closer to the Sun than ζ Aur A, and an inspection of ISM reddening maps of Paresce (1984; Figure 2) and Capitanio et al. (2017) suggest that λ Vel is in a very low-reddening line of sight. For ζ Aur A we therefore adopt A_V = 0.03. We note that at low ISM reddening the adopted wavelength-dependent extinction may not be very accurate. The low reddening of ζ Aur adopted here is typical of previous studies, and because of the very low expected reddening toward λ Vel the NUV surface flux comparisons should be robust to the uncertainties in the reddening or its wavelength dependence.

To estimate the effective temperature, T_{eff}, of λ Vel we combine the spectrophotometry of Kieling (1987) and Alekseeva et al. (1994), the 13 color photometry (0.34–11.1 μm) of Johnson & Mitchell (1975, 1977), Cassini-VIMS 1.1–4.5 μm spectra10 (Stewart et al. 2015), 2–10 μm infrared fluxes given in Blackwell & Shallis (1977), and the WISE (Wright et al. 2010) fluxes at 11.6 and 22.1 μm fluxes from the AllWISE data release (Cutri et al. 2021). λ Vel, the brightest K supergiant in the sky, was not included in the IRAS Point Source Catalog (Joint IRAS Science Working Group 1994), nor was it observed by ISO. However, we note that using the IRAS Scan Processing and Integration tool (Scanpi)11 gives non-color-corrected 25 and 60 μm fluxes are 58 and 9 Jy, respectively.

Two of the three 12 μm scans show a flux of ∼215 Jy, while the other scan is an extreme outlier. These three IRAS-band fluxes are consistent with the ζ Aur fluxes when scaled by the ratio of the angular diameters squared (5.0 ± 0.3).

Combining the bolometric flux and the angular diameter we obtain an T_{eff} = 3835 K, which is practically the same as the value adopted by Blackwell & Shallis (1977; who derive 11.1 ± 0.8 mas for an adopted T_{eff} = 3820 K), and is slightly smaller than ζ Aur A. A comparison of the properties of the ζ Aur A and λ Vel is given in Table 4.

Figure 8 presents examples of total eclipse spectra, STIS (blue), and GHRS (gray), plotted on a surface-flux scale determined as above. The spectra show some intrinsic ζ Aur AK-supertgiant chromospheric emission, but they are mostly dominated by B-star photons scattered into the line of sight by the K star’s wind, mostly from singly ionized transitions. Also shown for comparison is the GHRS spectrum for λ Vel (green), which helps us identify those features in ζ Aur A that are intrinsic to the K supergiant. The few features in this spectral region that are dominated by K-star emission are the optically thin emission lines from the electron-density sensitive multiplets: C II] 2324.69, 2325.40 Å, Si II] 2350.17 Å, and small regions of continuum. The strongest emission is mostly from wind-scattered B-star photons in the Fe II lines, which match the numerous P Cygni-like Fe II wind-scattered lines seen in the λ Vel spectrum. Smaller wind contributions come from Cr II, Ni II, Mn II, and Co II. A comparison of the overlapping SSA GHRS ECH-B (±110 mas in cross-dispersion direction) with the LSA GHRS G270M (±870 mas in cross-dispersion direction) spectra between 2321.5 and 2344.5 Å reveals no evidence that the larger aperture has significantly more scattered Fe II emission, indicating that this wind-scattered emission is predominantly within 110 mas of the system at the 1995 Epoch. This is consistent with the modeling by Baude et al. (1996). A comparison of the 2017 STIS E140H-2463 (±100 mas in cross-dispersion direction) and 1995 GHRS G270M spectra shows that most features agree in flux levels, but there are some differences in the Fe II UV3 wind emission, whose lower levels are in the ground term: the 2017 eclipse fluxes are weaker by ∼17 percent. An examination of the STIS detector images (25 mas pixels) does not reveal signs of significant spatial extension between the strong scattering lines as compared to the optically thin stellar emission lines.

Figure 8 (bottom) shows an enlargement of the region around the optically thin Si II] 2350.17 Å. The FWHM of the STIS line is ≈35 km s^{-1}, which compares to 38 km s^{-1} measured for λ Vel by Carpenter et al. (1999). If we assume a Gaussian emission profile and account for difference in the spectral resolution for λ Vel GHRS G270M SSA of R ~ 25,000 (∆V_{FWHM} = 12 km s^{-1}), we find that these two stars have essentially same turbulent velocities to within the measurement errors.

The strong C II] 2325.40 Å line (top figure) is blended with a strong, broad wind feature on the red wing. A multicomponent Gaussian fit gives an estimated GHRS Echelle FWHM of ∼50 km s^{-1} with a reddening-corrected 2325.40 Å flux of F_λ = 1.8 × 10^6 erg cm^{-2} s^{-1}, which is about twice that reported by Schröder et al. (1988), based on the average of two lower-resolution and lower-S/N IUE spectra from the 1979 and 1985 eclipses. This is broader than the 38 km s^{-1} reported for λ Vel by Carpenter et al. (1999), and the difference may be attributed to blending by the wind line and weaker underlying wind-scattered emission. For single evolved stars, the C II] line is typically ∼0−2 km s^{-1} broader than the Si II] 2350 Å line.
Table 4
Stellar Properties

| Property                | ζ Aur A | λ Velorum | References |
|-------------------------|---------|-----------|------------|
| MK spectral type        | K4 Iab  | K4 Ib     | Keenan & McNeil (1989) |
| Distance (pc)           | 261 ± 3 | 167 ± 3   | van Leeuwen (2007) |
| Angular diameter (mas)  | 5.27 ± 0.10 | 11.75 ± 0.26 | PDB1996, van Leeuwen (2007) |
| T_eff (K)               | 3960 ± 100 | 3835 ± 100 | PDB1996, This Work (See Appendix) |
| A_V                    | 0.25 ± 0.03 | 0.03 (< 0.05) | PDB1996, Capitanio et al. (2017) |
| Galactic long, l        | 165°0' | 265°9' | SIMBAD |
| Galactic latit, b       | -0°4   | +2°8    | SIMBAD |
| Radius (R_☉)            | 148 ± 3 | 211 ± 6  | PDB1996, From φ and Dist. |
| Mass (M_☉)              | 5.8 ± 0.2 | 7.15 ± 5 | PDB1996, Carpenter et al. (1999) |
| Luminosity (logL_☉)     | 3.68   | 3.92    | PDB1996, This Work |
| v sin i (km s⁻¹)        | 5.7 ± 1 | 5.6 ± 1  | Harper et al. (2016), De Medeiros et al. (2002) |
| Radial velocity (km s⁻¹) | γ = 12.11 ± 0.04 | ≈18.0 | Griffin (2005), Wilson (1953) and Gontcharov (2006) |
| IRAS 12 μm (Jy)         | 41.9 ± 2.1 | 215 ± 11 | PSC, This Work |
| IRAS 25 μm (Jy)         | 9.9 ± 0.7  | 58 ± 4   | PSC, This Work |
| IRAS 60 μm (Jy)         | 1.93 ± 0.19 | 8.6 ± 0.9 | PSC, This Work |

Note. PDB1996 is Bennett et al. (1996). γ is the center-of-mass of the binary system. Given uncertainties are 1σ. The IRAS fluxes given here are not color corrected.

![Figure 8](image1.png)

Figure 8. A comparison of total-eclipse spectra of ζ Aurigae with that of the spectral-type proxy λ Vel (K4 Ib), shown as surface fluxes. The ζ Aur A spectra are shown in blue (STIS E140H-2463) and gray (GHRS G270M), with λ Vel in green. Top: spectra where there is some overlap. Bottom: an annotated expanded view of the Si II 2350 Å line.

Figure 9 shows the two Fe I UV44 emission lines that are photoexcited by photons in the Mg II k line core (Gahm 1974; van der Hucht et al. 1979). The Mg II k line at 2795.528 Å, is excited by electron collisions, and the fluorescent Fe I UV44 emission is thought to come from deeper in the chromosphere, where there is ample Fe I, which is easily ionized to Fe II by the intrinsic chromospheric FUV radiation field (Harper 1990). The top figure shows the strongest and cleanest intrinsic K-supergiant chromospheric feature, and as can be seen it has an almost identical flux, with a FWHM of ≈25 km s⁻¹. For λ Vel, Carpenter et al. (1999) find a FWHM of 28 and 30 km s⁻¹ for 2823 and 2844 Å, respectively. If we allow for the broader line-spread function of the G270M spectrum, we conclude that these two stars have essentially the same turbulent velocities.

Figure 10 shows the Fe II 2772.723 Å UV63 line that shares a common upper level (J = 7/2) with 2739.547 Å, the latter has an A-value 2 × 10³ times larger (Fuhr & Wiese 2006; Raassen & Uylings 1998). The excitation of NUV Fe II emission from cool evolved stars has been discussed by Judge & Jordan (1991) and Judge et al. (1992). The UV63 multiplet is excited by electron collisions to metastable levels below 4 eV, followed by optical photospheric photoexcitation. The lack of significant wind-scattered emission is a result of its very small branching ratio into the 2772.723 Å line. The Fe II 2775.350 Å is from multiplet UV32, which is directly collisionally excited in single cool evolved stars has been discussed by Judge & Jordan (1991) and Judge et al. (1992). The UV63 multiplet is excited by electron collisions to metastable levels below 4 eV, followed by optical photospheric photoexcitation. The lack of significant wind-scattered emission is a result of its very small branching ratio into the 2772.723 Å line. The Fe II 2775.350 Å is from multiplet UV32, which is directly collisionally excited in single stars, but has small A-values, ~1.9 × 10³ s⁻¹ (Raassen & Uylings 1998; Schnabel et al. 2004).

Between 1888–1927 Å is a region of spectral overlap of the GHRS spectra of ζ Aur A and λ Vel. In that region the scattered light from the B star dominates the spectrum, but the strong K supergiant Si line at 1900.286 Å (UVI) is mostly isolated from the contribution of scattered light and has a surface flux comparable to λ Vel. The spectra compare well in the Si II] comparison shown in Figure 8 (bottom). Although the identification of the formation mechanism of this line is less secure than the others, it is thought to be formed by recombination from Si II following photoionization by the K star’s chromospheric λ < 1197 Å radiation field (Judge 1988).

5. Discussion

The STIS observations reveal Si I 2987.645 Å emission at both noneclipse orbital phases, and with a narrow line width in
agreement with the optical Si I 3905 Å. The line fluxes at both epochs are below that of Si I 3905 Å in agreement with the escape probability model of Harper et al. (2016). While at phase $\phi = .448$, the Si I 3905 Å flux is below that expected from the Eddington reflection effect with isotropic emission, the Si I 2987.645 Å line is above it. One potential explanation of this difference is that of nonisotropic emission from deep within the chromosphere, but the ratio of fluxes is also sensitive to the gas temperature in the line-forming region through the population of the lower levels, and hence optical depths. Between phases $\phi = .101$ and .448 the separation of the two stars changes and the irradiating B star’s FUV flux is reduced by a factor $\sim 3.2$, which suggests that the line-formation region shifts to a slightly greater radius in the extended K-supergiant atmosphere and perhaps a change in gas temperature. No other Si I lines, or the analogous C I lines, are detected. A preliminary attempt to model the Si I 3905 Å line has been reported by Ó Riain (2015); however, a quantitative modeling of the Si I and C I systems requires a solution for simultaneous ionization balance for Si I–Si II, Fe I–Fe II, and C I–C II in the irradiated K star chromosphere, as well as the radiative transfer solution for large Si I and C I model atoms—which, while worthwhile—is beyond the scope of the present work.

Figure 9. A comparison of the STIS E140H-2912 total-eclipse spectrum of ζ Aurigae and the G HRS G270M spectrum of the spectral-type proxy λ Vel (K4 Ib) showing the fluorescent Fe I UV44 emission. These lines are pumped by the Mg II k line at 2795.528 Å (Gahm 1974; van der Hucht et al. 1979), and are expected to be formed in the lower-middle chromosphere (Harper 1990). Top: Fe I 2823 Å (uv44). Bottom: Fe I 2844 Å (uv44).

Eaton (1992) has pointed out that not only does the electron-collisionally-excited Al II 2669 Å line have similar surface flux to λ Vel (the G HRS spectrum is shown in Harper et al. 2005), but so does the fluorescent Fe I UV44 emission. The former depends on the emission measure, while the latter also depends on the atmospheric column density and ionization structure. The high-spectral resolution HST spectra reveal that the intrinsic line widths observed during total eclipse are also the same. The similarity of the surface fluxes of ζ Aur A and λ Vel from both electron-collisionally-excited and fluorescent emission very strongly indicate that the same heating mechanisms are active in both stars. While acoustic shock models have been proposed for cool evolved stars (Cuntz et al. 1994), the predicted emission line profiles are not in accord with UV HST spectra (Judge & Carpenter 1998). While no theoretical models are currently available that predict the observed line profiles and chromospheric thermal structure, magnetic fields are likely to play a role. The turbulent velocities inferred during chromospheric eclipses, which run from 6 km s$^{-1}$ in the deepest chromospheric layers (Wilson & Abt 1954) to supersonic values of 15–20 km s$^{-1}$ in the middle to upper chromosphere (Schröder et al. 1990; Eaton 1993; Baade et al. 1996), strongly suggest the presence of magnetic fields because these motions are predominately perpendicular to the radial direction, in contrast to photospherically driven acoustic shock waves that would have large radial velocity variations. This is not really a surprise since magnetic fields are required to explain the mass loss from these systems (Kuin & Ahmad 1989).

6. Conclusions

The HST-STIS spectra reveal the presence of Si I 2987.645 Å emission at phases $\phi = .101$ and .448 in agreement with predictions based on a simple photon-counting model. However, rather than displaying a sub-Eddington Reflection efficiency at phase .448 like Si I 3905 Å, it shows a super-Eddington reflection efficiency. No other clear Si I enhanced emission is detected. The C I lines analogous to Si I 3905 Å and Si I 4102 Å at 2478.561 Å and 2582.898 Å also are not detected, and we can attribute this to the reduced bandpass of
the FUV flux that photoionizes C1. To make a quantitative analysis of the fluxes expected in these lines requires a
comprehensive radiative transfer line formation model, including full illumination and viewing-angle effects for the SiI and
C1 systems. This is nontrivial, in part because of the overlapping FUV bound-free continua and H I Lyα and Rayleigh scattering.

The high-resolution HST GHRS and STIS spectra confirm previous findings that the visible hemisphere of ζ Aur A, observed during total eclipse, is representative of single K supergiants and also other cool evolved stars. Previous IUE studies have shown that the intrinsic chromospheric fluxes are similar to single cool evolved stars, and the HST high-resolution and high-S/N spectra of resolved profiles of lines formed at low optical depths show the turbulent velocities fields are also very similar to λ Vel (K4 Ib). These combined results highlight the importance of constructing detailed spatially-resolved chromospheric models of ζ Aur systems to help understand the mechanisms that heat the extended atmospheres of cool evolved stars, and drive stellar outflows.

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Facilities: Cassini-VIMS, HST(GHRS,STIS), IRAS,WISE.
Software: Interactive Data Language (IDL) Version 8.7 (Exelis Vision Information Solutions, Boulder, Colorado), SCAN Processing and Integration (SCANPI; IRSA 2022).

Appendix

We measured the angular diameter of λ Vel with the near-infrared spectrotinterferometric instrument AMBER (Petrov et al. 2007) at the Very Large Telescope Interferometer (VLTI) of the European Southern Observatory. Our VLTI-AMBER observation of λ Vel took place on 2014 February 11 (UT) using the Auxiliary Telescope (AT) configuration of B2-C1-D0 with projected baseline lengths of 9.2, 18.5, and 27.8 m (Program ID: 092.D-0461A,P.I.: K. Ohnaka). We observed a spectral window between 2.28 and 2.31 µm with a spectral resolution of R = 12,000. The shorter half of the observed spectral region samples the continuum nearly free of molecular and atomic lines, while the CO first overtone lines of the ν = 2−0 transition are present longward of 2.294 µm. We observed α Cen as an interferometric calibrator. The data reduction was carried out with amdlib Ver 3.0.7 (Tatulli et al. 2007; Chelli et al. 2009). The details of the data reduction and calibration are described in Ohnaka & Morales Marín (2018).

We fitted the visibilities, i.e., the amplitude of the Fourier transform of the object’s intensity distribution, measured at three baselines with a uniform disk. The uniform disk diameter derived in the continuum between 2.28 and 2.293 µm, shortward of the CO band head, is φUD = 11.40 ± 0.25 mas. To derive the Rosseland angular diameter from the measured uniform disk diameter, we applied the conversion factor presented in Arroyo-Torres et al. (2015). One of their targets, HD 183589, has a spectral type (K5 Ib), i.e., close to λ Vel (K4 Ib). The measured uniform-disk diameter and the estimated Rosseland angular diameter of HD183589 were 2.95 mas and 3.04 mas, respectively (Table 3 of Arroyo-Torres et al. 2015). Applying this ratio, we obtained a Rosseland angular diameter of φRoss = 11.75 ± 0.26 mas for λ Vel.

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