OUTER ATMOSPHERES OF COOL STARS. VI. MODELS FOR ε ERIDANI
BASED ON IUE SPECTRA OF C ii, Mg ii, Si ii, AND Si iii

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ABSTRACT

Observations of the ultraviolet line spectrum of the active chromosphere star, ε Eridani, obtained with the IUE satellite have been analyzed. We have solved the coupled statistical equilibrium and radiative transfer equations for the prominent transitions of C ii, Mg ii, Si ii, and Si iii. A satisfactory fit to all of the line strengths can be achieved with a model similar to that recently proposed to explain bright points on the quiet Sun. We derive a surface pressure at the base of the transition region of 0.5 dynes cm⁻², which is a factor of 3 higher than the quiet-Sun value, but a factor of 3 smaller than predicted by scaling laws, assuming a conductively heated stellar transition region. We find that the surface fluxes of the C ii λ1334, 1335 and Si iii λ1892 emission lines are good diagnostics of pressure at the base of the transition region, but line ratio techniques using the λ1892 line for estimating electron densities may be invalid.

Subject headings: stars: atmospheres — stars: chromospheres — stars: individual — stars: late-type — ultraviolet: spectra

I. INTRODUCTION

Prior to the availability of spectra from the International Ultraviolet Explorer satellite (IUE), chromospheric models for several late-type stars were computed to match the wings and emission cores of the Ca ii H and K lines and the Mg ii h and k lines, which were the only useful diagnostics then available. Models based on these spectral lines have been computed recently for three G-K giants (Kelch et al. 1978) and 10 dwarfs of spectral type F0 V–M0 V (Kelch 1978; Kelch, Linsky, and Worden 1979). Although methods for analyzing the Ca ii and Mg ii lines have been carefully developed and extensively used, these two spectral features are sensitive probes of only the lower regions of stellar chromospheres where T < 7000 K. The analysis of the ultraviolet lines of Si ii, Si iii, and C ii, which are formed at temperatures of 5000–25,000 K, provides a means of extending chromosphere models into the high-temperature regions which, for the Sun, are commonly called the upper chromosphere and the base of the transition region.

With the IUE spacecraft (Boggess et al. 1978a, b), it is now feasible to obtain ultraviolet spectra of many late-type stars. The initial IUE observations of Capella, ε Eri, HR 1099, and λ And (Linsky et al. 1978) clearly show a number of strong emission lines, including Si ii λλ1260, 1265, 1526, 1533, 1808, 1816, 1817; Si iii λλ1206 1892; and C ii λλ1334, 1335. In this paper we analyze higher quality observations of ε Eri obtained later in the IUE mission. Our investigation of this K2 V star extends to an active chromosphere star the analyses of the solar Si ii and Si iii lines by Tripp, Athay, and Peterson (1978, hereafter TAP) and of the solar C ii lines by Lites, Shine, and Chipman (1978, hereafter LSC). As diagnostics of the solar atmosphere, the lines of ionized carbon and silicon provide independent checks on models deduced from other available spectroscopic features, e.g., the Lyman continuum and Lo; but for stars other than the Sun which can be observed by IUE, these emission lines become the principal source of information regarding structure of the hotter layers of the chromosphere. Our approach here is to solve explicitly the radiative transfer equations for the important transitions of the observed Si ii, Si iii, and C ii spectra along with the coupled multilevel statistical equilibrium equations for Si⁺, Si⁺⁺, and C⁺, and to apply the same technique to the previously analyzed Mg ii and Ca ii data.

Our paper is exploratory in that we are attempting to learn the extent to which the analysis of spectra of Si ii, Si iii, and C ii can lead to a self-consistent model for the upper chromosphere and base of the transition region of a dwarf star cooler than the Sun. In subsequent papers we will study the upper chromospheres of other stars and extend our models into the transition regions of late-type stars, using the high-temperature lines available in IUE spectra.

II. IUE OBSERVATIONS OF ε ERIDANI

We list in Table 1 the IUE emission line fluxes for the Si ii multiplets λ1260 + λ1265, λ1526 + λ1533, λ1808, and λ1816 + λ1817; the Si iii λλ1892 line; and the C ii λλ1334 + λ1335 multiplet. These multiplets are either unresolved or only partially resolved in the low-dispersion IUE data. Line strengths were measured from IUE image SWP 2376 obtained on 1978 August

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## TABLE 1
### OBSERVED AND COMPUTED INTEGRATED SURFACE FLUXES FOR ε ERIDANI

<table>
<thead>
<tr>
<th>Model Parameter or Spectral Line</th>
<th>Observed Surface Flux* (ergs cm(^{-2}) s(^{-1}))</th>
<th>Computed Surface Flux (ergs cm(^{-2}) s(^{-1}))</th>
<th>Model 1A</th>
<th>Model 1B</th>
<th>Model 1C</th>
<th>Model 2A</th>
<th>Model 2B</th>
<th>Model 2C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{\text{top}}) (dyn cm(^{-2}))</td>
<td>(\ldots)</td>
<td>(0.22)</td>
<td>(0.20)</td>
<td>(0.20)</td>
<td>(0.22)</td>
<td>(0.88)</td>
<td>(0.48)</td>
<td>(\ldots)</td>
</tr>
<tr>
<td>(\log m_0) (g cm(^{-2}))</td>
<td>(\ldots)</td>
<td>(-5.0)</td>
<td>(-5.0)</td>
<td>(-5.0)</td>
<td>(-5.0)</td>
<td>(-5.0)</td>
<td>(-4.5)</td>
<td>(-4.7)</td>
</tr>
<tr>
<td>(\Delta m_p) (g cm(^{-2})) (upper plateau)</td>
<td>(\ldots)</td>
<td>(1.0 (-6))</td>
<td>(2.0 (-6))</td>
<td>(2.0 (-6))</td>
<td>(1.0 (-6))</td>
<td>(1.0 (-6))</td>
<td>(2.0 (-6))</td>
<td></td>
</tr>
<tr>
<td>(T(K)) (lower plateau)</td>
<td>(\ldots)</td>
<td>(6800)</td>
<td>(6800)</td>
<td>(6800)</td>
<td>(6500)</td>
<td>(6500)</td>
<td>(6500)</td>
<td></td>
</tr>
<tr>
<td>(\xi_0) (km s(^{-1}))</td>
<td>(\ldots)</td>
<td>(10)</td>
<td>(10)</td>
<td>(5)</td>
<td>(10)</td>
<td>(10)</td>
<td>(10)</td>
<td></td>
</tr>
<tr>
<td>Ca II (K)</td>
<td>(9.5 (5)^a)</td>
<td>(9.6 (5))</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(8.4 (5))</td>
<td>(\ldots)</td>
<td>(8.4 (5))</td>
<td></td>
</tr>
<tr>
<td>Mg II (h + k)</td>
<td>(2.4 (6)^a)</td>
<td>(2.1 (6))</td>
<td>(2.1 (6))</td>
<td>(2.1 (6))</td>
<td>(1.8 (6))</td>
<td>(1.9 (6))</td>
<td>(1.9 (6))</td>
<td></td>
</tr>
<tr>
<td>Si II: (\lambda 1260 + \lambda 1265)</td>
<td>(7.1 (3)^a)</td>
<td>(3.2 (3))</td>
<td>(3.6 (3))</td>
<td>(4.7 (3))</td>
<td>(1.6 (3))</td>
<td>(3.8 (3))</td>
<td>(3.9 (3))</td>
<td></td>
</tr>
<tr>
<td>(\lambda 1256 + \lambda 1253)</td>
<td>(1.7 (4)^a)</td>
<td>(1.0 (4))</td>
<td>(1.1 (4))</td>
<td>(1.6 (4))</td>
<td>(4.8 (3))</td>
<td>(6.5 (3))</td>
<td>(6.7 (3))</td>
<td></td>
</tr>
<tr>
<td>(\lambda 1808)</td>
<td>(2.4 (4)^a)</td>
<td>(7.0 (4))</td>
<td>(7.2 (4))</td>
<td>(6.2 (4))</td>
<td>(4.2 (4))</td>
<td>(5.5 (4))</td>
<td>(5.6 (4))</td>
<td></td>
</tr>
<tr>
<td>(\lambda 1816 + \lambda 1817)</td>
<td>(5.4 (4)^a)</td>
<td>(1.6 (5))</td>
<td>(1.7 (5))</td>
<td>(1.4 (5))</td>
<td>(9.6 (4))</td>
<td>(1.2 (5))</td>
<td>(1.3 (5))</td>
<td></td>
</tr>
<tr>
<td>Si III: (\lambda 1206)</td>
<td>(\ldots)</td>
<td>(7.5 (3))</td>
<td>(9.4 (3))</td>
<td>(1.1 (4))</td>
<td>(7.4 (3))</td>
<td>(2.7 (4))</td>
<td>(2.2 (4))</td>
<td></td>
</tr>
<tr>
<td>(\lambda 1892)</td>
<td>(5.0 (3)^a)</td>
<td>(1.3 (3))</td>
<td>(1.9 (3))</td>
<td>(2.3 (3))</td>
<td>(1.3 (3))</td>
<td>(4.4 (3))</td>
<td>(4.2 (3))</td>
<td></td>
</tr>
<tr>
<td>C IV: (\lambda 1334 + \lambda 1335)</td>
<td>(3.1 (4)^a)</td>
<td>(2.3 (4))</td>
<td>(2.7 (4))</td>
<td>(3.3 (4))</td>
<td>(1.8 (4))</td>
<td>(5.8 (4))</td>
<td>(4.9 (4))</td>
<td></td>
</tr>
</tbody>
</table>

* For an angular diameter of 2.29 milli-arcsec.

^a Flux between \(K_2\) features from Linsky et al. 1979.

^b Flux between \(h\) and \(k\) features from Basri and Linsky 1979.

^c \(IUE\) spectrum SWP 2376 obtained 1978 August 23.
23 through the large aperture with an exposure time of 60 minutes, and converted to surface flux at the star using the angular diameter 0'00229 obtained from the Barnes-Evans relation (see Linsky et al. 1978). The Si III λ1206 line was not measured due to severe blending with stellar and geocoronal La.

These tabulated surface fluxes are systematically larger than those quoted by Linsky et al. (1978) by about a factor of 2. In searching for the cause of this discrepancy, we have found that the published data, obtained during the science commissioning phase of IUE, were not properly corrected for the dispersion constant of the SWR camera. Thus, all of the low-dispersion short-wavelength fluxes cited by Linsky et al. should be multiplied by the dispersion constant, equal to 2.326 angstroms per pixel. With this revision, the earlier results for ε Eri are in very good agreement (within a few percent) with the more recent surface fluxes presented in this paper.

After the theoretical calculations for this paper had been completed, we were informed by A. V. Holm of the Goddard Space Flight Center of an error in the IUE photometric calibration (intensity transfer function). As a result of this error, the line fluxes measured from the SWP 2376 image may be overestimated. The agreement of the SWR data obtained by Linsky et al. (which remain unaffected by the calibration error) with the more recent SWP fluxes suggests that the error is not significant enough to change the outcome of our investigation of ε Eri.

III. COMPUTATIONAL TECHNIQUES

a) The Radiative Transfer Equations

To solve the transfer equations for Mg++, C++, Si+, and Si++ we begin with a model atmosphere, which specifies temperature, electron pressure, and hydrogen ground-state departure coefficient versus mass column density. The electron pressures and hydrogen departure coefficients were obtained from solutions of the statistical equilibrium equations for a hydrogen atom of five bound levels plus continuum. The coupled radiative transfer equations for the Lyman continuum, λα, λβ, and Heα were solved explicitly in the complete redistribution (CRD) approximation; the higher continua were included as fixed rates scaled from the solar radiation temperatures. Our calculations assumed hydrostatic equilibrium with a turbulent pressure support term, ½ρσ(m)², where ρ denotes the mass density and σ(m) is the assumed run of microturbulence with mass column density. The electron pressure calculation assumed local thermodynamic equilibrium (LTE) for the ionization of He, He+, and the metals. The basic atomic data for hydrogen were adopted from Milkey and Mihalas (1973).

In our C II, Si II, and Si III line calculations, we assumed Voigt profiles including only radiative damping and CRD. The CRD assumption should be valid, as most of the flux in these emission lines lies within the Doppler cores and the low spectral resolution of many of the stellar data permits only comparison with the total emission flux in the lines. On the other hand, we used a full partial redistribution (PRD) treatment for the Mg II h and k lines as the IUE data are of high resolution and much of the line flux lies beyond the Doppler cores of these lines.

b) Model Atoms and Atomic Data

The atomic representation for the ions of magnesium, carbon, and silicon, and the adopted atomic parameters, are summarized in the Appendix.

c) Tests of our Computing Codes by Comparison with Solar Models

Because our versions of the basic LINEAR code of Auer, Heasley, and Milkey (1972) use numerical procedures that differ from those of LSC and TAP, we have tested the accuracy of our computer codes by reproducing the C++ solar calculations of LSC and the Si++ and Si++ calculations of TAP.

In these trial calculations, we were able to reproduce the electron pressures and hydrogen densities of the LSC solar Model 1 (given in their Table 3), using the same VAL microturbulence structure (Vernazza, Avrett, and Loeser 1973). Using their atomic data and the VAL σ(m), we also obtained C II λ1334 and 1335 intensities within a few percent of those computed by LSC, both for their Model 1 and the VAL model.

For Si II and Si III we assumed the same model atmosphere, atomic data, Doppler profiles, and σ(m) distribution as TAP, and solved for the same radiative transitions (1206, 1265, 1533, and 1817 Å). Our calculations reproduced the line shapes of these four transitions and the integrated line intensities of Si II λ1816 and Si III λ1206 multiplets, but we were unable to match the integrated intensities of Si II λ1533 and λ1265. Tripp (1978) has suggested that the f-values used by TAP for these latter two transitions may have differed from the values published in their Table 1B.

d) Comparison with Solar Observations

Since our analysis of silicon includes several individual transitions ignored by TAP, we have also compared our calculated line strengths directly with solar line fluxes obtained by the NRL ATM/Skylab experiment. Theoretical fluxes for the Si II λ1260 + λ1265, λ1526 + λ1533, λ1808, λ1816 + λ1817 and Si III λ1206 emission features are in good agreement with two sets of NRL ATM/Skylab lab data taken at 300° inside the solar limb (Nicolas et al. 1977; Kjeldseth Moe et al. 1976), but the predicted Si III λ1892 line is almost a factor of 4 weaker than is observed. The observed and theoretical fluxes (which refer to the emission above the local background or computed continuum) are compared in Table 2. The observations cited here are representative of quiet regions of the Sun (Nicolas 1977). For λ < 1800 Å the data are from the Kjeldseth Moe et al. atlas with a calibration correction for λ < 1400 Å (cf. Nicolas et al.); the fluxes for lines at λ > 1800 Å are an average of both sets of data. For this computation we chose the LSC...
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IV. CHROMOSPHERIC MODELS FOR ε ERI

The starting point for our calculations is the model for the lower chromosphere of ε Eri which Kelch (1978) derived from the observed Ca II and Mg II resonance line fluxes. We have retained his photospheric structure, temperature minimum, and values of microvelocity $\xi_0$ (where $m_0$ is the mass column density corresponding to $T = 8000$ K), but we have modified the chromospheric temperature structure in order to obtain by trial and error the best match to the Mg II, Si II, Si III, and C II data. Our calculations neglect macroturbulence and rotation, which smear the observed profiles without significantly altering the equivalent widths of the emission lines. Initially we have assumed an upper chromospheric plateau width, $\Delta m_p$, identical in mass column density to the LSC solar model ($\Delta m_p = 1.0 \times 10^{-6} \text{ g cm}^{-2}$), and we have assumed the same initial transition region temperature gradient as in the LSC and VAL models. In subsequent models we have varied these parameters in order to improve the fit to the IUE observations, except that, to preserve the analogy with the Sun and reduce the number of adjustable parameters, we have fixed the temperature within the upper chromospheric plateau at the value $T_p = 16,500$ K derived by LSC. Stellar parameters ($T_{\text{eff}}$, log g, and metal abundances) are discussed by Kelch (1978) and summarized in his Table 1.

Table 1 summarizes the theoretical emission line fluxes for two different grids of atmospheric models. Entries in this table have been defined except for $P_{\text{top}}$, which is the gas pressure at the highest point in our depth grid. $P_{\text{top}}$ is equivalent to the pressure at the base of the transition region, and is approximately equal to $P(m_0)$ since the steep temperature rise characteristic of solar-type model atmospheres occurs within one pressure scale height of the outer boundary. Each of the three versions of Model 1 assumes the same temperature distribution derived by Kelch (1978) for the lower chromosphere ($T < 8000$ K) and upper photosphere, but here we adopt a revised value of $\log m_0 = -5.0$. Compared with Kelch’s model, we have increased $m_0$ by an order of magnitude in order to raise the electron pressures in the upper chromosphere and reconcile the computed line strengths with the Si II, Si III, and C II observations from IUE. Kelch’s value of $\log m_0 = -6.0$ was not accurately determined as $m_0$ has only a small effect upon the Mg II $h$ and $k$ line fluxes.

The predicted line fluxes for Model 1A are in close agreement with the observed Ca II K line flux (Linsky et al. 1979) and the IUE Mg II $h$ and $k$ fluxes (Basri and Linsky 1979). However, the Si II $\lambda 1808$ and $\lambda 1816 + \lambda 1817$ features are more than a factor of 2 stronger than observed, the Si III $\lambda 1892$ line is more than a factor of 3 weaker, and the C II lines are about 25% weaker. Although the IUE flux of $\lambda 1892$ may be uncertain by 50-100%, because of the low contrast of this feature against a high stellar continuum and instrumental background, the measured Si II line strengths should be uncertain by no more than 30%, and the C II fluxes are unlikely to be in error by more than 20%. Observational error, therefore, cannot account for these large discrepancies.

a) Temperatures of Line Formation

Before various adjustments of the parameters of our stellar chromosphere model are discussed, it is useful to indicate the region of formation for each of the emission lines since this will make clear the influence of various model parameters on the synthesized line profiles. We have found that individual lines are formed at comparable temperatures in models...
for $\epsilon$ Eri and the Sun. Judging by the temperatures corresponding to optical depth unity at line center for each transition, the majority of the Si $\Pi$ lines are formed in the lower chromospheric plateau. These lines of ionized silicon appear to be very sensitive to temperatures and electron densities at depths where $T \leq 7000$ K, but not to atmospheric properties at higher temperatures. Line-center optical depth of unity for 1260 $\AA$ and 1265 $\AA$ corresponds to a slightly higher temperature, $T = 8000$ K, which occurs along the rise between the low- and high-temperature plateaus; conditions in the middle of the chromosphere, where hydrogen becomes highly ionized, control the rise between the low- and high-temperature plateaus; conditions in the middle of the chromosphere, where hydrogen becomes highly ionized, control the optical depth of a transition. The temperature gradient is small, than at the 35,000 K level in the TR where the temperature gradient is steep. Jordan’s calculations show that Si $^{++}$ is an abundant stage of ionization over a large temperature range, and the crossover from Si$^{+}$ to Si$^{++}$ as the dominant Si ion occurs near 13,000 K in our radiative transfer calculations compared with about 18,000 K in Jordan’s calculations, which ignore transfer effects and photoionization.

Doschek et al. (1978) have proposed a method for determining electron densities in the low TR ($T \approx 50,000$ K) of stars based on the ratio of emission line strengths of Si $\Pi$ 18192/C $\Pi$ 1909, assuming that both lines are formed in the low TR. Our result that $\lambda 1892$ is formed in the upper chromospheric plateau rather than at 50,000 K may invalidate their method. The line ratio method is strictly valid only for an isothermal atmosphere or an atmosphere of constant temperature gradient. Our calculations show that Si $\Pi$ 18192 is formed largely in a region of small temperature gradient (the 15,500 K plateau), whereas the C $\Pi$ 1909 line is presumably formed above the plateau in a region of steep temperature gradient. Thus, the Si $\Pi$ 18192/C $\Pi$ 1909 line strength ratio should depend critically on the thickness of the plateau and may not be a valid electron density diagnostic. To the extent that other lines used in density diagnostics (cf. Cook and Nicolas 1979) are formed in a temperature plateau, these line ratios may also not be useful density diagnostics.

b) Changes in the Model of the Upper Chromosphere

In attempting to improve upon the results of the preceding Model 1A, we first considered whether changes in the width of the plateau could reduce the discrepancy between the computed and observed Si $\Pi$ and C $\Pi$ line fluxes. Elimination of the plateau ($\Delta m_p = 0$) greatly reduces the computed fluxes of both lines. Moreover the relative effect is greater for $\lambda 1892$ so it is apparent that the sense of this change (either by itself or in combination with adjustments to other parameters) is incorrect. For this reason, in Model 1B we doubled the plateau width. As anticipated, the Si $\Pi$ 18192 and C $\Pi$ 18134 + 18135 line fluxes increase with the plateau width; however, more than a factor of 5 increase in $\Delta m_p$ would be needed to explain the Si $\Pi$ data. Such a drastic difference between the chromospheric structure of $\epsilon$ Eri and the Sun seems unlikely, but cannot be definitely excluded.

The predicted fluxes of lines formed in the plateau, and just below the plateau, are sensitive to the assumed microturbulence distribution in the upper chromosphere. Model 1C has a maximum microturbulent velocity of 5 km $s^{-1}$, instead of the 10 km $s^{-1}$ maximum assumed in our other models for consistency with the VAL and TAP solar models. The Si $\Pi$ and C $\Pi$ fluxes of this model represent an improved fit compared with Model 1B. For the optically thick lines (e.g., $\lambda 1334$ or $\lambda 1260$), the influence of the microvelocity on the line shapes and surface fluxes is predominantly an optical depth effect in the calculation of emergent flux. In these instances, the computed line profiles are self-reversed; the line source functions attain a maximum value in the chromosphere near the lower edge of the high temperature plateau and fall to smaller values at both greater and shallower depths in the model. Similar results were reported by TAP in their investigation of the Sun, and the reader is referred to that paper for an excellent detailed discussion. Although Model 1C suggests that the turbulence parameter can have a nonnegligible effect on the synthesized stellar line fluxes and, in turn, on the model parameters deduced from our fitting procedure, the present low-resolution IUE data do not warrant a broader experimentation. Nevertheless, in principle, observations of UV line profiles at high resolution could provide a practical diagnostic for a more complete study of atmospheric turbulence.

c) A Revised Model of the Lower Chromosphere

The computed fluxes for the Si $\Pi$ 1808 and 1816 + $\lambda 1817$ features in the different versions of Model 1 are substantially larger than observed; and since these lines are formed in the low chromosphere, we have constructed a second sequence of models having a reduced temperature (6500 K) in the lower chromospheric plateau. As in Model 1, we include a plateau at 16,500 K of thickness $\Delta m_p$ and a TR temperature gradient similar to the solar models of LSC and VAL. Fluxes for three versions of this Model 2 ar
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TABLE 3
ε Eridani (Model 2C)

\[
\begin{array}{cccccc}
\text{m (g cm}^{-2}\text{)} & \tau_e (K) & p_e (\text{dynes cm}^{-2}) & n_{\text{HI}} (\text{cm}^{-3}) & b_1 (\text{HI}) \\
1.603(-5) & 50000 & 2.34(-1) & 7.44(+6) & 7.88(+6) \\
1.608(-5) & 45925 & 2.33(-1) & 1.30(+7) & 7.00(+6) \\
1.611(-5) & 40430 & 2.31(-1) & 2.50(+7) & 6.13(+6) \\
1.616(-5) & 35645 & 2.29(-1) & 5.52(+7) & 5.26(+6) \\
1.622(-5) & 30837 & 2.26(-1) & 1.47(+8) & 4.36(+6) \\
1.632(-5) & 26070 & 2.22(-1) & 4.98(+8) & 3.33(+6) \\
1.645(-5) & 21285 & 2.14(-1) & 2.02(+9) & 1.83(+6) \\
1.659(-5) & 16500 & 2.08(-1) & 6.21(+9) & 3.03(+5) \\
1.751(-5) & 16500 & 2.16(-1) & 5.64(+9) & 2.57(+5) \\
1.845(-5) & 16500 & 2.26(-1) & 5.47(+9) & 2.32(+5) \\
1.984(-5) & 7250 & 1.07(-1) & 1.45(+11) & 6.63 (0) \\
1.990(-5) & 6875 & 9.78(-2) & 1.69(+11) & 2.33 (0) \\
1.996(-5) & 6500 & 8.89(-2) & 2.00(+11) & 7.30(-1) \\
2.482(-5) & 6500 & 5.80(-2) & 4.07(+11) & 3.49 (0) \\
3.563(-5) & 6500 & 6.93(-2) & 6.37(+11) & 3.81 (0) \\
5.972(-5) & 6500 & 4.68(-2) & 1.22(+12) & 1.62(+1) \\
1.134(-4) & 6500 & 4.81(-2) & 2.36(+12) & 3.02(+1) \\
2.328(-4) & 6500 & 7.65(-2) & 5.13(+12) & 2.60(+1) \\
4.988(-4) & 6500 & 1.29(-1) & 1.17(+13) & 2.10(+1) \\
1.091(-3) & 6500 & 2.27(-1) & 2.72(+13) & 1.58(+1) \\
2.410(-3) & 6500 & 5.27(-1) & 6.34(+13) & 6.84 (0) \\
4.721(-3) & 3911 & 1.95(-1) & 1.51(+14) & 8.81 (0) \\
9.265(-3) & 3322 & 8.24(-2) & 3.58(+14) & 7.72 (0) \\
1.819(-2) & 4733 & 6.37(-2) & 7.61(+14) & 3.97 (0) \\
3.574(-2) & 4144 & 8.31(-2) & 1.74(+15) & 1.29 (0) \\
5.010(-2) & 3850 & 6.86(-2) & 2.67(+15) & 4.82(-1) \\
1.000(-1) & 3930 & 1.30(-1) & 5.22(+15) & 5.24(-1) \\
1.585(-1) & 4010 & 2.10(-1) & 8.10(+15) & 5.65(-1) \\
3.610(-1) & 4160 & 4.90(-1) & 1.77(+16) & 6.47(-1) \\
9.080(-1) & 4325 & 1.23 (0) & 4.27(+16) & 7.62(-1) \\
1.816 (0) & 4530 & 2.75 (0) & 8.10(+16) & 9.19(-1) \\
2.870 (0) & 4800 & 5.48 (0) & 1.22(+17) & 9.82(-1) \\
3.899 (0) & 4997 & 8.54 (0) & 1.60(+17) & 9.85(-1) \\
\end{array}
\]

summarized in Table 1; Models 2A and 2B differ only in the value of \( \log m_0 \).

With this adjustment of 300 K in the lower chromospheric temperature, the discrepancies for the Si \( \Pi \) \( \lambda 1808 \) and \( \lambda 1816, 1817 \) features are largely removed, although not entirely. Model 2A predicts fluxes about 75\% stronger than the IUE observations, and this is reasonably close to the 50\% factor by which predictions of the TAP model exceeded the observed solar fluxes (see Table 2). Presumably, a slightly lower temperature would eliminate the remaining disagreement without worsening the fit of the Mg \( \Pi \) \( h \) and \( k \) lines.

To investigate the possibility of whether a larger gas pressure could account for the difficulties encountered in predicting the correct Si \( \Pi \) and C \( \Pi \) line strengths, we have increased the surface pressure by a factor of 3. As expected, the results for Model 2B demonstrate the strong influence of the value of \( m_0 \) on the C \( \Pi \) and Si \( \Pi \) lines formed in the high chromosphere, and a diminishing effect on the lines formed at progressively lower depths. The larger particle number densities in the plateau region are responsible for the enhancement of the optically thin \( \lambda 1892 \) line, while the overall increase in pressure results in a stronger coupling of the line source functions to the chromospheric temperature rise for the remaining optically thick transitions of ionized carbon and silicon.

Since the C \( \Pi \) \( \lambda 1334 + \lambda 1335 \) lines of this model are now a factor of 2 brighter than observed, in our final chromospheric model, Model 2C, we have reduced the top pressure and, to avoid a too-weak line of Si \( \Pi \), we have again extended the thickness of the plateau to twice the canonical solar value. The

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effect of these changes is to overestimate the strengths of the optically thick lines (\(\lambda 1334 + \lambda 1335, \lambda 1808\), etc.) and to underestimate the flux of \(\lambda 1892\). Taking into consideration the present uncertainties in both the observations and atomic data, we consider the fit to be satisfactory. However, we note that a further compromise to improve the fit of the Si II and C II lines at the expense of the Si III line could be achieved with a lower surface pressure of about \(P_{\text{Top}} \approx 0.35\) dynes cm\(^{-2}\). The resulting discrepancy for \(\lambda 1892\) would lie within the factor of 2 uncertainty in the observed line strength and the comparable uncertainties in the relevant atomic data.

For future reference, and the benefit of other investigators of cool-star atmospheres, Model 2C is tabulated in Table 3 and plotted in Figure 1.

V. CONCLUDING REMARKS

The star \(\epsilon\) Eridani is representative of a class of chromospherically active stars whose outer atmospheres can now be studied, using the spectographs on the IUE satellite, with the same theoretical techniques previously developed for the solar atmosphere. The first glimpses provided by IUE present unambiguous evidence of very high temperatures in cool-star atmospheres. By analogy with the Sun, emission lines of highly ionized elements (N III \(\lambda\lambda 1240,\;\text{Si IV} \;\lambda\lambda 1394,\;1403,\;\text{and}\;\text{C IV} \;\lambda\lambda 1550\)), which require temperatures of several times 10\(^6\) K, lead us to suppose that transition regions and 10\(^6\) K coronae must surely exist on other stars as well. The presence of strong ultraviolet lines of less highly ionized atoms (Mg\(^+\), Si\(^+\), Si\(^{++}\), C\(^+\)) not only places the reality of stellar chromospheres beyond doubt, but also provides the means for quantitative study of their properties.

In this paper we have carried out a “first-cut” analysis of IUE observations of \(\epsilon\) Eri with the objective of finding the proper diagnostic tools for understanding its chromosphere and, by extension, those of other stars available to IUE. Our trial-and-error approach has led us to a satisfactory model that accounts for the observed fluxes of the Mg II, Si III, and C II spectra. This investigation has not thoroughly exhausted all possible models, but it does outline the influence of several of the most significant atmospheric parameters.

Our best-fitting model (Model 2C) resembles models of bright, small-scale structures observed in the solar chromospheric network (Basri et al. 1979); except that the initial rise to the plateau in the middle of the chromosphere (\(T = 8000\) K) is placed slightly deeper in the solar model (Model BP, Table 8, Basri et al.) and the temperature in the low chromosphere is somewhat higher in our \(\epsilon\) Eri model. The surface pressures are virtually identical for the bright point solar model (\(P_{\text{Top}} = 0.50\) dyn cm\(^{-2}\)) and for our Model 2C (\(P_{\text{Top}} = 0.48\) dyn cm\(^{-2}\)), and both are about a factor of 3 larger than for the average quiet Sun (\(P_{\text{Top}} \approx 0.15\) dyn cm\(^{-2}\), Withbroe and Noyes 1977). By comparison, the hotter transition region lines in \(\epsilon\) Eri (e.g., Si IV \(\lambda\lambda 1394, 1403,\;\text{C IV} \;\lambda 1550,\;\text{and}\;\text{N V} \;\lambda 1239\)) have surface fluxes about 10 times that of the quiet Sun (data in Linsky et al. 1978 multiplied by 2.326 as suggested in § II). Haisch and Linsky (1976) showed that the transition region pressure should be proportional to the observed surface fluxes of transition region lines when the transition region is geometrically narrow and heated by the conduction of thermal energy from the corona. This factor of 3 discrepancy between \(P_{\text{Top}}\) derived from our analysis of the Si III and C IV lines compared with the Haisch-Linsky scaling law suggests that the assumptions upon which the scaling law is based may not be valid.

Although the calculations presented in this paper demonstrate the usefulness of the C II \(\lambda\lambda 1334 + \lambda 1335\) lines, and Si III \(\lambda 1892\), as pressure diagnostics, it might be argued that we cannot exclude the possibility of a much higher surface pressure. Baliunas et al. (1980) have derived surface pressures on the order of 1 dyn cm\(^{-2}\) for \(\lambda\) And and \(\alpha\) Aur from an analysis of the Ca II and Mg II lines of these stars. In our models for \(\epsilon\) Eri, higher pressures would be required if, for example, the lower temperature plateau was extended in thickness and the steep temperature rise was assumed to occur at a smaller mass column density. However, additional calculations undertaken in connection with a study of HR 1099 and UX Ari (Simon and Linsky 1979), two RS CVn type binaries which may be regarded as extreme cases of chromospherically active stars, appear to confirm the tentative conclusions reached here that pressures deduced from the Haisch-Linsky scaling law are inconsistent with the much lower values required to fit the chromospheric lines. The results summarized in Table 1 suggest a range of uncertainty of a factor of 2 in \(P_{\text{Top}}\); the permissible range is undoubtedly greater if the limitations of our study are taken into account. Although this particular problem will be the subject of future papers, it is true in any event that as a lower limit, the boundary pressure is likely to be at
At least a factor of 10 greater than an earlier estimate we have derived (Kelch 1978) from a study of only the resonance lines of Mg$^+$ and Ca$^+$. The possibility that coronal inhomogeneities, magnetic loop structures, spicules, or dynamical phenomena play a more significant role in the atmospheres of active stars like ε Eri suggests an answer for the contradiction raised here. Under these circumstances, an analysis of disk-integrated spectra might be quite misleading. Whether this proves to be true can only be shown by demonstrating that the approach taken in this paper fails to provide a reasonable interpretation of the available observations. To this end, it will be an important next step to obtain high resolution spectra with IUE, since these data would place very strong constraints on permissible chromospheric models.

This work is supported in part by NASA under grants NAS5-23274 and NGL 06-003-057 to the University of Colorado. We wish to thank Dr. A. Boggess and the staff of the IUE observatory for their assistance in the acquisition and reduction of these data. The authors gratefully acknowledge the support of the National Center for Atmospheric Research, operated by the University Corporation for Atmospheric Research, under contract to the National Science Foundation, for a grant of computing time. We also thank Dr. G. S. Basri, who developed the computer programs used in this study.

APPENDIX

MODEL ATOMS AND ATOMIC DATA

a) Mg$^+$

Our atomic model for singly ionized magnesium assumes three bound levels (3s $^2S_{1/2}$, 3p $^2P_{1/2}$, and 3p $^2P_{3/2}$) and the continuum (Mg$^+++$), and we solve explicitly for the h and k resonance lines using the PRD method discussed by Kelch et al. (1978). Photoionizations are treated as fixed rates, based upon radiation temperatures in the continua computed from the stellar models. The collision cross sections, photoionization cross sections, van der Waals constants, and other atomic parameters are from Kelch et al. (1978).

b) C$^+$

Our initial solutions for singly ionized carbon included 10 bound levels and the continuum (C$^++$) (see Fig.2), and we solved explicitly for both the λ1036 and λ1335 multiplets. However, we found that a satisfactory solution for the C ii λ1335 multiplet required just seven bound levels, including the $^2P^0$ ground state and $^2P$ and $^2D$ excited states, and an explicit solution only for the two transitions of the λ1335 multiplet. Trial calculations indicated that levels of neutral carbon, including the autoionizing states, can be ignored for the C ii λ1335 multiplet line-formation problem. We have used the atomic data given by LSC, except that we have included radiative damping based on the value of $\Gamma_{rad}$ adopted from Morton and Smith (1973). Photoionizations have been represented as fixed rates. Our ultraviolet radiation temperatures should be sufficiently accurate to compute line intensities, since the radiation temperatures we compute for the Sun (cf. §III) are in agreement with those given by LSC for C$^+$, TAP for Si$^+$, and by Pottasch (1970) in the range 600 Å < λ < 1900 Å, which includes the Lyman continuum.
The atomic model and data for silicon are summarized in Figure 3 and Table 4. We have adopted the collision and photoionization cross sections of TAP, with the exception of the photoionization cross section for the Si$^+$ $2P^o$ ground state. Initially, Si$^+$ calculations for the Sun discussed in § III were based on the theoretical total cross section of Daum and Kelly (1976), which includes subshell edges and the $3s$-$np$ resonances. However, we found by experimentation that the Si$^+$ integrated line fluxes computed with the VAL model (Vernazza, Avrett, and Loeser 1973) were closely reproduced by calculations assuming a fixed photoionization rate for the Si$^+$ ground state, the radiation temperature cited by TAP, and a threshold cross section of $1.4 \times 10^{-18}$ cm$^2$. This value is only 20% lower than the cross section employed by TAP. Consequently, in order to save computing resources in our stellar calculations, we have used this cross section and treated photoionization from the ground state as a fixed rate, based upon continuum radiation temperatures derived from the stellar models.

For all transitions except Si$^+$ $\lambda$1892, we have used the oscillator strengths and related radiative damping constants of Morton and Smith (1973). We have derived an oscillator strength for Si$^+$ $\lambda$1892 ($^3S_0$-$^3P^o_1$) by interpolating of values along the Mg I isoelectronic sequence in accordance with the electric dipole scaling relation $gf \propto Z^5$ (Garstang 1978) and the theoretical Mg I, Cl vi, and Ca ix electric dipole line strengths of Cheng and Johnson (1977). As a result of configuration mixing, we find an apparent oscillator strength minimum at $Z = 4$ (Garstang 1978).

We estimated collision strengths of the resonance transitions from the Si$^+$ rates of Nicolas (1977) and, in the case of Si$^+$, from the equations of Seaton (1962), using our adopted oscillator strengths and the theoretical effective Gaunt factor of Roberts (1970). We have used the same cross sections adopted by TAP for transitions between the excited levels and assumed a cross section of $100 \pi a_o^2$ between levels of the same term.

![Figure 3 - Model atom for silicon](image)

**Table 4A**

<table>
<thead>
<tr>
<th>Level Number</th>
<th>Ion</th>
<th>Designation</th>
<th>Ionization Threshold ($\times 10^{-15}$ Hz)</th>
<th>Statistical Weight</th>
<th>Photoionization Cross Section ($\times 10^{18}$ cm$^2$)</th>
<th>Collision Ionization Cross Section ($\pi a_o^2$)</th>
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<td>1</td>
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### TABLE 4B

Transition Data for Si$^+$ and Si$^{++}$

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<tr>
<th>Transition</th>
<th>Wavelength (Å)</th>
<th>E$^+$ (eV)</th>
<th>$\Gamma_{im}$ (s$^{-1}$)</th>
<th>Collision Cross Section (σa²)</th>
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<td>4.53 (6)</td>
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<td>5.6</td>
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<td>...</td>
<td>2.41 (9)</td>
<td>2.2</td>
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<td>2.14 (9)</td>
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<td>4.53 (6)</td>
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<td>4.48 (6)</td>
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<td>6.50 (8)</td>
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<tr>
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<td>1206.5</td>
<td>1.66</td>
<td>2.54 (9)</td>
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</table>

* Value of $\Omega_0$ from Nicolas 1977, where the collision excitation rate, $C_{ij}$, is $C_{ij} = 8.63 \times 10^{-9} \Omega_0 \exp (-h\nu_i/kT)/(8\sqrt{T})$.

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Garstang, R. H. 1978, private communication.


Rottman, G. J. 1978, private communication.


