THE ASTROPHYSICAL JOURNAL, 308:246–253, 1986 September 1

FAR-ULTRAVIOLET FLUORESCENCE OF CARBON MONOXIDE IN THE RED GIANT ARCTURUS. II. ANALYSIS OF HIGH-DISPERSION *IUE* SPECTRA

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Received 1985 October 14; accepted 1986 February 7

ABSTRACT

Faint, diffuse emissions near 1380 Å in deeply exposed *IUE* spectrograms of the red giant Arcturus very likely are associated with bands of the *A–X* fourth-positive system of carbon monoxide, fluoresced by multiplet UV2 of neutral oxygen near 1305 Å. Numerical simulations indicate that the strength of the CO bands is exceedingly sensitive, in the best available one-dimensional model of the chromosphere of Arcturus, to a delicate balance between the rapid inward attenuation of the oxygen radiation field and the rapid outward decline of the molecular absorptivity. The fortuitous character of the overlap region in the single-component model argues that one should also consider the possibility that the pumping occurs in a highly inhomogeneous chromosphere, of the type proposed in previous studies of Arcturus based on observations of the infrared absorption bands of CO.

Subject headings: line identifications — molecular processes — stars: individual — ultraviolet: spectra

I. INTRODUCTION

The far-ultraviolet spectrum of the archetype red giant Arcturus (α Boo: K1 III), as observed by the *International Ultraviolet Explorer* (*IUE*; Boggess *et al.* 1978), contains a number of distinct emissions which cannot be associated readily with known atomic or ionic transitions. Indeed, the regions of the spectrum where the unidentified lines fall at low dispersion (5 Å resolution) seem to be free of significant, isolated emission features at high dispersion (0.15 Å resolution), suggesting that the underlying spectral structure is diffuse (Ayres, Simon, and Linsky 1982). That property, and the appearance of emissions at similar wavelengths in spectra of comet tails and planetary atmospheres (Feldman *et al.* 1974; Durrance 1980), suggested to Ayres, Moos, and Linsky (1981; hereafter Paper I) that the unidentified features were bands of the *A–X* fourth-positive system of carbon monoxide radiatively fluoresced by the strong chromospheric emissions of neutral oxygen near 1305 Å (multiplet UV2). Evidence for such fluorescence in the solar spectrum is well established (Bartoe *et al.* 1978), although the important pumping species, and therefore the resulting fluorescence spectrum, is quite different than in the case of Arcturus.

Recently, Ayres *et al.* (1986) reported an extremely deep, 21.5 hr *IUE* exposure of Arcturus taken with the high-dispersion mode of the shortwavelength (1150–2000 Å spectrograph image SWP 20044). One of the important goals of the long exposure of Arcturus was to detect directly the strongest of the individual fluoresced lines of CO, in order to permit these features to be developed as diagnostics of physical conditions in the outer layers of the atmosphere of the red giant and other like stars.

As illustrated in Figure 1, statistically significant spectral structure in fact appears in SWP 20044 in the wavelength interval near 1380 Å, where the numerical calculations of Paper I suggested that the fluorescence of CO should be most intense.

Ayres *et al.* (1986) discuss in detail possible excitation channels for the CO bands, and tentative identifications of individual features in the spectral intervals near 1340 Å, 1380 Å, 1510 Å, and 1715 Å, primarily those transitions decaying from excited vibrational levels $V' = 9$ and 11. The authors conclude, as in Paper I, that the chromospheric emissions of O I UV2 are the dominant pumping mechanism.

I, therefore, have undertaken a more detailed modeling of the excitation of the fourth-positive system in order to assess the value of the emission bands of CO as atmospheric diagnostics. I will focus on the global properties of the fluorescence rather than on the individual line transitions, because the poor signal-to-noise of the best available ultraviolet spectra prevents a definitive assessment of the line strengths at the present time.

II. ANALYSIS

Note, in Figure 1, the considerable strength of the chromospheric emissions of hydrogen (Lyα) and oxygen (1305 Å triplet) compared with those of other species, including the faint structure attributed to CO. If the features identified as CO are pumped by the O I triplet, the weakness of the emissions indicates that the excitation must occur in a layer which either is optically thin in the fourth-positive system or which is subject to only a dilute radiation field in the O I triplet (or both). In particular, the combined strength of the features at 1340 Å, 1380 Å, and 1410 Å in low-dispersion spectra of Arcturus is only $\sim 10\%$ of the integrated emission of the oxygen triplet (Paper I; Carpenter, Wing, and Stencel 1985). If, instead, the carbon monoxide were optically thick to an undiluted O I radiation field, virtually all of the inwardly directed oxygen radiation would be absorbed by the overlapping bands of CO, and approximately *half* of the fluorescent emission would be scattered outward.

There are essentially two possibilities for the geometry of the fluorescence within the context of a single-component model atmosphere. On the one hand, the chromospheric oxygen radiation might penetrate into the deeper, cooler layers at the base of the

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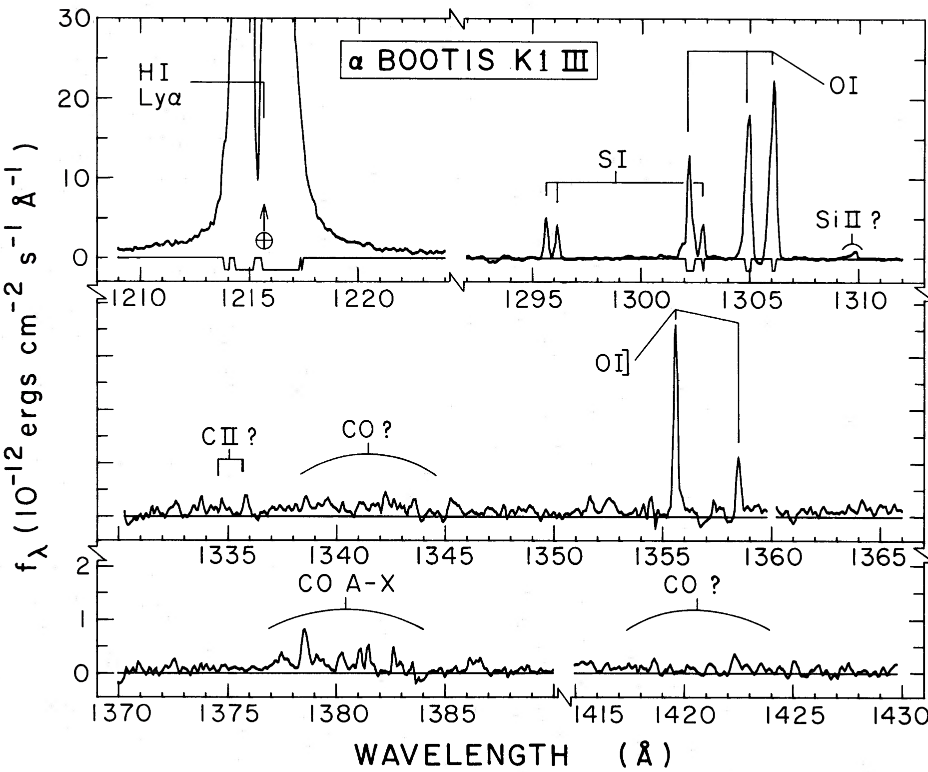

FIG. 1.—Selected wavelength intervals from the far-ultraviolet spectrum of Arcturus. The tracings were constructed from two high-dispersion (0.15 Å FWHM) *IUE* images, with exposure times of 7 hr and 21.5 hr, which were combined using a filtering procedure that eliminates many of the usual defects of the Vidicon images, particularly reseau marks and intensity spikes caused by cosmic-ray "hits" and "hot" pixels (see Ayres *et al.* 1986 for details). The "⊕" symbol refers to the approximate location of the geocoronal H I emission feature, which partially fills in the strong interstellar Lyα absorption core. The laboratory wavelengths of important spectral features are indicated by vertical tick marks. Three regions suspected to contain CO emission in low-dispersion *IUE* spectra also are indicated explicitly. The dropouts below the zero line indicate portions of the spectrum which are affected by saturation, reseau marks, and extrapolations of the intensity transfer function. The rms noise level is $\sim 0.2 \times 10^{-12}$ ergs cm^{-2} s^{-1} Å^{-1}. Note the change in flux ordinates between the top panel and the bottom two panels.

temperature inversion where the CO molecules are concentrated. The oxygen radiation can scatter to great depths because of the small probability of collisional destruction in the low-density chromosphere. On the other hand, the molecules might reside in a circumstellar shell far from the star, and the fluorescence therefore might occur outside the chromosphere, rather than beneath it.

a) Fluorescence in a Circumstellar Shell

One might ask whether the fluorescence could occur in the circumstellar material which is responsible for the well-known redward shading of the cores of the strong chromospheric emissions of Arcturus, like the O I triplet and Mg II *h* and *k* (2800 Å). The column density of Mg^+ ions required to produce the blueward absorption components in *h* and *k* is $\sim 10^{15}$ cm^{-2} (McClintock *et al.* 1978), which corresponds to a mass-loss rate of $\sim 3 \times 10^{-10}\ M_\odot$ yr^{-1} if the wind is mostly ionized and the outflow velocity is ~ 40 km s^{-1} (Ayres, Simon, and Linsky 1982). Recent microwave observations of Arcturus with the Very Large Array (VLA; Drake and Linsky 1986) are consistent with a mass flux of ionized material of this order, or smaller. Further, the lack of blueshifted absorption components in the emission core of the Mg I λ2852 resonance line indicates that Mg^+ is the dominant stage of ionization in the outflow (Ayres *et al.* 1986). Even if all of the carbon in the circumstellar material ($A_C/A_{Mg} \approx 4$) were completely associated into carbon monoxide (an unlikely possibility), the opacity of the flow in the strongest of the CO lines would be less than $\sim 10^{-2}$. That value is too small to explain the measured intensity of the putative CO emissions in the low-dispersion spectra of Arcturus.

b) Penetration of O I *Radiation into the Temperature Minimum Region*

Photons in the O I triplet are created in the middle chromosphere by Lyβ pumping (Haisch *et al.* 1977). After many scatterings in the Doppler cores of the line profiles, having diffused only a small geometrical distance from the point of creation, an oxygen photon will suffer an infrequent transition to one of the line wings where the comparative transparency will permit a long geometrical flight before the next scattering (whereupon the photon might return to the line core to be trapped at the new depth).

The O I photons will continue to scatter until they either escape completely from the atmosphere or are "destroyed" by (1) an inelastic collision, (2) absorption in a background continuum, or (3) photoexcitation of another species like CO. In the absence of a background absorber, the minimum line-center optical depth to which photons typically scatter before being thermalized is (Mihalas 1978; Doppler case):

$$\Lambda \approx \epsilon^{-1}\ , \tag{1}$$

where ϵ is the probability of a collisional deexcitation:

$$\epsilon = \frac{C_{ul}}{A_{ul} + C_{ul}} . \tag{2}$$

Here, C_{ul} is the collisional decay rate and A_{ul} is the spontaneous decay rate.

I have used expressions for the collision strength given by Haisch *et al.* (1977) and the value they cite for the spontaneous decay rate from the $3s\,^3S$ state to evaluate ϵ:

$$\epsilon \approx 4 \times 10^{-9}(T/5000)^{0.5}(n_e/10^9) . \tag{3}$$

Thus, photons in the oxygen triplet should be able to scatter to very large line-center optical depths ($\gtrsim 10^8$) in the chromosphere of Arcturus ($T \approx 5000$ K; $n_e \approx 10^9$ cm^{-3}: Ayres and Linsky 1975).

However, the photoionization continuum from the $3p^2\,^3P$ ground state of neutral silicon provides an important source of background opacity at 1305 Å. I, therefore, have undertaken numerical calculations to determine the depth at which the Si I continuum becomes optically thick and is able to shield photospheric carbon monoxide molecules from the chromospheric oxygen radiation.

I used the one-dimensional model of the chromosphere of Arcturus derived by Ayres and Linsky (1975) from calibrated measurements of the Ca II H and K lines. I adopted a surface gravity of 50 cm s^{-2}, a value consistent with the shapes of the damping wings of the resonance lines of neutral and ionized calcium (Ayres and Johnson 1977). I obtained differential abundances of the metals (relative to solar) from the extensive study by Mackle *et al.* (1975) and transformed them to the scale where $A_{\rm H} = 1$ by reference to the solar abundances of Vernazza, Avrett, and Loeser (1973).

Work by Lambert and Ries (1977; hereafter LR), concerning the CNO abundances of 11 G and K giants, derived factor of 2 larger (at the 2 σ level) differential abundances of N and O for Arcturus than Mackle *et al.*, although the carbon depletions were similar (at 20%–25% solar). I have used the Mackle *et al.* results, despite the fact that their inferred surface gravity is 0.6 dex lower than that adopted here (and by LR), simply because they provide differential abundances for all of the important metals that affect the ionization equilibrium. Nevertheless, the LR abundances of C and O would tend to enhance the optical depths of the CO bands.

I calculated the ionization equilibrium and chemical equilibrium of the chromospheric gas using the approach outlined by Kurucz (1970). I included all of the important diatomic molecules of the abundant species; H, C, N, O, and Si. For simplicity, I treated the ionization equilibrium of hydrogen according to the approach described by Linsky (1968): A two-level plus continuum model atom in which the principal transition—Lyα—is in detailed balance; the $1 \rightarrow \kappa$ photoionization continuum (LyC) is optically thick; but the $2 \rightarrow \kappa$ photoionization continuum (Balmer C) is optically thin, and is illuminated by a background photospheric radiation field described by a dilute Planck function, $J_\lambda = \frac{1}{2}B_\lambda(T_{\rm rad})$. The ionization approximation will fail in the uppermost portions of the model where radiative transfer effects in the Lyman series and Balmer α become important (see Haisch *et al.* 1977). Nevertheless, the approximation should be reasonable in the lower portions of the model, in the vicinity of the temperature minimum, where the Si I continuum becomes optically thick.

I treated the ionization equilibrium of silicon by a similar strategy: A one-level plus continuum atom for which photoionizations from the $3p^2\,^3P$ ground state ($\lambda_0 \approx 1525$ Å) by H I Lyα are balanced by radiative and dielectronic recombinations:

$$n_{\rm Si} R_{1\kappa} = n_e n_{\rm Si^+}(\alpha_{\rm rad} + \alpha_{\rm di}) . \tag{4}$$

With the cross section cited by Vernazza, Avrett, and Loeser 1976), the observed flux of Lyα from Arcturus yields a lower limit to the photoionization rate of $R_{1\kappa}^{(0)} = 7 \times 10^{-2}$ s^{-1}, assuming that the Lyα photons penetrate fully to the base of the chromosphere where the Si I continuum becomes optically thick. I calculated the temperature-dependent recombination rates using the coefficients tabulated by Aldrovandi and Pequignot (1973). I simulated the thermalization of the Lyα radiation field by modifying the photoionization rate as follows:

$$R_{1\kappa} = R_{1\kappa}^{(0)}\epsilon^{-\tau} + R_{1\kappa}^{\dagger}(1 - e^{-\tau}) . \tag{5}$$

Here, τ is the optical depth of the Si I continuum at Lyα (1216 Å), and

$$R_{1\kappa}^{\dagger} \equiv \frac{(\alpha_{\rm rad} + \alpha_{\rm di})}{(n_{\rm Si}^*/n_{\rm Si^+}^*)} \tag{6}$$

is the photoionization rate that would force detailed balance to obtain in local thermodynamic equilibrium (the asterisks indicate LTE populations). Thus, as τ becomes large the ionization equilibrium of silicon reverts to the LTE case.

In the prototype calculations I also included, at a similar level of approximation, the photoionization of carbon by Lyα from the low-lying metastable $2s^2 2p^2\,^1D$ state ($\lambda_0 = 1239$ Å). The ionization of carbon does not strongly affect the optical depth in the background continuum at Lyα but does affect the quantity of neutral carbon available in the temperature minimum region to associate into molecules like C_2, CH, CN, and CO.

I treated the ionization of all the other metals, including oxygen, in LTE.

Figure 2 summarizes results of the model simulations. Note that the silicon continuum attains unit optical depth at a column mass density of $\sim$0.2 gr cm^{-2}, well above the temperature minimum region of the model. The optical depth of the oxygen triplet, treated as a single line of oscillator strength 0.06, is nearly 10^6 at $\tau_{\rm Si} = 1$, well below the thermalization depth of 10^8, neglecting the background continuum. Thus, the penetration of the oxygen radiation into the lower chromosphere is controlled by the silicon continuum. The optical depths of the strongest transitions from the fourth-positive bands of CO capable of absorbing the oxygen

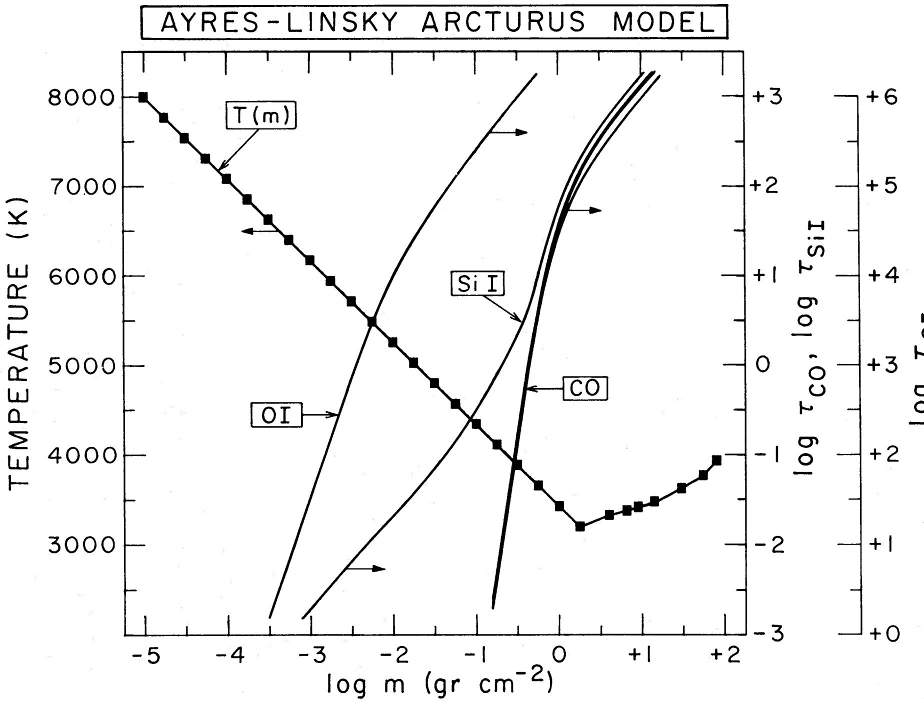

FIG. 2.—Comparison of optical depth scales of the O I triplet; the principal photoionization continuum of neutral silicon; and the strongest transitions from the 9–0, 11–1, and 13–2 bands of the A–X fourth-positive system of CO which are coincident with the O I triplet in the 1305 Å region. The optical depth scales were constructed using the Ayres-Linsky model of Arcturus: the temperature vs. mass column density profile is illustrated as connected filled squares. Notice that the Si I continuum achieves optical depth unity where the CO bands are still quite thin ($\tau_{CO} \approx 10^{-2}$), but the CO absorption increases inwardly rapidly below that level.

radiation are only $\sim 10^{-2}$ where $\tau_{Si} = 1$: the densities are too low and the temperatures are too high to support a large concentration of molecules well above the temperature minimum. Nevertheless, the optical depths of the CO lines increase very rapidly inward compared with the optical depth of the silicon continuum: τ_{CO} increases by an order of magnitude (to 0.1) before τ_{Si} doubles (to 2). The predicted overlap between the rapid inward dilution of the radiation field in the oxygen triplet and the rapid inward increase in the absorption by CO might be sufficient to produce the observed strength of the features identified as fourth-positive bands, particularly in view of the many uncertainties associated with the modeling. Thus, in the context of a single-component model, the CO could be pumped in a narrow layer above the temperature minimum which is optically thin in the fourth-positive bands and which supports a dilute radiation field in the oxygen triplet because of shielding by Si I absorption.

I undertake, below, a numerical simulation of the scenario of optically thin fluorescence with which to compare the high-dispersion measurements of the "CO" regions identified tentatively in the previous low-dispersion spectra of Paper I.

c) *Numerical Simulation of the Fluoresence of Carbon Monoxide*

The case of optically thin pumping of the CO permits several important simplifications in the numerical simulation of the process. First, the absorption by overlapping transitions of the fourth-positive system at a particular wavelength in the O I triplet region is linear, namely, the total absorption simply is the sum of the individual monochromatic absorptivities. Second, self-absorption in the fluoresced CO lines will be negligible. Thus, virtually all of the photons of CO created by the O I pump will escape from the interaction layer, although, of course, only those photons reemitted in the outward direction (and not absorbed by the Si I continuum) will escape from the atmosphere.

Third, the density in the interaction region is low enough that the frequency of vibration-rotation state-changing collisions is very small compared with the fast radiative decays of the excited electronic levels. Following Durrance (1980), the radiative lifetime of a typical vibration-rotation state in the excited $A\ ^1\Pi$ electronic complex is $\sim 10^{-7}$ s. The lifetime of the state to weak inelastic collisions is $\{\langle \sigma v \rangle [M]\}^{-1}$, where $[M]$ is the concentration of the dominant colliding species (in this case molecular hydrogen), v is the velocity of the particles, and σ is the cross section. The hard-sphere cross section for H_2 is $\sim 1 \times 10^{-15}$ cm^2, while the mean velocity is $7 \times 10^5\ (T/5000)^{0.5}$ cm s^{-1} If most of the hydrogen has associated into H_2 at $m = 0.3$ g cm^{-2} ($T \approx 3900$ K; $\tau_{CO} \approx 0.1$), then the number density is $\sim 2 \times 10^{13}$ cm^{-3}. The corresponding lifetime against state-changing collisions is nearly 10^{-4} s, or about three orders of magnitude longer than the lifetime against spontaneous radiative decays.

Consequently, the radiatively decaying states will reflect the parity of the original excitation, and absorptions into the Q-branch (i.e., $\Delta J = 0$) of one $V_l \rightarrow V_u$ band therefore will result in cascades *only* in the Q-branches of the accessible $V_u \rightarrow V_l'$ bands, while each R-branch ($\Delta J = +1$) or P-branch ($\Delta J = -1$) absorption will cascade only into the R- or P-branches (with equal probability) but not into the Q-branch. Accordingly, absorptions of oxygen radiation by a particular vibration-rotation line of the fourth-positive system will excite only a limited array of decay channels.

Schematically, the relative rate of excitation of vibration-rotation level $V'J'$ of the excited electronic complex $A\ ^1\pi$ by absorption of an O I photon in the $V''J''$ level of the $X\ ^1\Sigma^+$ ground state of CO is

$$R_{V'J'V''J''} \approx f_{V'J'V''J''} \tilde{n}_{V''J''} \int_{-\infty}^{\infty} \phi(\lambda - \lambda_L) \frac{J_\lambda}{(hc/\lambda)} d\lambda . \quad (7)$$

Here, f is the transition oscillator strength (Kurucz 1976); ϕ is the Doppler absorption profile centered at the rest wavelength, λ_L, of the CO line; J_λ is the monochromatic mean intensity of the radiation field in the 1305 Å region; and $\tilde{n}$ is the population of the $V''J''$ level of the ground electronic state relative to the total number density of CO:

$$\tilde{n}_{V''J''} = \frac{n_{V''J''}}{n_{CO}} = \frac{(2J''+1)}{Q_{CO}(T)} \exp\left(-\frac{E_{V''J''}}{kT}\right) , \quad (8)$$

where $Q_{CO}(T)$ is the partition function and $E_{V''J''}$ is the excitation energy (Roh and Rao 1974).

The excitations into upper level $V'J'$ decay through an array of transitions $V'J' \rightarrow VJ$ as follows:

$$F_{V'J'VJ} \approx \frac{hc}{\lambda_{V'J'VJ}} R_{V'J'V''J''} \omega_{V'V} \begin{cases} 1/2[\delta(J'-1, J) + \delta(J'+1, J)] , & J' = J'' \pm 1 \ (R, P \text{ branches}) , \\ \delta(J', J) , & J' = J'' \ (Q \text{ branch}) , \end{cases} \quad (9)$$

where the $\omega_{V'V}$ is the branching ratio for the band $V' \rightarrow V$ (no collisional quenching; see Durrance 1980), and the δ-functions select the appropriate decay channels that conserve parity (see above). I calculated wavelengths of the $V'J' \rightarrow VJ$ transitions using the excitation energies for the $A\ ^1\Pi$ complex of Simmons, Bass, and Tilford (1969) and those for the $X\ ^1\Sigma^+$ complex cited above.

I constructed the total spectrum of fluorescence numerically by summing equation (9) over all of the possible input channels. Figure 3 illustrates prototype radiation fields for the O I triplet (plus S I λ1303) and the absorption patterns of the CO features for temperatures of 1000 K, 2000 K, and 3000 K. (The pattern for 4000 K, the temperature near which $\tau_{CO} = 0.1$ in the simulations illustrated in Fig. 2, above, is essentially identical to that of the 3000 K case.) Figure 4 compares predicted relative fluorescence spectra for the oxygen radiation fields of the previous figure and a range of possible temperatures of the absorbing layers. The central tracing of each of the Figures 4a–4c, depicts the matching wavelength regions from the empirical high-dispersion spectrum smoothed somewhat to enhance the visibility of the faint spectral structure.

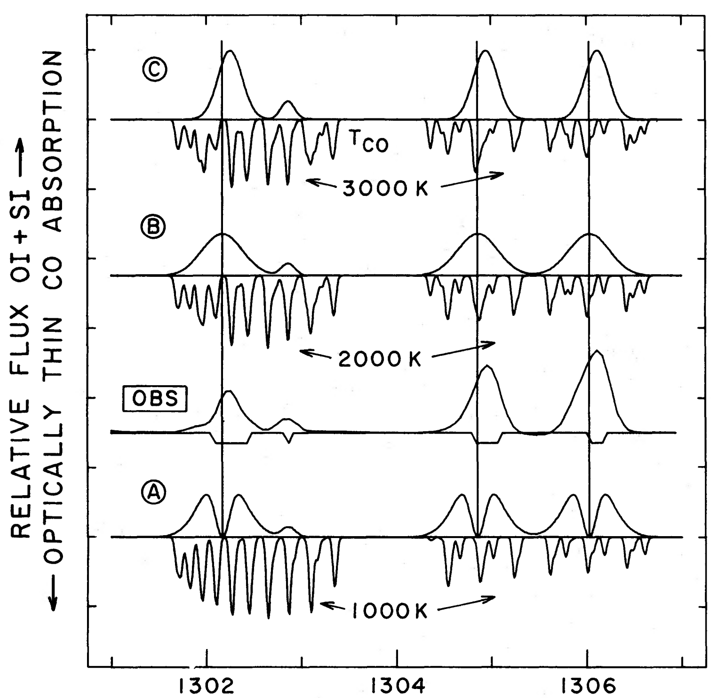

FIG. 3.—Comparison of observed spectrum in vicinity of the O I triplet with several prototype models for the oxygen (and S I λ1303) radiation fields at large depths in the chromosphere. The observed spectrum (designated "OBS") was smoothed to an effective resolution of 0.22 Å (50 km s^{-1} FWHM) to improve the signal-to-noise ratio. The vertical lines indicate the laboratory wavelengths of the O I triplet components: the apparent redward asymmetry of the oxygen profiles is caused by violet-displaced absorption by circumstellar material. Below each of the model radiation fields are absorption patterns calculated for transitions from the 9–0, 11–1, and 13–2 bands of CO. The absorption patterns are illustrated for temperatures of 1000 K, 2000 K, and 3000 K. As the temperature of the absorbing layer increases, the populations of the excited vibrational levels of the electronic ground state increase relative to that of $V'' = 0$ and the fluorescence channels through the 11–1 and 13–2 bands increase in importance.

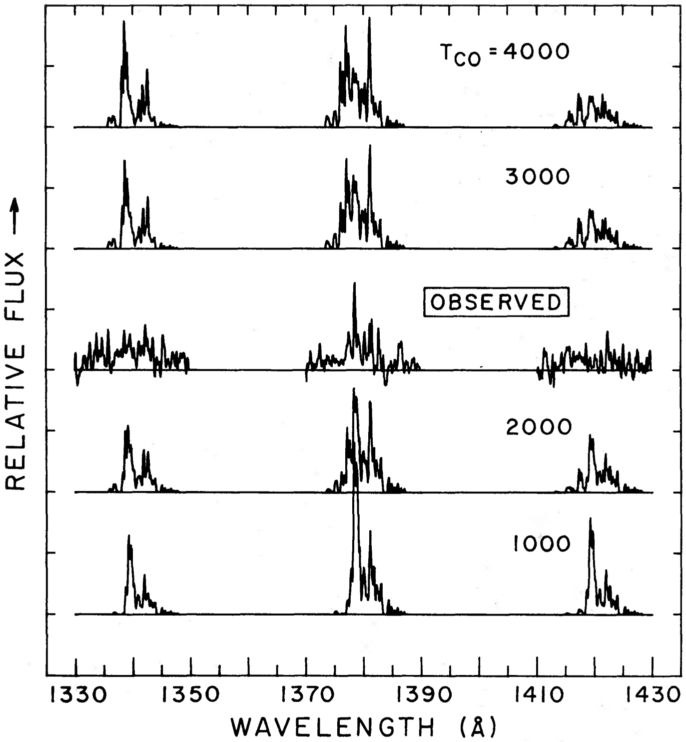

FIG. 4*a*

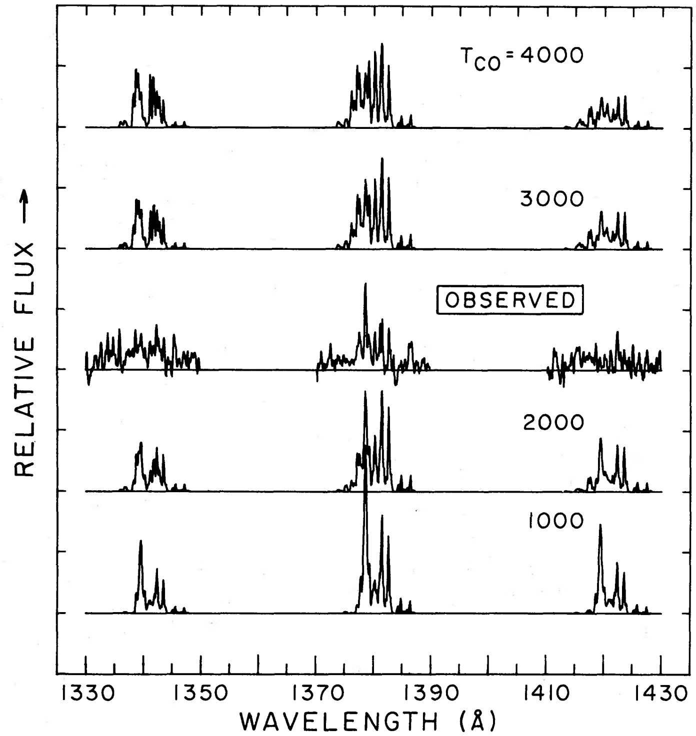

FIG. 4*b*

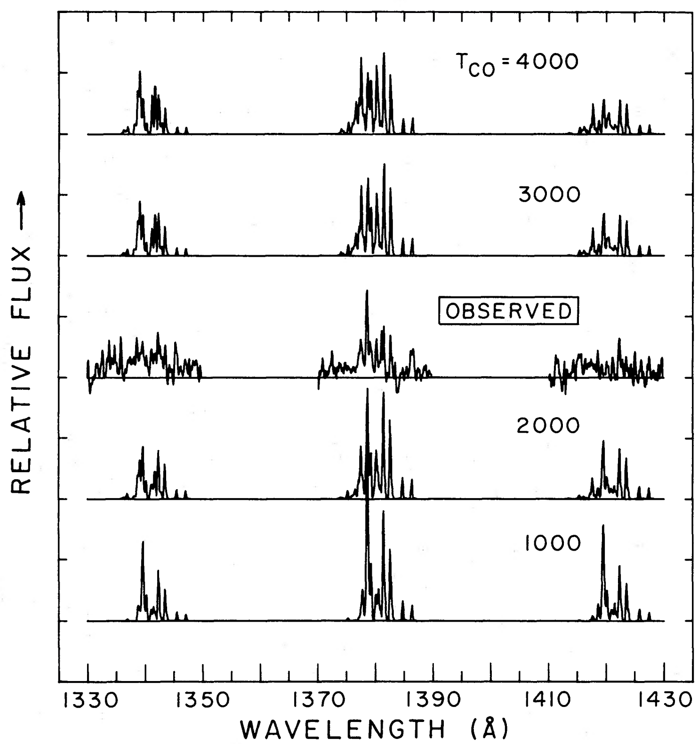

FIG. 4*c*

FIG. 4.—(*a*) Comparison of observed spectral structure (central tracing) and predicted fluorescent emission of CO in three intervals where suspected CO emission bands have been tentatively identified in low-dispersion *IUE* spectra of Arcturus. The strongest of the features at low dispersion is near 1380 Å and corresponds to the middle segment of the observed spectrum. The calculation was undertaken in an optically thin approximation for the simulated radiation field designated model (A) in the previous figure and for a range of possible temperatures in the absorbing layer (assumed isothermal). Each of the simulations were normalized by scaling the calculated flux of the 1380 Å band to the observed integrated flux over the interval 1375–1385 Å. The scaling factor is related to the column density of absorbers and the true mean intensity of the oxygen radiation field in the lower chromosphere, neither of which was calculated in detail in the present work. (*b*) Same as (*a*), for radiation field model B. (*c*) Same as (*a*), for radiation field model C.

The model A probably most closely describes the shape of the oxygen radiation field at large optical depths: the triplet components are broadened by diffusion of photons in frequency, and a pronounced central reversal develops because of scattering of photons out of the opaque core of the Doppler profile. Model B is similar to model A, but lacks the central self-absorption. Model C approximates the appearance of the *observed* shapes of the oxygen lines including the shading of the violet edges of the emission cores by circumstellar absorption. Model C would be appropriate for the pumping of CO molecules in a circumstellar shell.

Qualitatively, all of the models reproduce some of the essential characteristics of the observed "CO" spectral regions, particularly the strongest of the fluoresced bands at 1380 Å. If one considers only the 1380 Å band, the best matches are for the two low-temperature simulations. Indeed, the ratio of the strong 1378 Å component to the weaker 1381 Å and 1383 Å components would seem to suggest that the temperature of the absorbing layer is quite low, perhaps less than 2000 K. However, the comparative weakness of the 1420 Å band relative to those at 1380 Å and 1340 Å argues for a higher temperature of the absorbing layer, perhaps as high as expected near $\tau_{CO} \approx 0.1$ in the Ayres-Linsky model. It is worth noting that at low dispersion the 1420 Å feature is noticeably weaker than the 1340 Å emission, which in turn is only somewhat weaker than the 1380 A band (Ayres, Moos, and Linsky 1981; Carpenter, Wing, and Stencel 1985). Thus, the low-dispersion spectrum of Arcturus qualitatively supports a high temperature for the interaction region. Nevertheless, if the temperature of the CO layer is as high as 4000 K, then the observed pattern of the optically thin fluorescence in the 1380 Å band is quite inconsistent with the predicted pattern.

The origin of the disagreement is not clear, particularly given the many simplifications underlying the numerical simulations. Furthermore, the quality of the observational material is not high: the detection of the weak fluorescent emissions of CO is at the limit of the capabilities of the *IUE*. Nevertheless, the striking similarity in the appearances of the empirical and predicted spectral structure in the "CO" regions strongly suggests that fluoresced bands of the fourth-positive system are indeed responsible for the apparent emission at both low dispersion and high dispersion.

III. DISCUSSION

Even though the calculations for the Ayres-Linsky homogeneous model suggest that CO molecules in the low chromosphere of Arcturus plausibly can be radiatively pumped by the O I triplet, there certainly is no guarantee that the one-dimensional model is an appropriate description of physical conditions in the outer layers of the red giant. Indeed, studies of the fundamental ($\Delta V = 1$) vibration-rotation bands of CO in the middle-infrared (4.7 μm) spectrum of Arcturus by Heasley *et al.* (1978) suggest that the chromosphere of the red giant must be quite inhomogeneous: no single laterally homogeneous thermal profile can simultaneously reproduce the centrally reversed chromospheric emission core of the Ca II λ3934 K line (see the Ayres-Linsky model) and the deep absorption cores of strong lines from the fundamental bands of CO, which exhibit no evidence for emission reversals. Heasley *et al.* explained the discordance by postulating that the CO fundamental bands form preferentially in a radiative equilibrium component of the red-giant atmosphere which attains comparatively low temperatures in its outer layers because of the strong surface cooling by the CO molecules themselves. In the authors' model, the emission cores of the Ca II resonance lines would form preferentially in a second atmospheric component, having a steep chromospheric temperature inversion caused by substantial mechanical heating, but which covers less than half of the star. Thus, the spatially averaged spectrum would contain signatures of both the hot and cool atmospheric components. These would manifest themselves to different degrees in different spectral diagnostics, and thereby frustrate the development of a comprehensive one-dimensional model. Indeed, a similar situation seems to obtain on the Sun, where the behavior of the resonance lines of Ca II and the fundamental bands of CO is equally discordant (Ayres and Testerman 1981; Ayres 1981; Ayres, Testerman, and Brault 1986).

If the plasma is as cool above $m = 1.0$, as indicated by the Heasley *et al.* model, then virtually all of the carbon will associate into CO, and the optical depths of the strongest lines of the fourth positive system will be *directly* proportional to the column mass density:

$$\tau_{CO} \approx 1 \times 10^{-18} A_C N_H \leq 3 \times 10^1 \ m , \tag{10}$$

instead of the steep relation seen in Figure 2. The optical depth of the silicon continuum in the cool material should be similar to the optical depth relation in the warmer material since the electron density—determined by the easily ionized metals—does not strongly depend on temperature below 5000 K (see, Ayres 1979). Thus, the CO bands might become optically thick to the radiation field of the O I triplet *before* it could be thermalized by the Si I continuum. The fraction of the total O I radiation which could be absorbed and reprocessed by the CO will depend sensitively on the geometry of the cool and warm atmospheric zones; namely, on the amount of the O I radiation scattered *horizontally* out of the warm zones compared to the amount thermalized internally.

The major discriminant between the two hypotheses is that the CO must be pumped in an optically thin layer in the homogeneous scenario, while the CO might be optically thick in the inhomogeneous scenario.

However, the unknown geometry of the inhomogeneous scenario prevents a definitive simulation of the optically thick case at the present time. A concerted effort will be required to obtain diagnostic information of high quality in the ultraviolet (Mg II, Mg I), optical (Ca II, Ca I), and infrared (CO) in order to set limits on possible configurations of the inhomogeneous outer atmosphere of Arcturus, comparable to the approach taken by Ayres, Testerman, and Brault (1986) in the solar case. Such a study is beyond the scope of the present paper and will be deferred to future work.

This work was supported by grants NAG5-199 and NGL-06-003-057 from the National Aeronautics and Space Administration and by grants AST 8203450 and AST 8507029 from the National Science Foundation. Discussions with P. Judge were extremely valuable in the initial stages of this work. I also thank C. Jordan, J. Linsky, K. Carpenter, and A. Brown for their comments at various other stages of the study.

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