1976ApJ...210..199A

THE ASTROPHYSICAL JOURNAL, 210:199–210, 1976 November 15
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STELLAR MODEL CHROMOSPHERES. V. ALPHA CENTAURI A (G2 V) AND ALPHA CENTAURI B (K1 V)

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Received 1976 February 27; revised 1976 April 21

ABSTRACT

We propose models for the upper photospheres and lower chromospheres of α Cen A and B based on a partial redistribution (PRD) analysis of the Ca II K line cores and damping wings. Coudé spectrograms of the Ca II regions in these stars obtained with the Mount Stromlo 74 inch (1.9 m) telescope are calibrated by fitting the far wing profiles of K with synthetic fluxes based on radiative equilibrium (RE) models. The RE calibrations are verified by comparison with independent calibrations using Willstrop's absolute photometry and narrow band fluxes obtained at Mount Stromlo. Deviations of the empirical profiles from the RE fluxes in the inner wings of K suggest departures from radiative equilibrium in the upper photosphere of α Cen A comparable to those found previously for the Sun and Procyon. Alpha Cen B shows similar departures from RE when the effects of CO cooling near the temperature minimum are taken into account. We find similar ratios of $T_{\rm min}/T_{\rm eff}$ for both stars, which are within the range of $T_{\rm min}/T_{\rm eff}$ ratios determined previously for the Sun, Procyon, and Arcturus. In addition, we find similar mass column densities at the 8000 K levels of the α Cen A and B chromospheres comparable to those determined for the Sun and Procyon. Finally, α Cen A appears to be more evolved and possibly much older than the Sun, despite its similar chromosphere structure.

Subject headings: line profiles — stars: atmospheres — stars: chromospheres — stars: individual

I. INTRODUCTION

In previous papers of this series and elsewhere, we have proposed upper photosphere and lower chromosphere models for several late-type stars including Procyon (α CMi, F5 IV–V; Ayres, Linsky, and Shine 1974 [Paper II]), Arcturus (α Boo, K2 III; Ayres and Linsky 1975*a* [Paper III]), and the Sun (G2 V; Ayres and Linsky 1976). These models are based on the interpretation of calibrated profiles of strong resonance lines such as Ca II λ3934 (K) and λ3968 (H) and Mg II λ2796 (*k*) and λ2803 (*h*) using a spectrum synthesis approach. In this paper we continue our discussion of the outer atmospheres of late-type stars by deriving photosphere and chromosphere models for α Cen A (G2 V) and α Cen B (K1 V) using high-dispersion spectrograms of the Ca II K line emission cores and damping wings.

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Alpha Centauri A and B, and their proper-motion companion Proxima Cen (α Cen C, dM6e), are the closest and brightest stars of their spectral classes (except for the Sun). These stars are therefore ideally suited for the high-dispersion spectroscopy necessary to resolve weak chromospheric emission cores in deep absorption features such as Ca II K and Mg II *k*. In addition, the trigonometric parallaxes of both components are well determined, and the stellar masses have been accurately derived from measurements of the orbital elements. In this regard, α Cen A and B are well enough separated (semimajor axis $\sim$23 AU) that mass-exchange effects should be unimportant, but close enough that the orbital parameters can be measured easily ($P \sim 80$ yr).

Alpha Cen A is similar to the Sun and therefore provides an important test case for understanding the evolution of solar-type stars in general, and the evolution of solar-type chromospheres in particular. Furthermore, both α Cen A and B serve as prototypes for future detailed studies of main-sequence G and K dwarfs and subgiants which form a substantial portion of stellar populations.

The paper is divided into sections as follows: In § II we estimate effective temperatures and surface

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gravities for α Cen A and B consistent with the measured broad-band colors, metallicities, masses, and absolute luminosities. In § III we describe the observations and calibrations of the α Cen A and B Ca II K lines, which provide a basis for inferring upper photosphere and lower chromosphere models in § IV. Finally, in § V we compare the derived models for α Cen A and B with those proposed previously for Procyon, Arcturus, and the Sun, and comment on the implications of this comparison.

II. STELLAR PARAMETERS FOR α CENTAURI A AND B

In order to construct a model of a star's atmosphere we must know the stellar effective temperature ($T_{\rm eff}$; K), surface gravity (g; cm s^{-2}), and metallicity (Z; $Z_\odot \approx 0.02$, by mass). The first two of these quantities can be determined directly if the stellar mass, radius, and absolute bolometric luminosity are known (e.g., Procyon, Sirius). In the general case where one or more of the latter quantities are unknown, the effective temperature and gravity often can be estimated indirectly, for instance by using an empirical [$T_{\rm eff}$, $(B - V)_0$]-relationship (e.g., Johnson 1966) or from ionization ratios derived from measured equivalent widths. The third quantity, the stellar metallicity, can be estimated coarsely by means of two-color diagrams (e.g., $[U - B] - [G - I]$), or more accurately by means of differential curve-of-growth analyses based on high-dispersion spectrograms.

Table 1 lists the measured and estimated photospheric properties of α Cen A and B. The sources of these quantities are described individually below.

a) *Metallicity*

French and Powell (1971) have estimated the metallicity of the α Cen system relative to the Sun by a differential curve-of-growth technique. The mean abundances determined for the A and B components, and specifically the calcium abundances, are roughly a factor of 2 larger than solar, with the exception of magnesium in α Cen A. The similar compositions of both stars is consistent with their presumed common origin. French and Powell's (1971) analysis should be reasonably accurate for α Cen A, owing to its similarity to the Sun, but the use of LTE diagnostics adds an element of uncertainty. Therefore, we provisionally adopt a factor-of-2 metal abundance enhancement for α Cen A and B, but we also carry through our analysis assuming normal solar composition (e.g., Vernazza, Avrett, and Loeser 1973) for both stars as a check on

TABLE 1

STELLAR PARAMETERS

Parameter	α Cen A	α Cen B	Sun
M_V	4.35 ± 0.04[b,i]	5.69 ± 0.04[b,i]	4.83 ± 0.03[a,b]
$(B - V)_0$	0.68 ± 0.02[b]	0.88 ± 0.02[b]	0.64 ± 0.01[a,l]
	0.70 ± 0.02[l]	0.90 ± 0.02[l]	0.65[b]
$\delta(B - V)_0$	0.03 ± 0.01[c]	0.24 ± 0.02[a,b,l]	0.
	0.04 ± 0.02[a,b,l]		
$\delta M_{\rm bol}$	−0.51 ± 0.04[f,g]	+0.68 ± 0.04[f,g]	0.
[Metals/H]†:			
[Fe/H]	0.22 ± 0.05[h]	0.12 ± 0.04[h]	0.
[Ca/H]	0.27 ± 0.06[h]	0.34 ± 0.05[h]	0.
$[\bar{M}/H]$‡	0.31 ± 0.15[h]	0.26 ± 0.18[h]	0.
$[\bar{M}/H]$, [Ca/H] adopted	0.0 or 0.3	0.0 or 0.3	
$\mathfrak{M}^*/\mathfrak{M}^\odot$	1.07 ± 0.03[b,d,e]	0.88 ± 0.01[b,d,e]	1.0
	1.16 ± 0.08[i]	0.91 ± 0.06[i]	
$\mathfrak{M}^*/\mathfrak{M}^\odot$ adopted	1.1	0.9	
$T_{\rm eff}$ (K)	5770 ± 75[k]	5300 ± 150[k]	5770 ± 10[a]
	5700 ± 75[j]	5150 ± 150[j]	
log g (cm s^{-2})	4.27 ± 0.04[k]	4.50 ± 0.04[k]	4.44[b]
	4.25 ± 0.04[j]	4.45 ± 0.04[j]	

† The notation refers to abundances relative to solar on a logarithmic scale.

‡ Average includes Fe, Na, Al, Si, Ca, Ti, Cr, and Ni, but excludes Mg because value for α Cen A [Mg/H] = −0.48 ± 0.30 differs significantly from mean abundance enhancements and is based on essentially only one Mg I line.

[a] Labs and Neckel 1968.

[b] Allen (1973; M_V, $(B - V)_0$ from Gliese 1969, Cousins 1973, Cousins and Lagerweij 1967).

[c] Doherty 1972.

[d] Harris *et al.* 1963.

[e] van de Kamp 1971.

[f] H. L. Johnson 1966.

[g] Wesselink 1969.

[h] French and Powell 1971.

[i] Gasteyer 1966.

[j] Assuming normal solar abundances.

[k] Assuming French and Powell 1971 abundances and abundance-reddening corrections.

[l] Comparison of Willstrop 1965 narrow-band photometry.

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the sensitivity of our approach to uncertainties in the adopted metal abundances.

As in the previous papers of this series, we assume a 10 percent helium abundance (by number relative to hydrogen) for both α Cen A and B.

b) *Effective Temperature*

We estimate the effective temperatures of α Cen A and B semiempirically by comparing the measured $(B-V)_0$ colors of each star with the $[T_{\text{eff}}, (B-V)_0]$-relationships of Johnson (1966), Wesselink (1969), Schmidt (1972), and Travis and Matsushima (1973). In all cases the (effective temperature, color)-relationships are applied differentially with respect to the Sun. We adopt $(B-V)_0^{\text{A}} = 0.68 \pm 0.02$ (superscripts denote the particular α Cen component) and $(B-V)_0^{\text{B}} = 0.88 \pm 0.02$ from Cousins and Lagerweij (1967), and $\delta(B-V)_0^{\text{A}} = 0.03 \pm 0.01$ (Doherty 1972), where the last quantity refers to a measurement relative to the Sun.

Because direct measurements of $B-V$ for bright stars such as α Cen A and B can be more uncertain than comparable measurements for fainter stars, we checked the broad-band colors given by Cousins and Lagerweij by comparing Willstrop's (1965) narrow-band (50 Å) energy distributions for α Cen A and B with those of other G and K dwarfs in Willstrop's tables. Our results, $(B-V)^{\text{A}} \sim 0.70 \pm 0.02$ and $(B-V)^{\text{B}} \sim 0.90 \pm 0.02$, are in good agreement with the direct measurements cited above.

In practice we apply small corrections to the measured $(B-V)_0$'s, $\Delta(B-V)_0^{\text{A}} = -0.04$ mag and $\Delta(B-V)_0^{\text{B}} = -0.06$ mag, to account for the effects of enhanced metallicity on reddening the α Cen broad-band colors. The estimate for α Cen A is consistent with Wallerstein's (1962) sample of 21 G dwarfs where $\Delta(B-V)_0 = -0.04$ mag for a factor of 2 increase in metal abundance. The estimate for α Cen B is that necessary to remove the age anomaly cited by French and Powell (1971) and place α Cen B near the NGC 188 main sequence (cf. Bell and Rodgers 1969). Using the "corrected" colors, we estimate $T_{\text{eff}}^{\text{A}} \approx T_{\text{eff}}^{\odot} = 5770$ K and $T_{\text{eff}}^{\text{B}} \approx 5300$ K. Alternatively, the uncorrected colors suggest somewhat cooler effective temperatures, $T_{\text{eff}}^{\text{A}} = 5700$ K and $T_{\text{eff}}^{\text{B}} = 5150$ K. For consistency, we adopt the latter values for the "solar composition" α Cen models. The uncertainties in these T_{eff} estimates probably do not exceed ± 75 K for α Cen A and ± 150 K for α Cen B, aside from possible systematic errors in the abundance-reddening corrections.

c) *Surface Gravity*

Owing to the availability of reliable trigonometric parallaxes for the α Centauri system (Gasteyer 1966), the absolute visual luminosities of the bright A and B components can be accurately determined. The total luminosities relative to the Sun are given as δM_{bol} in Table 1 using the bolometric corrections of Johnson (1966) and Wesselink (1969). In addition, the masses of α Cen A and B have been inferred from the orbital elements: $\mathfrak{M}^{\text{A}}/\mathfrak{M}^{\odot} \approx 1.1$ and $\mathfrak{M}^{\text{B}}/\mathfrak{M}^{\odot} \approx 0.9$ (van de Kamp 1958; Harris, Strand, and Worley 1963; Gasteyer 1966; Allen 1973). For fixed luminosity and mass, the surface gravity of a star scales as the "surface luminosity" σT_{eff}^4. Using the composition-dependent effective temperatures of the previous section, we estimate a range of surfaces gravities for α Cen B comparable to solar, while the corresponding values for α Cen A are somewhat smaller than solar ($g^{\text{A}} \sim 70\%$ of $g^{\odot}$).

d) *Age of the* α *Centauri System*

Although α Cen A and B are classified as main-sequence (MS) dwarfs, both stars lie significantly above the Hyades MS ($\Delta M_V^{\text{A}} \sim -0.8$ mag, $\Delta M_V^{\text{B}} \sim -0.4$ mag). In fact, α Cen A should probably be classified as a subgiant owing to its similarity to neighboring stars on the HR diagram such as 31 Aql (G8 IVp), δ Pav (G5 IV), and 83 Leo A (K0 IV). On the other hand, α Cen B is probably close enough to the Hyades MS to justify its luminosity class V designation. In any case, both stars appear to be significantly more evolved than the Sun. Owing to its proximity to the NGC 188 main sequence, the α Centauri system is probably comparable in age to that old open cluster ($\sim 10^{10}$ yr; cf. French and Powell 1971), and therefore perhaps *twice* as old as the Sun.

The faintest member of the α Centauri system, Proxima Centauri (α Cen C), is a dM6e or dM4e flare star (Shapley 1951) and is probably a physical member of the system (van de Kamp 1971; Gasteyer 1966). Haro and Chavira (1964) argue on the basis of cluster ages that dMe flare stars are typically less than 1×10^9 years old. On the other hand, dMe stars with old disk kinematics are known, and are presumed to be old. In addition, Grossman, Hays, and Graboske (1974) compute that a low-mass star such as α Cen C with $L/L_{\odot} = 1.8 \times 10^{-3}$ would require about 10^9 years simply to contract to the zero-age main sequence, and would remain on the main sequence considerably longer. Because Joy and Abt (1974) find that all dwarf stars later than M5.5 are dMe stars, we conclude that the presence of Proxima Cen in physical association with α Cen A and B is not inconsistent with an age estimate of 10^{10} years for the system.

Comparing this result with an α Cen A age of 3.6×10^9 years estimated from the statistical correlation of apparent rotational line broadening with age (Boesgaard and Hagen 1974), suggests that caution should be exercised when applying statistical correlations, such as rotation and Ca II emission versus age (van den Heuvel and Conti 1971; Skumanich 1972), to individual cases.

III. OBSERVATION AND CALIBRATION OF Ca II K IN α CENTAURI A AND B

a) *Observations*

Coudé spectrograms covering the spectral range 3825–4100 Å were obtained by one of us (A. W. R.) at the Mount Stromlo 74 inch (1.9 m) telescope. The

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spectral dispersion was 2.5 Å mm^{-1} on baked IIa-O plates. The spectrograms were microphotometered at the High Altitude Observatory and corrected for the nonlinear intensity response of the film by means of characteristic curves derived from spectrograms of uniformly illuminated calibration wedges (Hewitt, Linsky, and Rodgers 1973). In addition, the digitized spectra were Fourier-filtered to remove noise.

An independent measurement of the instrumental scattered light level in the Mount Stromlo coudé system is not presently available. An estimate of this quantity was obtained by comparing deep absorption features (on the flat part of the curve of growth) in the α Cen A tracings with the corresponding features in the high dispersion, low scattered light Kitt Peak Solar Atlas (Brault and Testerman 1972) degraded with a 5.5 km s^{-1} Gaussian to simulate the $\lambda/\Delta\lambda \sim 6 \times 10^4$ spectral resolution of the α Cen spectrograms. The scattered light level derived from this comparison was somewhat less than 3 percent of the quasi-continuum points at 3950.7 and 3954.2 Å (Hewitt, Linsky, and Rodgers 1973). Note, however, that a correction of this magnitude represents a substantial relative change ($\sim$25 percent) at the H_1 and K_1 minimum features owing to the extreme depth of the Ca II resonance line cores.

The observed K line cores and damping wings of α Cen A and B are illustrated in Figure 1. Included in this figure is an integrated light profile of the solar K line core synthesized by a weighted average of the $\mu = 1.0$ and 0.2 profiles in the Kitt Peak Solar Atlas. Notice that the relatively weak α Cen A double reversal is very similar to its solar counterpart, although the K_{2v}/K_{1v} contrast and core width appear to be slightly larger. Both stars show stronger violet peak emission and brighter K_{1v} compared with the corresponding long-wavelength features. On the other hand, α Cen B shows a substantially larger K_2/K_1 contrast and a more symmetric doubly reversed emission core ("2" on Wilson and Bappu's [1957] scale), with slightly enhanced K_{1r} compared with K_{1v}.

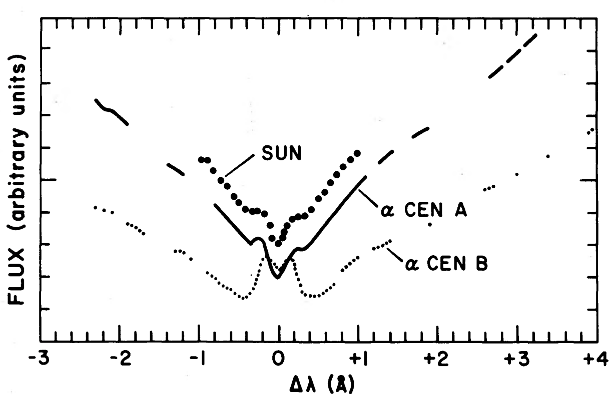

FIG. 1.—Relative flux profiles of the α Cen A and B Ca II K lines. An integrated light solar profile of K degraded to the spectral resolution of the α Cen observations is represented by filled circles. For clarity the solar profile has been shifted upward by one division, and absorption features in K wings have been omitted.

b) Calibration Relative to RE Model Photospheres

Following Ayres (1975*a*) we calibrate the measured profiles of the Ca II K far wings ($\Delta\lambda \gtrsim 5$ Å), which are formed near $\tau_{5000} \sim 0.1$, relative to synthetic fluxes based on radiative equilibrium (RE) photospheric models appropriate to the surface gravities and effective temperatures of α Cen A and B inferred in § II. We adopt this approach partly for simplicity, but primarily because it readily provides estimates for the relative departures from radiative equilibrium in the surface layers ($\tau_{5000} \lesssim 0.01$) of the particular star modeled. In fact, for the two stars—Procyon and Arcturus—for which independent narrow-band calibrations and accurate angular diameters are available, the two approaches give essentially identical results (Ayres 1975*b*). The RE relative calibration technique is particularly suited for the large number of stars, such as α Cen A and B, for which reliable angular diameters are not available.

i) *Application of Radiative Equilibrium Relative Calibration*

The RE relative calibration is based on the premise that the photospheric properties of a late-type star are best known in those layers of the atmosphere where the optical continuum emission is formed ($1 \gtrsim \tau_{5000} \gtrsim 0.1$). In particular, well-observed quantities such as $(B - V)_0$ and narrow-band spectral colors are determined primarily by the shape of the temperature-pressure structure near $\tau_{5000} = 1$. We assume that these deep photospheric properties can be described adequately by a line-blanketed, radiative equilibrium model (including mixing-length convection) appropriate to estimated values of $T_{\rm eff}$, g, and Z for the particular star. This assumption should be reasonably accurate for the majority of late-type stars where radiation transport dominates the energy balance above $\tau_{5000} = 1$, but can be expected to become progressively less reliable for those stars with appreciable convective transport above $\tau_{5000} = 1$, because the treatment of convection in the RE models is almost certainly the greatest source of uncertainty.

The synthesis of K wing intensities for a particular RE model is based on an LTE partial coherent scattering formalism (Ayres 1975*a*) specialized to a five-level representation of Ca II including the LTE Ca I–Ca II–Ca III ionization equilibrium. We expect LTE to be adequate for the damping wings ($\Delta\lambda > 0.5$ Å) of Ca II because the line-center optical depths in the upper photosphere greatly exceed the Doppler core thermalization lengths, and the ultraviolet radiation fields ($\lambda \lesssim 1500$ Å) responsible for photoionizations of Ca II in the chromosphere are also well thermalized in the upper photosphere. The important effect here is not departures from LTE, but rather departures from complete redistribution (CRD; see Shine, Milkey, and Mihalas 1975; Ayres 1975*a*). In this regard, we expect the partial coherent scattering approximation to be reasonably accurate for the K wings ($\Delta\lambda \gtrsim 0.5$ Å), because even the inner wings are formed many Doppler widths from line center where the $R^{\rm II}$ redistribution function assumes the functional character of pure

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coherent scattering. In fact, in the far wings of the solar K line beyond $\Delta\lambda \approx 2$ Å complete redistribution is itself a reasonable approximation owing to the rapid inward density increase in the photosphere, because the coherence of the resonance scattering process is destroyed by pressure broadening (e.g., Milkey, Shine, and Mihalas 1975).

We determine the elastic collision parameter (in this case primarily ordinary van der Waals) semiempirically by fitting absolute specific intensity profiles of the solar K line damping wings with synthetic profiles based on a detailed LTE line-blanketed RE model of the solar photosphere (Kurucz 1974). We minimize the effect of possible errors in this "calibration" of the van der Waals coefficient by using RE models for α Cen A and B constructed in the same manner as the adopted solar RE model.

ii) *RE Calibration of the α Cen A and B K Lines*

As described in § II above, we estimate two sets of T_{eff} and g for each star corresponding to the assumptions of normal solar abundances and factor of two enhanced abundances. A small grid of line-blanketed radiative equilibrium models spanning the appropriate T_{eff}–g range was computed by one of us (R. L. K.). We interpolate models from this grid according to the following scheme: the temperature scaling is simply

$$T_e'(m) = (T_{\text{eff}}'/T_{\text{eff}})T_e(m)\,, \qquad (1)$$

where m is the mass column density in grams cm^{-2}, which we adopt as a depth variable. The mass column densities (or equivalently the total pressures, $P_{\text{tot}} = gm$) are modified in such a way as to preserve the scaled temperature versus τ_{5000} structure (see, e.g., Carbon and Gingerich 1969), i.e., to preserve the continuum energy distribution appropriate to T_{eff}'. The derived pairs of temperature models for α Cen A and B and the basis solar model [5770, 4.44, 1.0][1] are illustrated in Figure 2.

Synthesized far wing K line fluxes for these adopted RE temperature models are illustrated in Figure 3. Notice that the nominally much different α Cen A models impose essentially identical absolute flux calibrations on the empirical K profile because the increased line broadening attributable to the larger calcium abundance used with the [5770, 4.27, 2.0] model compensates for the somewhat cooler temperatures of the [5700, 4.25, 1.0] model. On the other hand, the differences between the two α Cen B calibrations are larger owing to the greater spread in the inferred effective temperatures.

By matching the theoretical RE profiles of Figure 3 to the empirical K line profiles in the far wings, we derive emission indices (πF_{K}), which are defined as the flux integrated between K_{1v} and K_{1r}. These quantities and the $K_{1v} - K_{1r}$ bandpasses are compared in Table 2 with the K indices previously derived for the Sun and Procyon (Ayres 1975*a*) and Arcturus (Paper III). We caution that the K indices estimated for α Cen A and B are somewhat sensitive to the adopted scattered light correction. In particular, if we had used the original data uncorrected for the estimated scattered light level of § III*a* above, we would have derived K indices roughly 25 percent larger for α Cen A and 20 percent larger for α Cen B.

The K index is a physically significant quantity because the Ca II H and K emission cores are important sources of radiative cooling in stellar chromospheres. Because radiative losses must balance the divergence of the nonradiative flux, the absolute K index will typically follow increases or decreases in chromospheric heating. Therefore, the K index serves as a convenient indicator of chromospheric "strength." Another characteristic feature of the K line profile frequently also associated with chromospheric strength or activity is the K_2/K_1 intensity contrast. However, this quantity, which is essentially the Wilson-Bappu Ca II index, depends on photospheric properties as well as on chromospheric properties, because the K_1 intensity is determined primarily by the thermal structure of the upper photosphere and temperature

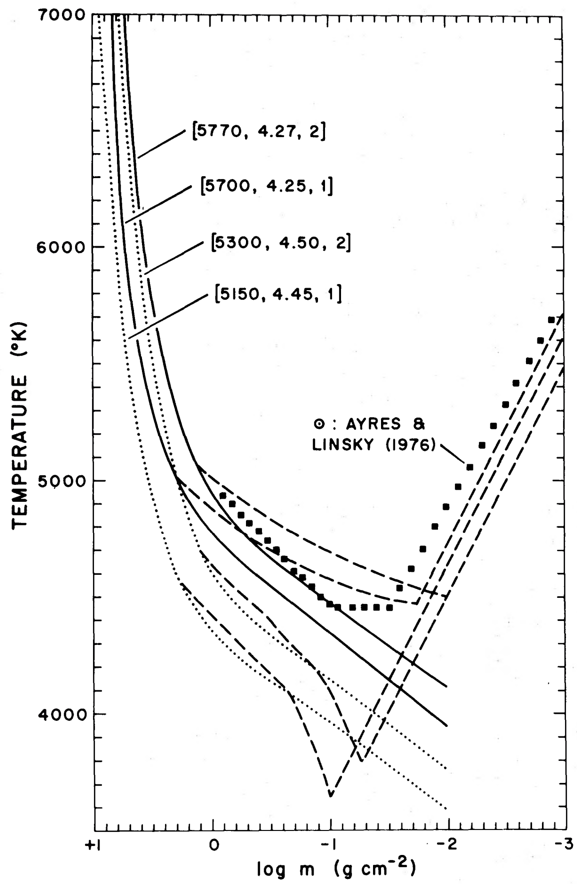

FIG. 2.—Radiative equilibrium model photospheres for α Cen A (*solid curves*) and α Cen B (*dotted curves*), and inferred semiempirical upper photosphere and lower chromosphere models (*dashed curves*, both stars). For comparison, the semiempirical solar model proposed by Ayres and Linsky (1976) is also illustrated (*filled squares*).

[1] [T_{eff}(K), log g (cm s^{-2}), relative metallicity (⊙ = 1).]

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TABLE 2

Estimated Temperature Minimum and Chromosphere Parameters

Star	Basis RE Model	$\log m_{T_{min}}$ (g cm^{-2})	T_{min} (K)	T_{min}/T_{eff}	πF_K (10^5 ergs cm^{-2} s^{-1})	Bandpass (Å)	$\log m_0$	$\xi_t^{(0)}$ (km s^{-1})	P_0 (dyn cm^{-2})	P_0^2/g
Sun........	[5770, 4.44, 1]	−1.50	4450	0.77	4.2 ± 0.84	−0.30 → +0.30	−5.25	10	0.16	8.8×10^{-7}
Procyon....	[6500, 4.0, 1]	−1.00	5200	0.80	21.0 ± 4.2	−0.50 → +0.50	−5.0	10	0.10	1.0×10^{-6}
α Cen A....	[5770, 4.27, 2]	−2.0	4500	0.78	4.4 ± 0.9*	−0.35 → +0.30	−5.3 ± 0.4	10	0.091	4.6×10^{-7}
	[5700, 4.25, 1]	−1.75	4475	0.79	4.3 ± 0.9*	−0.35 → +0.30				
α Cen B.....	[5300, 4.50, 2]	−1.25	3800	0.72	4.2 ± 0.8†	−0.45 → +0.50	−5.5 ± 0.3	5	0.095	3.0×10^{-7}
	[5150, 4.45, 1]	−1.00	3650	0.71	3.4 ± 0.7†	−0.45 → +0.50				
Arcturus....	[4250, 1.7, 0.3]	+0.25	3150	0.74	0.68 ± 0.20	−0.75 → +0.75	−4.5	15	0.0016	5.0×10^{-8}

* Mount Stromlo photometry $\pi F_K = (4.2 \pm 0.4) \times 10^5$ ergs cm^{-2} s^{-1};
Willstrop photometry $\pi F_K = (4.3 \pm 0.8) \times 10^5$ ergs cm^{-2} s^{-1}.

† Mount Stromlo photometry $\pi F_K = (3.2 \pm 0.5) \times 10^5$ ergs cm^{-2} s^{-1};
Willstrop photometry $\pi F_K = (3.1 \pm 0.7) \times 10^5$ ergs cm^{-2} s^{-1}.

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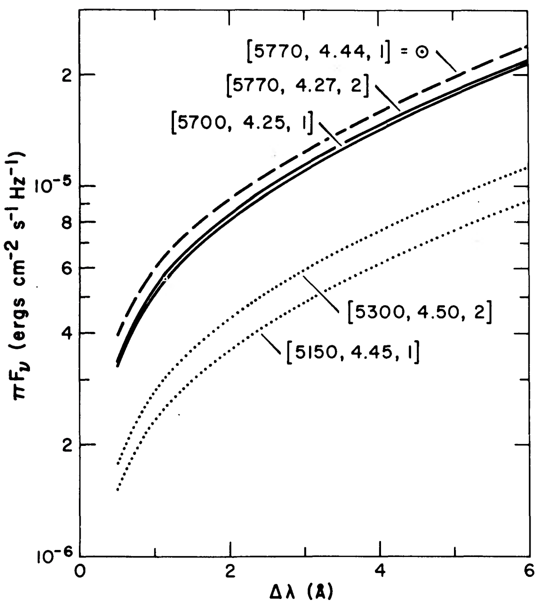

FIG. 3.—Synthesized K wing fluxes for the RE models of Fig. 2. Also shown is a synthesized profile for the solar RE model (*dashed curve*).

minimum regions (see, e.g., Ayres, Linsky, and Shine 1975). In fact, the use of K_2/K_1 contrasts to compare chromospheric strengths of stars spanning a wide range of T_{eff} will very likely produce misleading results. For instance, Arcturus is "2" on the Wilson-Bappu scale whereas the Sun is "0," but Arcturus's K index is only 0.16 solar. Therefore, despite the "stronger" appearance of Arcturus's Ca II emission compared with the solar K line, Arcturus's chromospheric energy budget is very likely much smaller than the Sun's (Ayres 1975*b*). A similar argument holds for the α Centauri system: α Cen B has a "strong" K line emission core like Arcturus (also "2" on W-B scale), whereas α Cen A has a relatively weak solar-type double reversal. However, the A and B K indices, and hence probably also the underlying chromospheric energy budgets, are very similar.

iii) *How Reliable Are the Derived RE K Indices? Comparison with Narrow-Band Calibrations*

Owing to the inherent uncertainty in T_{eff} governing the choice of the basis RE models used to calibrate the α Cen A and B K wings, we cannot guarantee the absolute accuracy of the RE K indices. In fact, aside from the uncertainties in T_{eff}, the application of the RE calibration technique is susceptible to uncertainties in the empirically derived van der Waals coefficients and to errors in the α Cen/Sun differential abundances. However, using reasonable estimates for these uncertainties, we find that the random errors in the derived RE K indices probably do not exceed ± 20 percent, exclusive of possible systematic errors in the scattered light correction.

As a check that the RE calibrated K indices are not grossly in error, we applied two independent narrow-band calibrations to the Ca II regions of α Cen A and B according to the methods cited in Papers II and III. One calibration was based on 17 Å relative photometry obtained at Mount Stromlo and tied to Hayes and Latham's (1975) calibration of Vega, while the second was based on Willstrop's (1965, 1972) 50 Å photometry also normalized to Hayes and Latham's $V = 0$ absolute flux. It is important to recognize that in the absence of direct measurements of the stellar angular diameter, any absolute calibration must depend on measurements of the stellar luminosity, effective temperature, and distance in order to determine the geometrical dilution factor. We chose the absolute bolometric luminosities in Table 1, the values of T_{eff} estimated in § II*b*, and the parallactic distance given by Gasteyer (1966) to derive the absolute K indices listed in the footnote to Table 2. The errors cited there refer primarily to the effect of uncertainties in $T_{eff}^{A,B}$ on deriving the associated stellar radii, but also include the photometric accuracies of the narrow-band colors.

It is encouraging to find reasonable agreement between the RE and narrow-band calibrations, although we stress that the conclusions drawn in § V concerning the chromospheric models proposed in § IV do not depend strongly on the absolute accuracy of the RE K indices.

IV. MODEL ATMOSPHERES AND SYNTHETIC SPECTRA

a) *Lower Chromosphere Models*

i) *Method*

Following the procedure described in previous papers of this series, we construct simplified lower chromosphere thermal and microvelocity models, namely, linear (in log m) increases of both quantities from the temperature minimum (T_{min}, $\xi_t^{T_{min}}$, and $m_{T_{min}}$ fixed) up to the base of the upper chromosphere-transition region, which we define as the $\tau_{LyC} = 1$ level. We vary the mass column density and surface microvelocity at $\tau_{LyC} = 1$, m_0, and $\xi_t^{(0)}$, respectively, to produce a range of temperature and microvelocity gradients in the lower chromosphere. In practice, a steep temperature gradient above $[m_0, T_0]$ is adjusted to force $\tau_{LyC} = 1$ at m_0. We determine the location of T_{min} in temperature and mass column density by trial-and-error synthesis of the K line inner wings and K_1 features, systematically perturbing the particular basis RE model in such a way as to produce a good fit between the synthetic and measured profiles (see Ayres and Linsky 1976). As in Papers II and III, we fix the value of T_0 in all models at 8×10^3 K by analogy with the observed constancy of T_e ($\tau_{LyC} = 1$) between solar active and quiet regions (Noyes and Kalkofen 1970). Each model is then specified by $[m_0, \xi_t^{(0)}]$. For simplicity, we adopt a depth-independent microvelocity $\xi_t = \xi_t^{T_{min}} = 2$ km s^{-1} in the upper photospheres of the α Cen A and B models, consistent with French and Powell's (1971) estimate for this quantity.

The temperature-density structure of each model is constructed on the basis of plane-parallel geometry, hydrostatic equilibrium (including turbulent pressure support), and lateral homogeneity. We expect these

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assumptions to be as accurate (or inaccurate) for α Cen A and B as they are for the solar atmosphere, owing to the similarity in surface gravity among the three late-type stars and because the K emission cores of each are reasonably symmetric. The latter suggests relative stability in those levels of the atmosphere where the K source functions peak. These assumptions may be very inaccurate, however, for stars with extended chromospheres or very asymmetric emission profiles.

The ionization balance in the lower chromosphere models is determined using a three-level-plus-continuum representation of hydrogen, treating the Lyman continuum and Hα explicitly, while assuming radiative detailed balance for Lα and Lβ. We include the Balmer and Paschen photoionization continua in an optically thin approximation by means of prespecified fixed rates (see, e.g., Ayres and Linsky 1975*b* [Paper IV]). The electron contributions of metals are taken in LTE, considering the first ionization stages only (see Vernazza, Avrett, and Loeser 1973). The details of the computational methods, inelastic collision rates, photoionization cross sections, and fixed radiative rates (for the solar case) are described in Paper IV. We estimate the fixed Balmer and Paschen photoionization rates for α Cen A and B by scaling the solar values in T_{eff} according to model fluxes and blocking factors in the Carbon-Gingerich grid (Carbon and Gingerich 1969).

ii) *Model Parameters*

Table 2 lists the [$m_{T_{\min}}$ (g cm^{-2}), $T_{\min}$(K)] inferred for each pair of α Cen A and B models. The detailed upper photosphere thermal structures of these models (including the "best-fit" lower chromosphere models derived below), are illustrated in Figure 2. Also illustrated is the solar model derived previously by Ayres and Linsky (1976), who used essentially the same approach.

For each of the stellar upper photosphere models, we construct a grid of lower chromosphere models as follows: $m_0 = 10^{-5.0}$, $10^{-5.5}$ (both stars); $\xi_t^{(0)} = 7.5$, 10.0 (α Cen A); and $\xi_t^{(0)} = 5.0$, 7.5 (α Cen B).

b) *Synthetic Spectra*

i) *Method*

We adopt the "emission-factor" approach to the so-called "partial redistribution" (PRD) formulation for the Ca II resonance lines of Milkey, Shine, and Mihalas (1975) as described by Ayres and Linsky (1976). For numerical tractability, we use a simplified three-level-plus-continuum representation for Ca II, treating K and the subordinate infrared triplet line λ8542 explicitly. We ignore the neutral calcium populations, which are everywhere small in the solar atmosphere (Linsky 1968; Auer and Heasley 1976) and probably also in α Cen A and B, and treat the 4*s*, 4*p*, and 3*d* photoionization continua by means of prespecified fixed rates.

In adopting the three-level, two-transition approach we sacrifice some accuracy to gain a factor of ~10 in computational speed compared with the five-level, five-transition approach used by Shine, Milkey, and Mihalas (1975). The loss of accuracy affects mainly the K_2/K_3 contrast and K index, amounting to perhaps a 20 percent overestimate of the former quantity and comparable underestimate of the latter, but it does *not* affect the important K_1 flux. We minimize the possible inaccuracy of the three-level, two-transition approach by comparing the inferred models with similarly derived models for the Sun and other stars.

The details of the computational methods, inelastic collision rates, photoionization cross sections, and fixed radiative rates for Ca II (for the solar case) are described by Ayres and Linsky (1976). For simplicity, we adopt the solar photoionization rates for both α Cen A and B. In practice, even relatively large errors in these rates have little effect on the emergent profiles of the collision-dominated K line, at least compared with the effects of varying the $T_e(m)$ and $\xi_t(m)$ structures.

ii) *Computed Profiles*

The results of the spectrum synthesis calculations for the grid models of § IV*a*(ii) above are illustrated in Figures 4 and 5. The computed K indices for α Cen A and B as functions of m_0 and $\xi_t^{(0)}$ are plotted in Figure 4, together with the observed values as calibrated by each RE basis model. Figure 5 illustrates representative profiles for the pairs of α Cen A and B models. In all cases, the synthetic profiles have been convolved with a 5.5 km s^{-1} Gaussian to simulate the instrumental function of the Mount Stromlo spectro-

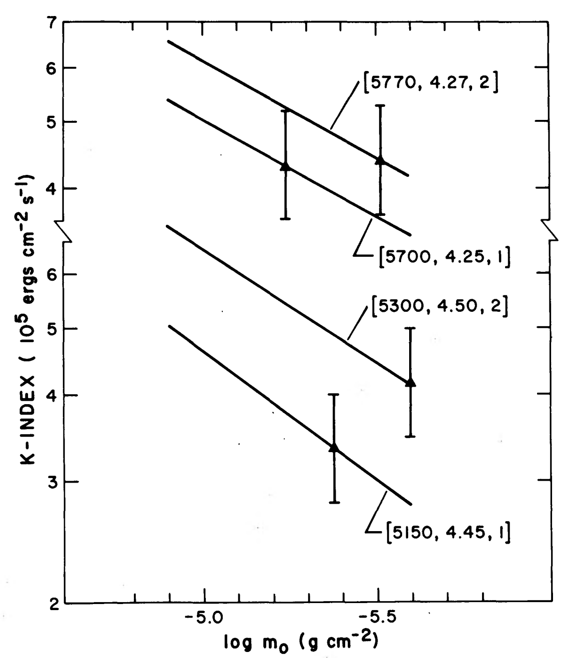

FIG. 4.—K indices as functions of log m_0 for each α Cen A and B basis RE model. Filled triangles represent observed indices as calibrated by designated RE model. Error bars represent the estimated ±20 percent uncertainty in the RE calibration of the K indices.

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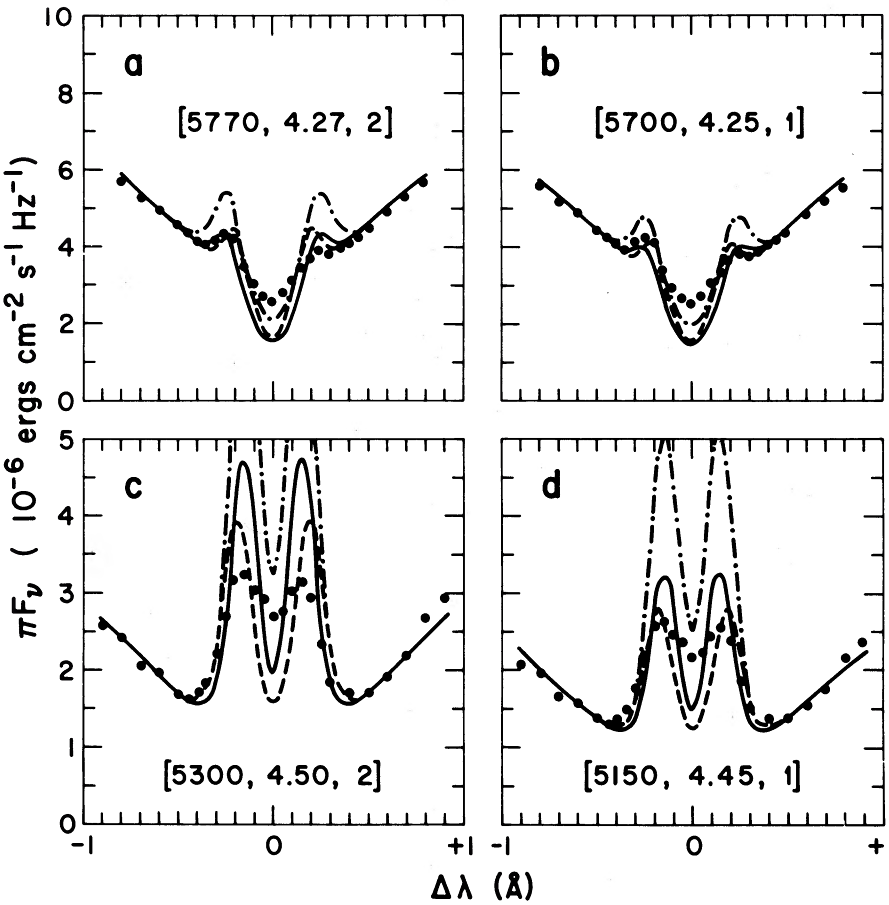

FIG. 5.—Synthetic core and inner wing profiles of the Ca II K line compared with measured α Cen A and B profiles (*filled circles*). Models for α Cen A are $\{\log m_0, \xi_t^{(0)}\} = \{-5.5, 7.5\}$ (— — —), $\{-5.5, 10\}$ (———), $\{-5.0, 10\}$ (-·-·-); and for α Cen B are $\{-5.5, 7.5\}$ (— — —), $\{-5.5, 5\}$ (———), $\{5.0, 5\}$ (-·-·-).

graph. Better fits to the measured profiles in the line cores, particularly at the K_3 features, could be obtained by using the more accurate five-level, five-transition Ca II model, but at the cost of far greater computing time. Notice that the best fits to the K_2 wavelength displacements are obtained for $\xi_t^{(0)A} \approx 10\ \mathrm{km\ s^{-1}}$ and $\xi_t^{(0)B} \approx 5\ \mathrm{km\ s^{-1}}$, and the K indices (Fig. 4) imply $\log m_0^A = -5.3 \pm 0.4$ and $\log m_0^B = -5.5 \pm 0.4$, where the errors in m_0 include the calibration uncertainties in the K indices and difference in K indices arising from the different RE basis models. These values compare with $\{\log m_0, \xi_t^{(0)}\} = \{-5.25, 10\}$ for the Sun (Ayres and Linsky 1976), $\{-5.0, 10\}$ for Procyon (Ayres 1975*b*), and $\{-4.5, 15\}$ for Arcturus (Paper III).

We have also compared λ8542 line profiles for the various α Cen A chromospheric models and microturbulent velocity distributions with calibrated tracings of the infrared triplet line from Mount Stromlo $5\ \mathrm{Å\ mm^{-1}}$ I-N plates. However, the computed profiles differ very little from each other, and all are consistent with the observations. Therefore, this comparison unfortunately provides no additional information.

V. DISCUSSION

The chromosphere and photosphere models proposed for α Cen A and α Cen B in this paper bring to five the number of stars that have been studied in this manner. Although the sample is limited in spectral types (F5–K2), luminosity classes (V–III), and does not contain any stars with active or extended chromospheres, it is now possible to discern trends which may be applicable to quiet chromospheres in this range of the H-R diagram. We describe these trends below, and indicate where we think further study would be most useful.

1. The ratio $T_{\min}/T_{\mathrm{eff}}$ is indicative of roles played by various heating and cooling mechanisms at the boundary between the photosphere and chromosphere of a late-type star. The values of this ratio in Table 2 are relatively independent of the metal abundance options adopted for the α Cen A and B analysis. Further, the value of $T_{\min}/T_{\mathrm{eff}}$ appears to be similar for the hotter stars (Procyon, Sun, and α Cen A) but smaller for the cooler stars (α Cen B and Arcturus).

It is instructive to compare the empirical $T_{\min}/T_{\mathrm{eff}}$ ratios with "boundary temperatures" $T_{\mathrm{RE}}^{(0)}$

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determined by radiative equilibrium models. Carbon and Gingerich (1969) have computed a grid of LTE line-blanketed RE model atmospheres and find that for $4000\ \mathrm{K} \leq T_{\mathrm{eff}} \leq 7000\ \mathrm{K}$ and $2.0 < \log g < 4.0$ the ratio $T_{\mathrm{RE}}^{(0)}$ ($\sim T[\tau_{5000} = 10^{-3}])/T_{\mathrm{eff}}$ lies in the narrow range 0.79–0.82. Johnson (1973) has included the rotation-vibration bands of CO, ignored by Carbon and Gingerich, in his grid of line-blanketed RE model atmospheres. He finds similar values of $T_{\mathrm{RE}}^{(0)}/T_{\mathrm{eff}}$ for $3000\ \mathrm{K} \leq T \leq 5500\ \mathrm{K}$ when CO opacity is ignored, but significant decreases in $T_{\mathrm{RE}}^{(0)}/T_{\mathrm{eff}}$ when CO is included. In particular, the decrease in $T_{\mathrm{RE}}^{(0)}/T_{\mathrm{eff}}$ is greatest for T_{eff} near 5000 K, more for low-gravity than for high-gravity stars, and essentially of no effect for stars as hot as the Sun, α Cen A, and Procyon. Comparing the $T_{\mathrm{RE}}^{(0)}/T_{\mathrm{eff}}$ values cited above with the empirical values of $T_{\min}/T_{\mathrm{eff}}$ in Table 2 suggests that the value of the stellar temperature minimum is determined primarily by "RE" processes, rather than by nonradiative heating. An interesting analogy to this notion is seen in the behavior of the K line in solar plages (see, e.g., Shine and Linsky 1972). Although the K emission cores of strong plages can be an order of magnitude brighter than the typical quiet-Sun double reversal, the photospheric damping wings *and* K_1 features are only about 10 percent brighter ($\Delta T_B \sim$ 100 K) than their quiet-Sun counterparts. Because the strength of the K emission core is a relatively direct measure of chromospheric heating, we infer from the comparison of active and quiet-Sun K profiles that the nonradiative energy dissipation necessary to sustain the local radiative losses in the Sun is small compared with the energy available in absorbed radiation (radiative heating) at K_1, but becomes much larger than the RE component at K_2 and K_3. This dramatic shift in relative importance between the two energy sources occurs over a seemingly narrow height range, and is attributable to the rapid decrease in the dominant opacity source H^- with decreasing density above the photosphere, owing to the pressure-squared dependence of H^- formation.

2. The entire upper photosphere of α Cen A ($-1.4 \leq \log m \leq 0.0$) appears to be somewhat warmer (see Fig. 2) than the RE line-blanketed model. Similar deviations from RE were found previously for the Sun, Procyon, and Arcturus (Paper III). Alpha Cen B shows basically the same behavior, although masked by the fact that the RE models themselves are probably too hot near $T_{\min}$ because CO cooling was neglected.

We can estimate the effect of ignoring CO line blanketing in the RE models by extrapolating the differences in boundary temperatures with and without CO ($\equiv \Delta T_{\mathrm{CO}}$) in Johnson's (1973) tables to the effective temperature and surface gravity range appropriate to α Cen B ($T_{\mathrm{eff}} \approx 5150$–$5300$ K; $\log g \sim 4.5$). In this manner, we estimate $\Delta T_{\mathrm{CO}}^{\mathrm{B}} \gtrsim -600$ K. Referring to Figure 2, we note that a correction of this magnitude would place the α Cen B RE models up to several hundred degrees *below* the empirically derived values of $T_{\min}$, and therefore more nearly consistent with the sense and magnitude of the departures from RE shown by α Cen A, the Sun, Procyon, and Arcturus. We caution that the CO cooling correction for α Cen B cited above is only a rough estimate: more detailed calculations of the effects of CO blanketing in K dwarfs would certainly be desirable.

The question of radiative losses and energy balance in the photospheres and chromospheres of late-type stars will be considered in detail in Paper VI of this series, but we do wish to point out here that the small photospheric departures from RE are very likely caused by the dissipation of short-period (10–20^{s}) acoustic waves produced by turbulence in the subsurface convection zone and heavily damped at the low densities of the upper photosphere (see also Ulmschneider 1974). The small fraction of these short-period waves not dissipated below the temperature minimum may be important heaters in the initial temperature rise of the lower chromosphere. Because the acoustic transmission function for high-gravity stellar chromospheres is heavily weighted toward low frequencies (Ulmschneider 1974), progressively longer period waves up to perhaps hundreds of seconds are probably responsible for heating the upper chromosphere (Ayres 1975*b*).

3. By fitting the wavelength displacements of the K_1 features, we obtain estimates of the mass column densities at the temperature minimum $m_{T_{\min}}$. There is a general trend of increasing $m_{T_{\min}}$ with decreasing gravity which we feel may be responsible for the well-known Wilson-Bappu effect (Wilson and Bappu 1957). This matter has been discussed by Ayres, Linsky, and Shine (1975) and will be considered in greater detail in Paper VII of this series. However, α Cen A may have a significantly smaller $m_{T_{\min}}$ and α Cen B a significantly larger $m_{T_{\min}}$ than the Sun, contrary to the general trend, but perhaps explicable in terms of metallicity effects.

4. Despite the 2250 K range in effective temperature, factor of 600 range in gravity, and factor of 30 range in K index, all five stars have very similar values for the mass column density m_0 at the $T_0 = 8000$ K level, where we have forced $\tau_{\mathrm{LyC}} = 1$. In fact, except for Arcturus, all of the stars are consistent with $\log m_0 = -5.25$. Unfortunately, we as yet cannot reliably estimate how well a value of m_0, as derived from a stellar K (or *k*) index, measures the actual location of the upper chromosphere of that star. Such information is more properly determined by transition region (TR) lines and the H I Lyman series. We do find reasonable agreement for the solar case (Ayres and Linsky 1976), but a single confirmation is by no means conclusive. On the other hand, if m_0 as derived from K or *k* indices is shown to be a reliable measure of upper chromosphere location, then the striking similarity between the m_0 values for the five stars studied in this series would suggest the possibility of a common physical explanation, presumably in terms of the energy balance where the Lyman continuum and H I resonance lines are the dominant cooling mechanisms.

In any case, our results suggest that for a first approximation one can estimate the chromospheric properties of late-type dwarfs and subgiants with

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TABLE 3

COMPUTED Mg II SURFACE FLUX INDICES

STAR	BASIS RE MODEL	log m_0	ξ_t (km s^{-1})	BANDPASS (Å) h	BANDPASS (Å) k	πF_h*	πF_k*
α Cen A............	[5770, 4.27, 2]	−5.5	2–10	±0.45	±0.50	3.2	4.2
α Cen A............	[5700, 4.25, 1]	−5.5	2–10	±0.45	±0.50	2.7	3.5
α Cen B............	[5300, 4.50, 2]	−5.5	2–5	±0.60	±0.75	4.6	6.2
α Cen B............	[5150, 4.45, 1]	−5.5	2–5	±0.60	±0.75	3.2	4.3

* 10^5 ergs cm^{-2} s^{-1}.

quiet chromospheres by assuming $T_0 = 8000$ K and $\log m_0 = -5.25$.

5. By fitting the K_2 emission peak wavelength displacements, we derive values of the microvelocity gradient and $\xi_t^{(0)}$ comparable to the inferred solar values for α Cen A, but somewhat smaller for α Cen B. The value of $\xi_t^{(0)}$ for Procyon is also similar to that of α Cen A, but Arcturus appears to have significantly larger $\xi_t^{(0)}$. The implications of these results for understanding the Wilson-Bappu effect will also be discussed in Paper VII.

6. We have computed absolute flux indices πF_h and πF_k for the Mg II h (λ2803) and k (λ2796) lines using the α Cen chromospheric models and PRD spectrum synthesis for a three-level Mg II ion. Atomic parameters for these calculations are described by Ayres and Linsky (1976), and computed indices are given in Table 3. When observations of the Mg II lines in α Cen A and B become available, they can be used to assess the accuracy of our chromospheric models, in particular $m_0^{A,B}$.

7. It has been suggested that the surface brightness of a transition-region emission line scales as $P_0 = gm_0$, while a coronal emission line scales as P_0^2/g (Gerola *et al.* 1974; McClintock *et al.* 1975). In addition, the line strengths should scale as the element abundance relative to the Sun. Accordingly, the *surface* brightness of TR lines should be similar in α Cen A and α Cen B and comparable to the quiet-Sun surface brightness. The *absolute flux* of TR lines in α Cen A, however, should be 2 times that of α Cen B owing to the larger angular diameter of the G star. If the coronal temperatures of the two stars are the same, then the surface brightness of α Cen A in coronal lines should be 1.5 times that of α Cen B.

Listed in Table 4 are the TR line fluxes at Earth predicted on the basis of these scaling laws and factor-of-2 metal enhancements assuming the solar fluxes of Rottman (1975) obtained from his 1972 December 13 rocket flight at low solar activity. We tabulate these predicted fluxes so that they may be compared with observations (e.g., Dupree 1974) to test the scaling laws. We caution that these scaling laws may indicate only crudely the general trends of TR and coronal emission-line intensities with P_0 and g. In particular, the TR scaling law is based on solutions of a TR energy equation which includes only conductive heating and radiative losses and predicts a conductive flux proportional to P_0 contrary to solar observations (Withbroe and Gurman 1973). Also, the value of P_0 in Table 2 for Procyon is consistent with the observed surface brightness of O VI λ1032 but not Si III λ1206 (Evans, Jordan, and Wilson 1975).

8. The arguments in § II suggest that the α Centauri system may be significantly older than the Sun, perhaps by as much as a factor of 2. We find, however, that the chromospheric properties (m_0, $\xi_t^{(0)}$, and K index) of α Cen A are not measurably different from its presumably younger solar counterpart. If α Cen A is indeed older than the Sun, then the correlations previously obtained by Skumanich (1972) relating Ca II emission and age may be correct only in a statistical sense and should not be used in estimating ages of individual stars.

The authors wish to thank the High Altitude Observatory and the National Center for Atmospheric Research, operated by the University Corporation for Atmospheric Research under contract to the National Science Foundation, for providing microphotometering facilities and the bulk of the computing time used in this investigation, and Kitt Peak National Observatory, operated by the Association of Universities for Research in Astronomy, Inc., also under contract to the National Science Foundation, where several of the RE models were constructed. We also wish to thank Tom Hewitt for microphotometering the plates and determining the scattered light level, G. J. Rottman and R. V. Willstrop for use of their data prior to publication, P. S. Conti and A. M. Boesgaard for critically reading the manuscript, and M. S. Bessell for obtaining some of the scans. This work was supported by grants NAS5-23274 and NGR-06-003-057 from the National Aeronautics and Space Administration to the University of Colorado.

TABLE 4

PREDICTED TR LINE FLUXES AT EARTH (photons cm^{-2} s^{-1})

Line	α Cen A	α Cen B
Si III λ1206.................	0.12	0.059
N V λ1239+1243............	0.018	0.0089
Si II λ1260+1265............	0.025	0.013
C II λ1335+1336............	0.19	0.10
Si IV λ1394+1403...........	0.10	0.050
C IV λ1548+1551...........	0.27	0.13

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