

STELLAR MODEL CHROMOSPHERES. IX. CHROMOSPHERIC ACTIVITY IN DWARF STARS

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ABSTRACT

High-resolution Ca II K line profiles are used to derive photospheric and lower chromospheric models of eight main-sequence stars of spectral types F0 through M0. These stars exhibit different degrees of chromospheric activity as indicated by their chromospheric radiative losses. Plane-parallel homogeneous models are computed on the basis of partial redistribution diagnostics. We find that the more active stars generally have steeper temperature gradients in their lower chromospheres and may be hotter in the temperature minimum region than other quiet-chromosphere stars of similar spectral type. Computations of H α profiles for 61 Cyg B (dM0) and EQ Vir (dK7e), using models derived from the K line analysis, correctly predict H α absorption from 61 Cyg B and H α emission from EQ Vir. Thus the dMe star phenomenon can be simply explained by enhanced chromospheric temperature gradients, presumably due to enhanced nonradiative heating rates which imply magnetic fields. Comparing K line observations of all dwarf and subgiant stars analyzed in this series, we find that the K₁ emission width ($\Delta\lambda_{K_1}$), indicative of the mass column density at the temperature minimum, is systematically greater in the active-chromosphere stars. This suggests that the temperature minimum moves outward to lower values of mass column density with decreasing nonradiative heating in the lower chromosphere. Previous work has suggested that this occurs as stars evolve. We also find that the separation of the K₂ emission features decreases with increasing nonradiative heating. Both this narrowing of K₂ and the broadening of the base of the K emission with greater activity agree qualitatively with the theoretical scaling arguments of Ayres. Finally, we find that the chromospheric radiative losses for all the dwarfs analyzed in this series confirm the trends with effective temperature originally presented by Linsky and Ayres.

Subject headings: Ca II emission — stars: chromospheres — stars: emission-line — stars: late-type — ultraviolet: spectra

I. INTRODUCTION

Bright emission in the cores of strong lines such as the Ca II H and K lines serves to define active regions (plages) empirically in the solar chromosphere. Shine and Linsky (1974) and Kelch and Linsky (1978) have shown that this bright emission results from steeper temperature gradients in the active regions, presumably due to enhanced nonradiative heating. Similarly, the inner wings of the Mg II *h* and *k* lines are brighter in solar active regions than in quiet regions, implying that the upper photosphere and temperature minimum

region of active regions are hotter (Morrison and Linsky 1978). Presumably this is also indicative of enhanced nonradiative heating.

By analogy with solar active regions, active-chromosphere stars are empirically defined by their unusually bright Ca II H and K line emission cores compared with other stars of similar spectral type (Linsky 1976). Kelch (1978, hereafter Paper VIII) has computed homogeneous model chromospheres for the active-chromosphere stars ϵ Eri (K2 V) and 70 Oph A (K0 V). These models show steeper temperature gradients in their lower chromospheres than models of quiet-chromosphere stars such as α Cen A and B (Ayres *et al.* 1976, hereafter Paper V) and models of quiet regions on the Sun (Ayres and Linsky 1976). The upper photospheres of the models are generally hotter than theoretical radiative equilibrium models for these stars, similar to the case for solar active regions.

The present study pursues these points further by modeling the upper photospheres and lower chromo-

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spheres of eight main-sequence stars ranging in spectral type from F0 to M0. Six of the stars were chosen because they form pairs of stars of similar spectral type (late F, late G, and late K–early M) but differing chromospheric activity. The object γ Vir N (F0 V) is included because it is the earliest dwarf with known chromospheric emission (Warner 1968), although it cannot be labeled an active-chromosphere star. Its inclusion in this study extends the stellar chromospheric modeling of this series to a much earlier spectral type. One other star (HD 76151) is similar in spectral type to the Sun but shows a greater K_2/K_1 contrast, similar to that in solar plages.

Our intent in this study is to model chromospheres as a function of spectral type and as a function of activity for stars of similar spectral type. Specifically, we look for (1) evidence of enhanced nonradiative heating in the upper photospheric models of the more active stars and in the ratio of minimum temperature at the base of the chromosphere to effective temperature ($T_{\min}/T_{\text{eff}}$); (2) a correlation between activity and the temperature gradients in the lower chromosphere (expected to be steeper in the more active stars); and (3) a correlation between the width at the base of the K line emission core ($\Delta\lambda_{K_1}$) and at the K_2 features ($\Delta\lambda_{K_2}$) with activity. Using theoretical arguments, Ayres (1979) has shown that these widths should depend on the nonradiative heating rates, but in opposite senses. We also present estimates of the chromospheric radiative losses for these and other main-sequence stars that have been analyzed previously in this series, extending the work of Linsky and Ayres (1978, hereafter Paper VI).

We have obtained $H\alpha$ profiles for the two coolest stars, EQ Vir, a dMe flare star with $H\alpha$ in emission, and 61 Cyg B, a normal early M dwarf with $H\alpha$ in absorption. Using chromospheric models computed to match the K line data, we are able to match qualitatively the observed $H\alpha$ profiles. This agreement of theory with observation as well as the similarity

of the EQ Vir chromospheric model with models of hotter active-chromosphere stars and solar plages strengthens the argument that dMe flare stars exhibit fundamentally solar-type activity but on an increased scale.

In § II we present the stellar data and our adopted stellar parameters; in § III we discuss the method of analysis, the atomic data, and the observations and their calibration; in § IV, we present our results and discuss their significance as introduced above; and in § V we summarize our conclusions.

II. STELLAR PARAMETERS

The stellar parameters adopted for our stars are listed in Table 1.

a) Effective Temperatures

Effective temperatures are needed only to specify radiative equilibrium models for comparison with our derived models. Our adopted effective temperatures are based on color temperatures from the Johnson *et al.* (1966) photometry and the (mean color, T_{eff})-relations of Johnson (1966). We then modified these temperatures so that the flux in the far wings of the K line ($\Delta\lambda \gtrsim 4 \text{ \AA}$) predicted from the radiative equilibrium models matched the calibrated K line observations. We estimate that our adopted effective temperatures are accurate to within $\pm 200 \text{ K}$, the principal contributions to the uncertainty arising from uncertainties in the absolute calibration of the data (see § IIIc), the calcium abundance, and the van der Waals broadening parameters.

b) Surface Gravities

The surface gravities used for γ Vir N and ξ Boo A are from Gray (1969). For the rest of the stars, the surface gravities are obtained from estimates of the stellar radii and masses. The radii are derived from

TABLE 1
ADOPTED STELLAR PARAMETERS

Star (spectral type)*	T_{eff} (K)	$\log g$	Angular Diameter†	Metallicity	K Intensity‡	Rotation ($v \sin i$)	Eq. Width ($\text{\AA}$)
γ Vir N (HR 4826) (F0 V)	7000	4.2	0'00101	solar	...	16 km s ⁻¹ §	8.4
θ Boo (HR 5404) (F7 IV–V)	6200	4.0	0'00109	solar	1	32 km s ⁻¹	11.6
59 Vir (HR 5011) (F8 V)	6100	4.4	0'00072	solar	...	...	13.0
HD 76151 (HR 3538) (G5 V)	5600	4.6	0'00058	solar	...	...	13.6
61 UMa (HR 4496) (G8 V)	5350	4.5	0'00088	solar	3	...	13.7
ξ Boo A (HR 5544) (G8 V)	5250	4.4	0'00132	solar	5	...	14.8
EQ Vir (HD 118100) (dK7e)	4000	4.4	0'00040	solar	...	...	...
61 Cyg B (HR 8086) (dM0)	3700	4.4	0'00193	solar	5	...	12.8

* As listed by Hoffleit (1964) except for θ Boo, EQ Vir, and 61 Cyg B (Joy and Abt 1974), and HD 76151 (Buscombe 1977).

† From the $V - R$ relation of Barnes and Evans (1976), except for 59 Vir and HD 76151, for which no $V - R$ colors are available and we use the $B - V$ relation instead.

‡ Zirin (1976).

§ Warner (1968).

|| Kraft (1967).

measured parallaxes (Hoffleit 1964; Jenkins 1952) and the angular diameters computed from the relations of Barnes and Evans (1976), as noted in Table 1. As no relevant colors are available for EQ Vir, we used the mean $V - R$ color for its effective temperature (Johnson 1966). The masses are obtained by interpolation along the main sequence among the evolutionary tracks of Iben (1965) and Hayashi (1966). We estimate uncertainties of ± 0.2 in $\log g$ owing to uncertainties of the order of 15% in both the radii and masses.

A test of the accuracy of this method is that our derived gravity of $\log g = 4.0$ for θ Boo is consistent with the Joy and Abt (1974) spectral type of F7 IV–V and the gravity of $\log g = 4.0$ previously found for Procyon (F5 IV–V) (Ayres, Linsky, and Shine 1974; Gray 1967). Also, our method derives the same surface gravity for ξ Boo A as obtained by Gray (1969).

c) Metallicities

For all stars we assume the solar abundances of Ross and Aller (1976), except for the Mount and Linsky (1975) carbon abundance, the solar value of $\text{Mg}/\text{H} = 3.89 \times 10^{-5}$ of Ayres and Linsky (1976), and the solar value of $\text{Ca}/\text{H} = 2.40 \times 10^{-6}$ of Ayres (1977). Our assumption of solar abundances is based on Hartmann and Anderson (1977), who derived solar abundances for 61 Cyg B and EQ Vir, and on Herbig (1965), who derived solar Fe/H for HD 76151 and 59 Vir, and for lack of any evidence to the contrary. Furthermore, most stars appear to be young and hence unlikely to be metal-deficient in the important species. This is supported by the following evidence: (1) $[\text{Li}/\text{Ca}]$ values are significantly greater than solar for γ Vir N (Danziger and Conti 1966), 59 Vir, HD 76151, 61 UMa, and ξ Boo A (Herbig 1965); (2) magnetic fields may have been detected in γ Vir N and ξ Boo A (Boesgaard 1974); and (3) γ Vir N and θ Boo show rapid rotation (see Table 1) which is correlated with youth (see Huang and Struve 1960).

III. PROCEDURES

a) Computational Methods

Our method for computing model atmospheres is described in detail elsewhere (Kelch *et al.* 1978, hereafter Paper VII). In general outline, we derive photospheric models that are modifications of radiative equilibrium (RE) temperature structures for the adopted effective temperatures. The modifications are made such that our calculated K wing fluxes, based on partial coherent scattering, agree with the observed fluxes. We then derive chromospheric models such that partial redistribution calculations for the cores of the Ca II and Mg II resonance lines are consistent with the data. Mg II h and k observations are not yet available, however, for the stars of the present analysis. Thus we can derive temperature versus mass column density structures of these stars from the upper photosphere to the middle chromosphere, including

the temperature minimum region and the base of the chromosphere ($T \lesssim 7000$ K), but we cannot accurately derive the value of m_0 , the mass column density where the Lyman continuum becomes optically thin ($T_0 \approx 8000$ K). We can, however, derive a lower chromospheric temperature gradient.

As in earlier papers of this series, we characterize the nonthermal motions as isotropic Gaussian microturbulence (ξ) that has a photospheric value of 2.0 km s^{-1} and increases linearly in $\log m$ from the temperature minimum to a value of ξ_0 at 8000 K. Our choice of ξ_0 for a given star is determined by fitting the separation of the K_2 emission peaks, $\Delta\lambda_{\text{K}_2}$, which may itself be related to the chromospheric nonradiative heating (see § IVc). Typically, stars such as 61 Cyg B with narrow emission cores require small values of ξ_0 , while stars such as HD 76151 with broader emission cores require larger values of ξ_0 (see Table 3). We include turbulent pressure, as $\frac{1}{2}\rho\xi^2(m)$, in our hydrostatic equilibrium models.

We derive plane-parallel, homogeneous, hydrostatic equilibrium models of the upper photosphere ($\tau_c \lesssim 0.3$) and chromosphere. We do not assume radiative equilibrium or an alternative energy balance equation, as in purely theoretical models. Since these are homogeneous models based on disk-averaged observations, they may not accurately model the mean atmosphere if inhomogeneities are important. In particular, our models may correspond more to active regions analogous to solar plages and the chromospheric network, which are bright in the H and K lines, rather than “quiet” stellar surface areas (see Heasley *et al.* 1978).

b) Model Atom and Atomic Data

For Ca^+ we use a three-level-plus-continuum representation, solving explicitly for the Ca II K and Ca II $\lambda 8542$ lines. We use the same collision cross sections, atomic parameters, photoionization cross sections, and van der Waals broadening parameters as in Paper VII. Photoionizations are treated as fixed rates, using the α CMi radiation temperatures from Ayres (1975) for θ Boo, since both stars have the same gravity, and values approximating the solar radiation temperatures from Ayres (1975) for the other stars. Inaccuracies in the assumed stellar radiation temperatures do not affect our results because the flux in the K emission core is only weakly sensitive to changes of the order of 200 K in the radiation temperatures for these continua.

c) The Observations and Their Absolute Calibration

The calibrated Ca II K line profiles shown in Figure 1 and analyzed in this paper were obtained by Linsky *et al.* (1979), using the Cassegrain echelle spectrograph and Singer Camera on the KPNO 4 m telescope. Linsky *et al.* describe in detail the acquisition and absolute radiometric calibration of these 120 mÅ resolution data, but since the calibration technique is new we summarize it here. The method is based on

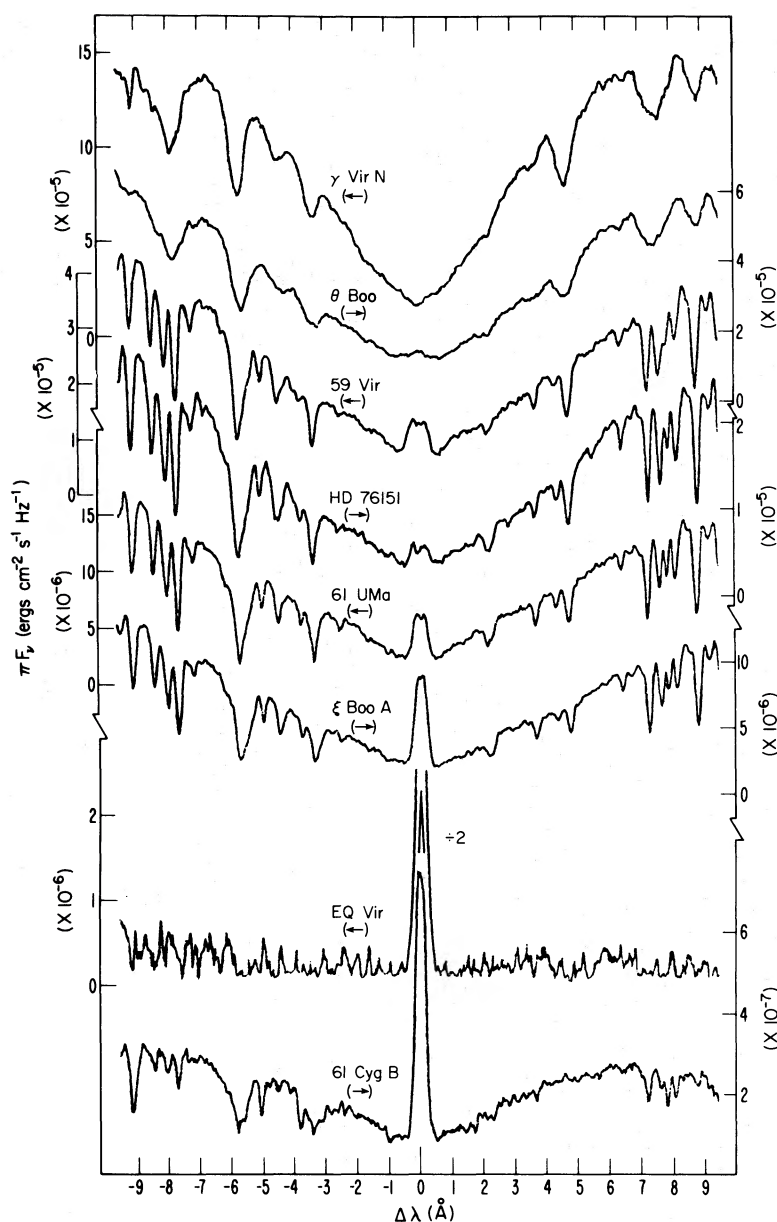


FIG. 1.—Absolute flux spectra of 120 mÅ resolution obtained with the Kitt Peak 4 m echelle spectrograph by Linsky *et al.* (1979). Arrows indicate proper flux scales.

Willstrop's (1965, 1977) measured absolute fluxes of some 200 stars, using a 50 Å bandpass centered on 3950 Å. For those stars with available $V - R$ colors cooler than spectral type F0, Linsky *et al.* derived stellar surface fluxes in the 3950 Å band from the measured fluxes at Earth and the stellar angular diameters, using the Barnes and Evans (1976) relation as in Papers VII and VIII. Linsky *et al.* found that these surface fluxes are tightly correlated with $V - R$ colors. We therefore invert this relationship to determine the 3950 Å surface fluxes for the eight stars of interest from their $V - R$ colors and determine the surface fluxes per angstrom at the K line by equating

the total relative flux in the 3950 Å passband to the surface flux from the empirical relation. Since several stars do not have published $V - R$ colors, we estimated $V - R$ colors for HD 76151 and 59 Vir from their $B - V$ colors and Johnson's (mean color, T_{eff}) relations and estimated the $V - R$ color for EQ Vir from the $V - K$ color of Bopp, Gertz, and Hackwell (1974) and the Johnson relations.

Only one exposure each of γ Vir N, HD 76151, EQ Vir, and 61 Cyg B is available, and that for EQ Vir is underexposed in the wings. As a result, our photospheric analysis of EQ Vir is crude, but the flux at the K_1 features is roughly measurable through

the noise. For θ Boo and 59 Vir, two exposures are available and both are included in the analysis. There are three exposures of 61 UMa and four of ξ Boo A, from which we selected for each star the two with the least apparent noise. In none of the four stars for which we have multiple exposures do we notice any significant variation in the shape or intensity of the emission flux or of the K_1 features other than what can be attributed to noise. This is in contrast to the known variations of the emission profiles for the giants α Boo (Chiu *et al.* 1977) and α Tau (Paper VII).

Several characteristics of the Ca II K line are apparent in Figure 1. Stars significantly hotter than the Sun show narrower K line absorption as Ca^+ becomes increasingly ionized in hotter photospheres. This profile narrowing in the hotter stars is nicely illustrated in the spectra of Abt *et al.* (1968). Our measured equivalent widths for the K line absorption profile, deleting the contributions of other absorption lines, are listed in Table 1 and suggest a maximum width in the late G- or K-type stars. Lutz, Furenlid, and Lutz (1973) have called attention to the dependence of the K line absorption equivalent width on luminosity.

There is also a general trend of increasing K_2/K_1 flux ratios with cooler effective temperature. This trend is not simply explained because neither the line core emission nor the flux in the inner wings is formed in LTE, but the trend is a consequence of moderate changes in the chromospheric K line source functions from star to star compared with the very rapid decrease in the 3933 Å Planck function in the upper photosphere with decreasing local temperature. Monochromatic surface fluxes at K_1 and in the line cores are tabulated in Linsky *et al.* (1979).

It is apparent in Figure 1 that absorption lines in the K line wings of γ Vir N and θ Boo are relatively broad, consistent with faster rotation as noted in Table 1. Our theoretical line profiles are rotationally broadened for these two stars. In our 120 mÅ resolution data, the K line emission cores in 59 Vir, HD 76151, and 61 UMa clearly show self-reversals, whereas the other stars do not. For γ Vir N and θ Boo rotational broadening obliterates any self-reversals that might ordinarily be present. The emission peak of ξ Boo A is either flat-topped or weakly self-reversed in three of our four spectra. EQ Vir and 61 Cyg B exhibit very narrow emission cores with no suggestion of self-reversal, but we could not see weak self-reversals narrower than 120 mÅ at our resolution.

The $\text{H}\alpha$ spectra for EQ Vir and 61 Cyg B were also obtained with the KPNO 4 m echelle spectrograph on

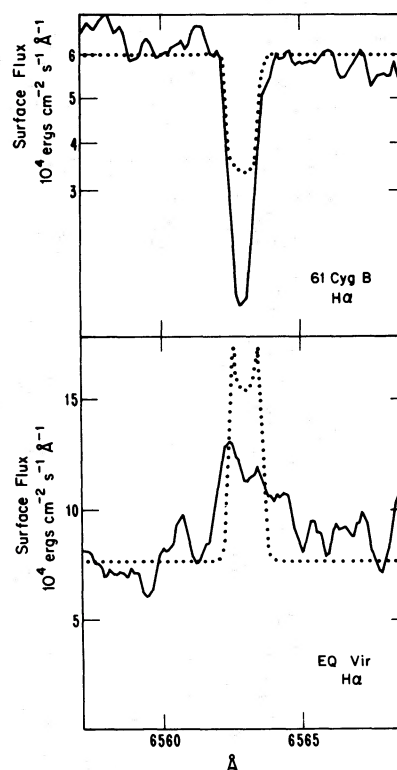


FIG. 2.—Observed (solid lines) and computed (dotted lines) $\text{H}\alpha$ profiles for EQ Vir and 61 Cyg B.

1975 November 18 and were reduced in an identical manner as the K line data. The calibrated $\text{H}\alpha$ profiles for these two stars are shown in Figure 2. Unfortunately, the EQ Vir $\text{H}\alpha$ data are crude, due to underexposure and only 0.3 mm widening. We note that the EQ Vir $\text{H}\alpha$ line is in emission, whereas the 61 Cyg B $\text{H}\alpha$ line is in absorption. Absorption- and emission-line equivalent widths were computed by fitting a straight line to the adjacent continuum, and are listed in Table 2. The adopted errors are based mainly on the estimated uncertainty in the straight-line fits to the continuum. We convert the EQ Vir $\text{H}\alpha$ equivalent width to an absolute flux measurement by comparison with the M dwarf model atmospheres of Mould (1976). Assuming an effective temperature of 4000 K and solar composition, we derive a continuum flux of $8.57 \times 10^4 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$ and emission-line flux of $9.2 \pm 1.9 \times 10^4 \text{ ergs cm}^{-2} \text{ s}^{-1}$.

TABLE 2
 $\text{H}\alpha$ RESULTS FOR EQ VIR AND 61 CYG B

Star	Continuum Flux ($\text{ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$)	Line Equivalent Width	Line Flux ($\text{ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$)	Radiative Loss ($\text{ergs cm}^{-2} \text{ s}^{-1}$)
EQ Vir.....	8.57 (+4)	-1.077 ± 0.216	9.2 ± 1.9 (+4)	1.7 (+5)
61 Cyg B.....	6.04 (+4)	$+0.901 \pm 0.030$	...	...

IV. RESULTS AND DISCUSSION

Figure 3 presents a comparison of our derived semiempirical temperature distributions with radiative equilibrium (RE) models for each star, and Table 3 lists the derived parameters of our models. Also included are the observed and computed K_1 indices,

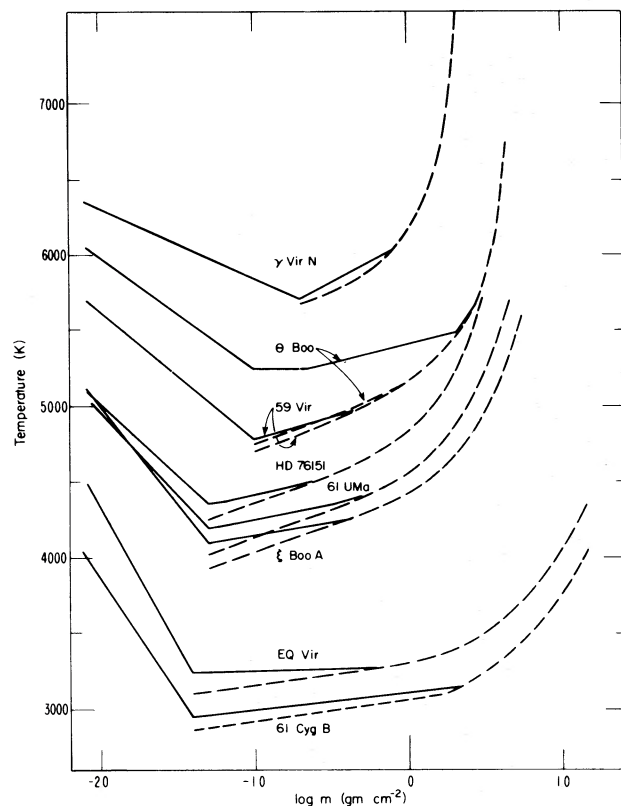


FIG. 3.—Proposed semiempirical models (solid lines) and comparison RE models (dashed lines) with the effective temperatures and gravities for each star given in Table 1. The RE models are scaled from reference models (T_{eff} , $\log g$) of (7000, 4.0) (Carbon and Gingerich 1969), (6500, 4.0) (Kurucz 1974a; Ayres 1975), (5150, 4.45) (Kurucz 1974a; Paper V), a Kurucz solar model (Kurucz 1976, 1974b), or (4000, 4.75) (Mould 1976), whichever reference model is closest in T_{eff} and $\log g$.

defined as the total surface flux above the zero flux level between the K_1 minimum features. Listings of the distribution of atmospheric parameters with mass column density, m , for the eight models are available on request.

a) Upper Photospheric Nonradiative Heating

We find in Figure 3 a general trend of hotter temperatures in the outer photospheric layers of our semiempirical models compared with the theoretical RE models. This trend is also seen in our previous studies of dwarfs and giants (Papers V, VII, VIII; Ayres and Linsky 1975). Our model for θ Boo shows very large temperature enhancements similar to the rather uncertain model of α Aur (see Paper VII). Since the rotation of θ Boo can smear line profiles only by 0.8 Å, rotation alone cannot explain the relative shallowness of the K profile, and our hot photospheric model represents a real physical structure. Both 61 UMa and ξ Boo A show relatively large temperature enhancements, and we believe that EQ Vir and 61 Cyg B may exhibit them as well. We are somewhat uncertain concerning the latter point because the RE model used for comparison with EQ Vir and 61 Cyg B (Mould 1976) does not include CO opacity, which should be the dominant opacity in the upper photospheres of these stars and should cool these layers considerably (see Johnson 1973).

The ratio of minimum to effective temperature ($T_{\text{min}}/T_{\text{eff}}$) is a simple parameter that may indicate the importance of nonradiative heating in the upper photospheres of stars. In Figure 4 we plot this ratio as a function of T_{eff} for all the stars analyzed in this series. Several stars depart significantly from the mean trend in Figure 4. There is evidence that α Cen B is metal-rich by a factor of 2 (Flannery and Ayres 1978; French and Powell 1971). If so, then the CO density at the top of the photosphere would be enhanced by a factor of 4 and the low value of $T_{\text{min}}/T_{\text{eff}}$ is perhaps explained by enhanced CO cooling (see Johnson 1973).

Capella A and θ Boo lie appreciably above the mean trend. As discussed in Paper VII, the K_1 intensity for Capella A is uncertain due to the uncertain correction for the flux from Capella B. Nevertheless, the conclusion in Paper VII was that $T_{\text{min}}/T_{\text{eff}}$ for Capella A is abnormally large, indicative of unusually

TABLE 3
PRINCIPAL RESULTS

STAR	$T_{\text{eff}}(\text{K})$	$T_{\text{min}}(\text{K})$	$T_{\text{min}}/T_{\text{eff}}$	$\xi_0(\text{km s}^{-1})$	$n_e(m = 10^{-3})$ (cm^{-3})	K_1 INDEX ($\text{ergs cm}^{-2} \text{s}^{-1}$)	
						Observed	Computed
γ Vir N.....	7000	5700	0.81	7.5	6.3 (+11)	4.9 (+6)	5.2 (+6)
θ Boo.....	6200	5250	0.85	7.5	3.6 (+11)	2.7 (+6)	2.7 (+6)
59 Vir.....	6100	4770	0.78	7.5	3.7 (+11)	2.1 (+6)	2.1 (+6)
HD 76151.....	5600	4350	0.78	7.5	1.6 (+11)	9.2 (+5)	9.2 (+5)
61 UMa.....	5350	4190	0.78	5.0	1.3 (+11)	8.0 (+5)	7.8 (+5)
ξ Boo A.....	5250	4115	0.78	5.0	1.5 (+11)	9.9 (+5)	1.01 (+6)
EQ Vir.....	4000	3240	0.81	5.0	2.5 (+10)	3.6 (+5)	3.55 (+5)
61 Cyg B.....	3700	3000	0.81	5.0	1.0 (+10)	6.6 (+4)	6.6 (+4)

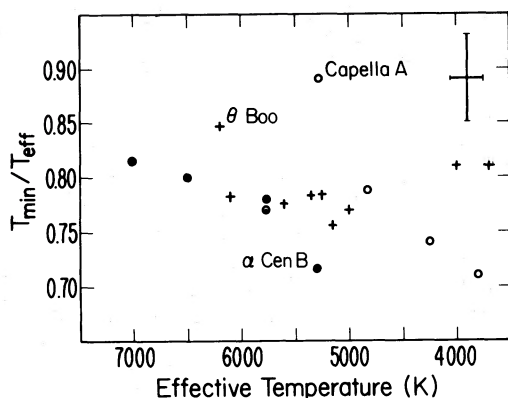


FIG. 4.— $T_{\min}/T_{\text{eff}}$ versus T_{eff} for all stars analyzed in this series, including the relatively active dwarfs and subgiants (+), quiet dwarfs and subgiants (●), the Sun (⊙), and the giants (○). Typical error bars are given in the upper right corner.

large nonradiative heating in the upper photosphere of this star. Evidence for unusually large nonradiative heating in the chromosphere (Paper VI) and transition region (Vitz *et al.* 1976; Linsky *et al.* 1978) is consistent with the result that $T_{\min}/T_{\text{eff}}$ is abnormally large. Thus despite the small K_2/K_1 ratio, we should consider Capella A an active-chromosphere star.

Theta Boo also lies above the mean trend in Figure 4. In § IIIc we show that the chromospheric radiative loss rate for θ Boo is also large compared with stars of similar spectral type. We have no simple explanation for the relatively large amount of nonradiative heating in the upper photosphere (implied by the

large value of $T_{\min}/T_{\text{eff}}$) and in the chromosphere, as this star is not a known spectroscopic binary and as a subgiant it cannot be young. The small K_2/K_1 contrast, which results from the bright inner wings, is very similar to the small contrast in Capella.

We cannot tell at this time whether the $T_{\min}/T_{\text{eff}}$ ratios for the two coolest dwarfs, EQ Vir and 61 Cyg B, are abnormally large. However, the comparison with the two coolest giants, α Boo and α Tau, suggests that there is considerable nonradiative heating in the upper photospheres of these two cool dwarfs.

Comparison of semiempirical and RE models (Fig. 3) and the $T_{\min}/T_{\text{eff}}$ ratios (Fig. 4) provides evidence that nonradiative heating is important in the upper photospheres of late-type dwarf stars and that this heating is enhanced in active-chromosphere stars as it is in active regions (plages) on the Sun.

b) K Line Radiative Losses and Chromospheric Temperature Gradients

We began by noting that bright emission in the cores of such lines as the Ca II H and K lines empirically defines active regions on the Sun and by analogy active-chromosphere stars. It is important to quantify this empirical definition. In Paper VI, Linsky and Ayres showed that the excess radiative loss in the K line due to the chromosphere itself is the integrated surface flux between the K_1 features minus the integrated surface flux in the same bandpass computed by using a RE model. Listed in Table 4 are the observed K_1 indices, defined as all the surface flux above the zero flux level integrated between the K_1

TABLE 4
STELLAR CHROMOSPHERIC RADIATIVE LOSSES ($\text{ergs cm}^{-2} \text{s}^{-1}$)

STAR	K ₁ INDEX			TOTAL RADIATIVE LOSS IN LINES*	Loss/ σT_{eff}^4	$\frac{dT}{d \log m}$ (K)	$\log m(T_{\min})$ (g cm^{-2})
	Observed	Correction for RE Profile	Corrected				
γ Vir N† (F0 V).....	4.9 (+6)	80%	1.0 (+6)	1.2 (+7)	8.8 (−5)	460	−0.7
α CMi† (F5 IV–V).....	2.0 (+6)	50%	1.0 (+6)	1.25 (+7)	1.2 (−4)	653	−1.0
θ Boo† (F7 IV–V).....	2.7 (+6)	35%	1.8 (+6)	1.8 (+7)	2.1 (−4)	743	−1.0
59 Vir (F8 V).....	2.1 (+6)	40%	1.3 (+6)	1.3 (+7)	1.7 (−4)	861	−1.0
Average Sun§ (G2 V)...	4.2 (+5)	43%	2.4 (+5)	3.0 (+6)	4.8 (−5)	940	−1.5
α Cen A (G2 V).....	4.2 (+5)	35%	2.7 (+5)	3.4 (+6)	5.4 (−5)	1060	−1.9
HD 76151 (G5 V).....	9.2 (+5)	40%	5.5 (+5)	5.5 (+6)	1.0 (−4)	961	−1.3
61 UMa (G8 V).....	8.0 (+5)	25%	6.0 (+5)	6.0 (+6)	1.3 (−4)	1073	−1.3
ξ Boo A (G8 V).....	9.9 (+5)	15%	8.4 (+5)	8.4 (+6)	1.9 (−4)	1253	−1.3
70 Oph A# (K0 V).....	7.6 (+5)	18%	6.2 (+5)	6.2 (+6)	1.6 (−4)	1580	−1.2
α Cen B (K1 V).....	3.2 (+5)	30%	2.3 (+5)	2.9 (+6)	6.5 (−5)	990	−1.2
ϵ Eri# (K2 V).....	9.7 (+5)	9%	8.8 (+5)	7.3 (+6)	2.1 (−4)	2030	−1.3
EQ Vir (dK7e).....	3.6 (+5)	5%	3.4 (+5)	2.8 (+6)	1.9 (−4)	1831	−1.4
61 Cyg B (dM0).....	6.6 (+4)	8%	6.0 (+4)	6.0 (+5)	5.6 (−5)	1563	−1.4

* See text (§ IVc) for explanation of estimates.

† Estimate of unrotated K_1 index based on partial redistribution calculations convolved with the proper rotational velocities.

‡ Data from Ayres (1975).

§ Data from Paper VI.

|| Data from Paper V.

Data from Paper VIII.

features. The listed correction factors are the percentages of the K_1 indices that can be ascribed to the K line for the RE models shown in Figure 3. For these calculations the RE models were extended toward smaller values of m at constant temperature. As noted in Paper VI, these correction terms decrease toward later spectral type, but they are very large for the F stars.

The corrected K_1 indices are given in Table 4 and plotted with respect to T_{eff} in Figure 5. Also plotted is the range of corrected K_1 indices for solar plages (Shine and Linsky 1972; Kelch and Linsky 1978) and for solar flares (Machado and Linsky 1975). We have computed fluxes from the measured solar intensities by multiplying by π . This implicitly assumes no limb darkening.

Four stars (the quiet Sun, α Cen A, α Cen B, and 61 Cyg B) appear to lie below the trend of the other stars and may define a quiet-chromosphere line. However, the slope of a best-fit (dashed) line through these four points in Figure 5 [$K_1(\text{corr}) \sim T_{\text{eff}}^{3.7}$] is much different from the $\sim T_{\text{eff}}^7$ slope found in Paper VI for the Mg II h and k line flux from 29 stars with $\log T_{\text{eff}} \leq 3.8$. Since the Mg II and Ca II lines are formed in similar regions of the chromosphere, and since the nonradiative heating rate may be assumed to be approximately constant with height in this region of the chromosphere (see Ayres 1979), we might expect the slope of the corrected K_1 index line for quiet-chromosphere stars also to be T_{eff}^7 . The solid line in Figure 5 is drawn with a T_{eff}^7 slope through the

quiet Sun and α Cen A points. With our small sample of stars we cannot yet tell which quiet-chromosphere line is more valid. We note that a common characteristic of these four quiet-chromosphere stars is that none is known to be a young dwarf.

We consider those stars lying well above the quiet-chromosphere lines to be active-chromosphere stars. We have drawn two possible active-chromosphere lines in Figure 5 parallel to the quiet-chromosphere lines but displaced upward about a factor of 5 in flux. We point out that the subgiant θ Boo (F7 IV-V) is clearly an active-chromosphere star despite its evolutionary age and the general decrease in K line flux with age noted by Wilson (1963), Skumanich (1972), and others. Another subgiant, α CMi (F5 IV-V), also lies not too far below the active-chromosphere lines in Figure 5. Since the active-chromosphere lines are consistent with the midrange of solar plages, we suspect that active regions cover a much larger fraction of the surface areas of these stars compared with the Sun. The data in Figure 5 suggest that we have several useful pairs of active/quiet-chromosphere stars of similar T_{eff} : HD 76151/quiet Sun or α Cen A, ξ Boo A or 70 Oph A/ α Cen B, and EQ Vir/61 Cyg B.

Shine and Linsky (1974) called attention to a significant trend of increasingly steep chromospheric temperature gradients in their solar plage models needed to explain K line cores of increasing brightness. Since Kelch (1978) found a similar trend for early K dwarfs, it is important to see whether this correlation is more generally valid and whether it is an important quantitative measure of chromospheric activity. There are two complicating factors. (1) Very often the data lead to models in which $dT/d \log m$ is not constant. When $dT/d \log m$ is constant, m_0 in effect measures this gradient. Otherwise, we use the value of $dT/d \log m$ in the lower portion of the chromosphere. (2) When we do not have Mg II data available for analysis, as is the case for the stars analyzed in this paper, we can determine only the temperature structure in the lower chromosphere.

Values of $dT/d \log m$ are given in Table 4 and Figure 6 for the stars studied in this and previous papers as noted in the table. Figure 6 includes temperature gradients for the solar plage and flare models of Shine and Linsky (1974), Kelch and Linsky (1978), and Machado and Linsky (1975). The correlation between $dT/d \log m$ and chromospheric activity, as measured by the corrected K_1 index, is highly suggestive but not conclusive. There is a trend of increasing $dT/d \log m$ with decreasing T_{eff} independent of activity. Values of $dT/d \log m$ for the quiet-chromosphere stars 61 Cyg B, α Cen B, and the quiet Sun define a line drawn in Figure 6, consistent with values for the hotter stars. The active-chromosphere stars EQ Vir, ϵ Eri, and 70 Oph A as well as solar plage regions clearly lie above this line. However, HD 76151 lies on the quiet-chromosphere line and α Cen A lies somewhat above. Since the corrected K_1 indices for these two stars suggest the reverse behavior, either some aspect of the models is in error or other

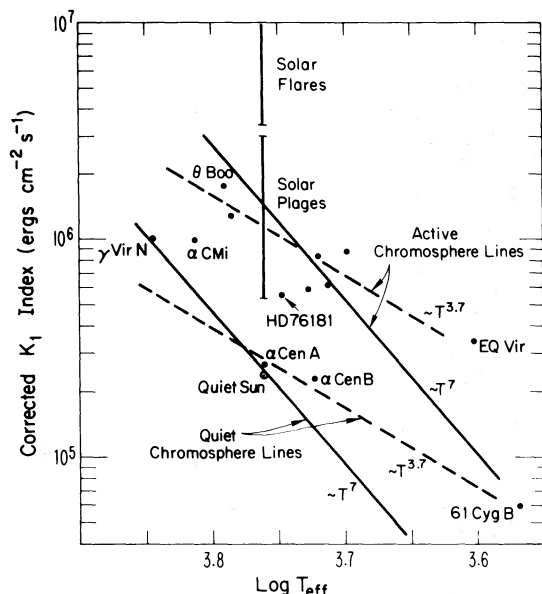


FIG. 5.—Corrected K_1 index versus effective temperature for all dwarfs and subgiants, including solar plages and flares (see § IVb for references). The solid lines representing possible fits to the active- and quiet-chromosphere stars have slopes of T_{eff}^7 , corresponding to results for the Mg II data in Paper VI. The dashed lines, which are also possible fits to the active- and quiet-chromosphere stars, have slopes of $T_{\text{eff}}^{3.7}$.

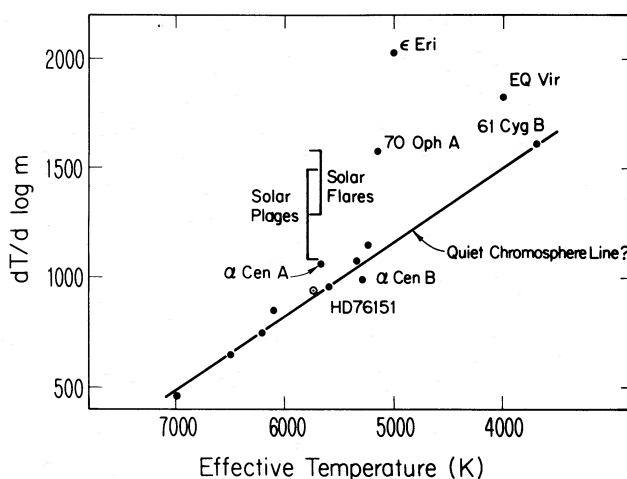


FIG. 6.—Lower chromosphere temperature gradient, $dT/d \log m$, versus effective temperature for the stars of Fig. 5. See text (§ IVb) for details. A tentative quiet-chromosphere relation is indicated by the solid line.

model parameters besides $dT/d \log m$ may be important. For example, the quiet Sun has a relatively small corrected K_1 index and is matched by a model with a value of $\log m(T_{\min}) = -1.5$, which is small compared with values for the late F- and early G-type dwarfs (see Table 4). As a consequence, the K line in the quiet Sun thermalizes closer to the temperature minimum compared with late F and early G dwarfs, which results in a narrower emission core, the observed smaller corrected K_1 index, and a relatively large value of $dT/d \log m$ (see Fig. 6).

c) An Estimate of Chromospheric Radiative Losses for Dwarf Stars

In this section we extend the analysis of Paper VI by estimating the total chromospheric radiative losses in spectral lines for the sample of 14 stars studied here and in previous papers of this series. Since only K line data are available for all the stars in this sample, we base our estimates on the corrected K_1 indices. Linsky and Ayres (Paper VI) estimate that the total radiative loss in lines from the quiet solar chromosphere is in the following proportion: 30% from Mg II h and k , 15% H α , 12% Ca II H and K (based on the corrected K_1 and H_1 indices), 14% Ca II infrared triplet, 7% L α , 10% Mg I, Ca I, Na I, and Fe I and II, and the rest He I and II and other UV emission lines. They also find that the relative strengths of the important chromospheric emission lines of Mg II, Ca II, and H I L α are approximately constant in their small sample of stars.

However, for the active-chromosphere stars ϵ Eri and 70 Oph A, the data in Paper VIII give $\mathcal{F}(K)/\mathcal{F}(\text{Mg II } h + k) \approx 0.55$ (ϵ Eri) and ≈ 0.45 (70 Oph A), if we assume the same k/h ratio as for ϵ Eri, compared with the solar ratio of 0.24 given in Paper VI. This indicates that $\mathcal{F}(K)/\mathcal{F}(\text{Mg II})$ may be twice as large in the more active stars as in the quiet Sun. If we assume that, as in Sun, the sum of the emission from

Mg II + Ca II + L α represents half of the total chromospheric radiative loss from the dwarfs, and if we use the result that $\mathcal{F}(K)/\mathcal{F}(L\alpha)$ is roughly the same in ϵ Eri as in the average Sun (McClintock *et al.* 1975), then the K line represents about 12% of the total chromospheric radiative loss in the lines in ϵ Eri.

Since ϵ Eri and EQ Vir appear to be the most active stars in our sample, based on the K_1 indices and Figure 5, we compute the total chromospheric line radiative losses for these two stars assuming that their K_1 indices represent 12% of that total. For the other active stars we compute the total by assuming that the K_1 index is 10% of the total, midway between the proportions for ϵ Eri and the quiet Sun. For the quiet-chromosphere stars, we assume that the K_1 index is 8% of the total radiative loss. The estimated chromospheric radiative losses in lines are given in Table 4, and, as in Paper VI, we compute an estimate of the chromospheric radiative loss normalized to the surface luminosity by dividing the total radiative loss by σT_{eff}^4 .

Our values for the normalized chromospheric radiative losses for the dwarf stars confirm the general trends shown in Figure 3 of Paper VI. In that paper it was shown that radiative losses decrease with decreasing T_{eff} for $\log T_{\text{eff}} \lesssim 3.8$ (spectral type F5). We also suspect that radiative losses decrease with increasing T_{eff} in the F stars, but our γ Vir N value is quite uncertain. Theta Boo, 59 Vir, ϵ Eri, and EQ Vir lie above the general run of radiative losses by factors of 2–3. Our value for α CMi is in agreement with that of Paper VI, and our value for ϵ Eri is nearly a factor of 2 above the lower limit given in Paper VI. Note that, since our radiative loss values represent the total loss in all lines, whereas the Paper VI values represent losses only in the Mg II lines, there is approximately a factor of 3 difference between our two scales. Our results strengthen the hypotheses of Paper VI and Renzini *et al.* (1977) that the chromospheric radiative losses for stars of similar

gravity decrease with decreasing T_{eff} , perhaps because convective velocities decrease with decreasing T_{eff} .

d) Comparison between Predicted and Observed H α Profiles

We computed H α profiles for 61 Cyg B and EQ Vir by using the atmospheric models derived from the Ca II K line analysis. We used a five-level-plus-continuum treatment of hydrogen, solving explicitly for L α , L β , H α , and the Lyman continuum. As shown in Figure 2, the models predict emission for EQ Vir and absorption for 61 Cyg B, in qualitative agreement with the observations. Since the primary difference between the models for these two stars is that the EQ Vir model has a steeper chromospheric temperature gradient, the difference between dMe and normal M dwarf stars appears to be analogous to the difference between plage and quiet regions on the Sun and may result from the same cause, enhanced magnetic fields. The qualitative agreement between observed and computed H α profiles provides confirmation of the models for these two stars.

Although we have not computed an H α line profile for a RE model of EQ Vir, we can estimate the H α radiative losses for this star by assuming that the H α absorption equivalent width for the quiet-chromosphere star 61 Cyg B is close to the RE value for EQ Vir. In this approximation the radiative loss in H α for EQ Vir is 1.7×10^5 ergs cm $^{-2}$ s $^{-1}$, one-half the value of the radiative loss in the K line.

e) The Relation of the K $_1$ and K $_2$ Emission Widths to Chromospheric Activity and Stellar Age

Figure 7 shows the K line profiles of α Cen A, the quiet Sun, and HD 76151 on a relative scale. The

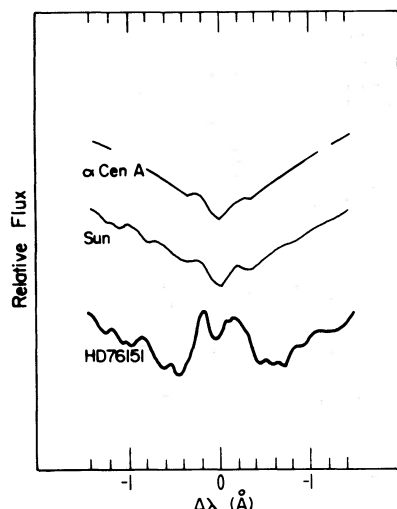


FIG. 7.—Relative flux observations of HD 76151, the Sun, and α Cen A. The solar profile is an integrated light observation from Linsky *et al.* (1979), and the α Cen A profile is from Paper V. The profiles have been displaced vertically from one another to facilitate comparison.

separation of the K $_1$ features, $\Delta\lambda_{K_1}$, is largest in HD 76151, the star with the largest chromospheric radiative loss. We believe this to be a result of greater chromospheric activity (nonradiative heating) in HD 76151 for the following reasons: (1) both the surface gravity and luminosity of HD 76151 are similar to those of the Sun so that the luminosity-width (Wilson-Bappu effect) and luminosity-gravity correlations are not relevant; (2) the wing absorption features (due to iron and other metals) are as sharp in the HD 76151 spectrum as in the reflected solar spectra (Moon and morning sky) taken by Linsky *et al.* (1979), so that rapid rotation is not a possible explanation; and (3) if the large $\Delta\lambda_{K_1}$ were an abundance effect, then $[\text{Ca}/\text{H}]_{\text{HD 76151}} \approx +1.0$ is required. Furthermore, the similarity of the HD 76151 K profile to Shine and Linsky's (1972) plate no. 3 is striking.

The separation of the K $_2$ peaks, $\Delta\lambda_{K_2}$, is noticeably smaller in HD 76151 than in the quiet Sun and α Cen A. The active-chromosphere stars 61 UMa, ξ Boo A, and EQ Vir in Figure 1 also exhibit small values of $\Delta\lambda_{K_2}$, suggesting a general trend of decreasing $\Delta\lambda_{K_2}$ with increasing chromospheric activity.

The trends in $\Delta\lambda_{K_1}$ and $\Delta\lambda_{K_2}$ correlate well with stellar age. As noted in § IIc, HD 76151 is lithium-rich relative to the Sun and thus likely to be younger, and Flannery and Ayres (1978) determine an age for the α Cen system of 6×10^9 years, slightly older than the Sun. Furthermore, as noted § IIc and in Paper VIII, the active-chromosphere stars 59 Vir, 61 UMa, ξ Boo A, and 70 Oph A show one or more signs of youth. Thus, if $\Delta\lambda_{K_1}$ is an indicator of the value of the mass column density at the temperature minimum $m(T_{\text{min}})$, then the evidence suggests that $m(T_{\text{min}})$ decreases (the temperature minimum moves outward) as a star's chromospheric heating decreases with increasing age. The values of $m(T_{\text{min}})$ for the dwarf stars determined directly in our models (see Table 4) confirm this trend.

Ayres (1979) has derived theoretical expressions relating $\Delta\lambda_{K_1}$ and $\Delta\lambda_{K_2}$ to basic stellar parameters. Since he finds these relations consistent with the quiet Sun and plage data, we now consider whether they are consistent with our sample of eight main-sequence stars.

Ayres finds that $\Delta\lambda_{K_1} \sim \tilde{A}_{\text{Fe}}^{1/4} \tilde{F}^{1/4} \tilde{g}^{-1/4} \tilde{T}_{\text{eff}}^{7/4 \pm 1/2}$ (his eq. [11]) and

$$\Delta\lambda_{K_2} \sim \tilde{A}_{\text{Fe}}^{-1/4} \tilde{F}^{-1/4} \tilde{g}^{-1/4} \tilde{T}_{\text{eff}}^{-(5/4 \pm 1/2)} \tilde{\xi}_0^{1/2}$$

(his eq. [15]), where $\tilde{A}_{\text{Fe}}$ is the stellar metal abundance relative to the Sun, $\tilde{F}$ is the chromospheric non-radiative heating rate relative to the quiet Sun, $\tilde{g}$ is the surface gravity relative to the Sun, $\tilde{T}_{\text{eff}}$ is the effective temperature in solar units, and $\tilde{\xi}_0$ is the broadening velocity appropriate to the Doppler core of the line compared with the solar value of 10 km s $^{-1}$ (Ayres and Linsky 1976). The $\tilde{T}_{\text{eff}}$ dependences noted above come largely from the $\tilde{T}_{\text{eff}}$ dependence of $F(\text{Mg II})/\sigma \tilde{T}_{\text{eff}}^4 (\sim \tilde{T}_{\text{eff}}^{2 \pm 2})$ for the 31 stars in Figure 3 of Paper VI. For stars cooler than the Sun, we estimate a

T_{eff}^3 dependence and thus find $F_{\text{NR}}^{\text{tot}} \sim \tilde{F} \tilde{T}_{\text{eff}}^7$, assuming $F(\text{Mg II}) \sim F_{\text{NR}}^{\text{tot}}$, the total nonradiative heating rate in the chromosphere. We then find that $\Delta\lambda_{K_1} \sim \tilde{A}_{\text{Fe}}^{1/4} \tilde{F}^{1/4} \tilde{g}^{-1/4} \tilde{T}_{\text{eff}}^2$ and

$$\Delta\lambda_{K_2} \sim \tilde{A}_{\text{Fe}}^{-1/4} \tilde{F}^{-1/4} \tilde{g}^{-1/4} \tilde{T}_{\text{eff}}^{-3/2} \tilde{\xi}_0^{1/2}.$$

The increase by one-fourth in the exponent of T_{eff} in the expression for $\Delta\lambda_{K_1}$ and decrease by one-fourth in the expression for $\Delta\lambda_{K_2}$ are due to our assumption that $F_{\text{NR}}^{\text{tot}} \sim T_{\text{eff}}^7$ rather than T_{eff}^6 and Ayres's result that $\Delta\lambda_{K_1} \sim (F_{\text{NR}}^{\text{tot}})^{1/4}$ and $\Delta\lambda_{K_2} \sim (F_{\text{NR}}^{\text{tot}})^{-1/4}$.

We list in Table 5 measured values of $\Delta\lambda_{K_1}$ and $\Delta\lambda_{K_2}$, as well as estimates of $\tilde{F}$ derived by taking ratios of the total chromospheric radiative losses in lines (Table 4) to the solar radiative loss, correcting for the estimated $\tilde{T}_{\text{eff}}^7$ dependence of the radiative loss. Also listed in Table 5 are theoretical estimates of $\Delta\lambda_{K_1}$ and $\Delta\lambda_{K_2}$ based on the equations cited above, values of $\tilde{\xi}_0$, $\tilde{g}$, $\tilde{F}$, and $\tilde{T}_{\text{eff}}$ given in Tables 1, 3, 4, and 5, and the assumption that all the stars have solar abundances except α Cen A and B, which are assumed to have twice the solar metal abundances. There are reasonable agreements between measured and theoretical values of $\Delta\lambda_{K_1}$ and $\Delta\lambda_{K_2}$.

We next test whether the data are consistent with the prediction that $\Delta\lambda_{K_1} \sim \tilde{F}^{1/4}$ and $\Delta\lambda_{K_2} \sim \tilde{F}^{-1/4}$. To explicitly test these predictions we need to correct the measured values of $\Delta\lambda_{K_1}$ and $\Delta\lambda_{K_2}$ for the different values of $\tilde{\xi}_0$, $\tilde{g}$, $\tilde{A}_{\text{Fe}}$, and $\tilde{T}_{\text{eff}}$ among our sample of stars. We therefore plot in Figure 8 the quantities

$$\Delta\lambda_{K_1}^* = \left[\frac{\Delta\lambda_{K_1}(\text{meas})}{\Delta\lambda_{K_1}(\odot)} \right] / \tilde{g}^{-1/4} \tilde{T}_{\text{eff}}^2 \tilde{A}_{\text{Fe}}^{1/4}, \quad (1)$$

$$\Delta\lambda_{K_2}^* = \left[\frac{\Delta\lambda_{K_2}(\text{meas})}{\Delta\lambda_{K_2}(\odot)} \right] / \tilde{g}^{-1/4} \tilde{T}_{\text{eff}}^{-3/2} \tilde{\xi}_0^{1/2} \tilde{A}_{\text{Fe}}^{-1/4}, \quad (2)$$

where $\Delta\lambda_{K_1}(\odot)$ and $\Delta\lambda_{K_2}(\odot)$ are the measured quiet Sun widths, with respect to $\tilde{F}$, deleting the rapid

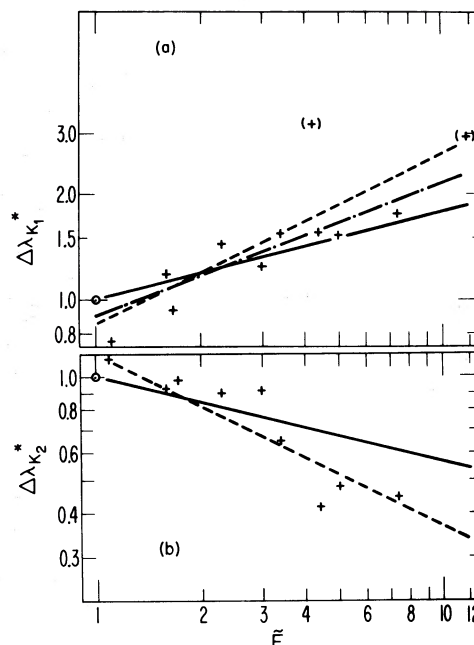


FIG. 8.—A test of the functional dependences of $\Delta\lambda_{K_1}$ and $\Delta\lambda_{K_2}$ on the chromospheric nonradiative heating rate $F_{\text{NR}}^{\text{tot}}$ relative to the quiet Sun and correcting for the $\tilde{T}_{\text{eff}}^7$ dependence found from Paper VI ($\tilde{F}_{\text{NR}}^{\text{tot}} \sim \tilde{F} \tilde{T}_{\text{eff}}^7$). Plotted in (a) is $\Delta\lambda_{K_1}^*$ defined by eq. (1). Solid line, predicted relation (Ayres 1979) with a slope of +0.25; dashed line, least-squares fit to all the data with a slope of +0.47; dot-dashed line, least-squares fit to the data deleting 61 Cyg B and EQ Vir, which has a slope of +0.37. Plotted in (b) is $\Delta\lambda_{K_2}^*$ defined by eq. (2). Solid line, predicted relation with a slope of -0.25; dashed line, least-squares fit to the data with a slope of -0.50.

rotators γ Vir N and θ Boo. The slopes to the least-squares regression curves are +0.47 and -0.50, respectively, compared with the predicted values of +0.25 and -0.25.

It appears that $\tilde{F}$ is correlated both with $\Delta\lambda_{K_1}^*$ and

TABLE 5
MEASURED AND THEORETICAL K_1 AND K_2 WIDTHS

Star	$\tilde{F}$	$\frac{\Delta\lambda_{K_1}(\text{meas})}{\Delta\lambda_{K_1}(\odot)^*}$	$\Delta\lambda_{K_1}(\text{th})$	$\frac{\Delta\lambda_{K_2}(\text{meas})}{\Delta\lambda_{K_2}(\odot)}$	$\Delta\lambda_{K_2}(\text{th})$
α CMi.....	1.7	1.50	1.87	1.30	1.16
θ Boo.....	3.5	...	2.03	...	0.73
59 Vir.....	3.0	1.42	1.51	0.74	0.62
Average Quiet Sun.....	1.0	1.00	1.00	1.00	1.00
α Cen A.....	1.1	0.97	1.34	1.04	0.92
HD 76151.....	2.3	1.25	1.06	0.74	0.67
61 UMa.....	3.4	1.28	1.13	0.50	0.56
ξ Boo A.....	5.0	1.28	1.27	0.40	0.56
70 Oph A.....	4.4	1.31	1.18	0.44	0.72
α Cen B.....	1.6	1.15	1.09	0.60	0.58
ϵ Eri.....	7.4	1.27	1.20	0.38	0.52
EQ Vir.....	11.9	1.46	0.91	0.00	0.67
61 Cyg B.....	4.2	1.31	0.59	0.00	0.70

* The solar line widths $\Delta\lambda_{K_1}(\odot) = 0.67 \text{ \AA}$ and $\Delta\lambda_{K_2}(\odot) = 0.50 \text{ \AA}$ were obtained from integrated-light line profiles (see Paper VI, Fig. 1) degraded to the spectral resolution of the stellar observations.

$\Delta\lambda_{K_2}^*$ and with slopes of different signs as predicted. For the K_1 widths in Figure 8a, the points for 61 Cyg B and EQ Vir diverge greatly from the regression curve, perhaps because of the crudeness of our radiative loss estimates and the finite resolution of the observations. Neglecting these two stars, we find a slope of $+0.37$ (*dot-dashed line*, Fig. 8a), in better agreement with the prediction of Ayres. Although the observed slope for the K_2 widths does not agree with the predicted slope in Figure 8b, we believe that the data are too scattered either to confirm or to contradict the predicted $\tilde{F}^{-1/4}$ dependence. Also, the 0.120 Å resolution of our data makes the measurement of $\Delta\lambda_{K_2}$ uncertain in the more active stars for which $\Delta\lambda_{K_2}$ is only a few tenths of an angstrom and for which the values of $\Delta\lambda_{K_2}(\text{meas})$ (see Table 5) are systematically low, resulting in a slope that could be too steep. In conclusion, the data appear not to be inconsistent with the scaling relations found by Ayres, but a larger data sample including giants and supergiants is needed to test better his scaling relations.

V. SUMMARY

In this paper we have presented absolute flux K line profiles for eight main-sequence stars, and have computed model atmospheres which match these data with computed line profiles, using partial redistribution spectroscopic diagnostics. A comparison of computed and observed line profiles and computed models with corresponding RE models for these stars suggests the following conclusions:

1. Nonradiative heating is an important phenomenon in the upper regions of the photospheres of late-type dwarf stars. Evidence for this is that upper regions of the photospheres of all eight stars studied are significantly hotter than the RE models predict. One star in particular, θ Boo (F7 IV–V), exhibits very large temperature enhancements. The ratio of minimum to effective temperature ($T_{\text{min}}/T_{\text{eff}}$) is a simple parameter that may be a useful indicator of nonradiative heating at the top of the photosphere. This parameter is unusually large for θ Boo and α Aur, and the two coolest dwarfs, EQ Vir and 61 Cyg B, appear to show a significantly larger ratio than the K giants.

2. Two parameters, the corrected K_1 index and the chromospheric temperature gradient ($dT/d\log m$) appear to separate active- from quiet-chromosphere stars of the same spectral type and may be useful parameters by which to quantify the term "chromospheric activity." The corrected K_1 index is the total flux in the K line between the K_1 minimum feature and above the K line profile computed for a radiative equilibrium model of the star. We find that four stars (the quiet Sun, α Cen A, α Cen B, and 61 Cyg B) have corrected K_1 indices below the trend of the other stars and may define a quiet chromosphere line in a plot of corrected K_1 index versus $\log(T_{\text{eff}})$. A number of stars lie clearly above these four stars and may define an active-chromosphere line in this diagram a

factor of 5 above the quiet-chromosphere line. Corrected K_1 indices for solar plages are consistent with this active-chromosphere line.

In a similar way, active- and quiet-chromosphere stars appear to be separated in a plot of chromospheric temperature gradient ($dT/d\log m$) versus effective temperature. The stars 61 Cyg B, α Cen B, and the quiet Sun define an apparent quiet-chromosphere line, which is consistent with the F star data, whereas 70 Oph A, ϵ Eri, EQ Vir, and solar plage regions lie clearly above this line and on this basis can be considered active-chromosphere stars. This diagnostic scheme cannot yet be considered definitive, as α Cen A lies somewhat above and HD 76151 on the quiet-chromosphere line, contrary to their locations in the corrected K_1 diagram.

3. By assuming relative emission-line strengths like those of the Sun, we use corrected K_1 indices to estimate total chromospheric radiative losses in lines for the 14 stars studied to date. We find that the total radiative loss in lines decreases with decreasing T_{eff} as previously found in Paper VI and by Renzini *et al.* (1977).

4. As a test of our chromospheric models based only on the K line data, we computed $H\alpha$ profiles for the two coolest stars. We find that $H\alpha$ is in absorption in the quiet-chromosphere star 61 Cyg B and in emission in the dMe flare star EQ Vir, in qualitative agreement with the data. Since the primary difference between the models for these two stars is that the EQ Vir model has a steeper chromospheric temperature gradient, the difference between dMe and normal M dwarf stars appears to be analogous to the difference between plage and quiet regions on the Sun and may result from the same cause, enhanced magnetic fields.

5. We find that $\Delta\lambda_{K_1}$ and $\Delta\lambda_{K_2}$ correlate well with our estimates of the total chromospheric heating rates $\tilde{F}$ in the sense that $\Delta\lambda_{K_1}$ increases with $\tilde{F}$ and $\Delta\lambda_{K_2}$ decreases with $\tilde{F}$. Our regression curves are of the same sense as predicted by Ayres (1979), but the slopes are only in rough agreement. The increase in $\Delta\lambda_{K_1}$ with $\tilde{F}$ is consistent with the displacement of the temperature minimum upward in the atmosphere with decreasing nonradiative heating as stars evolve from the main sequence.

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