OUTER ATMOSPHERES OF COOL STARS. XV. HIGH-DISPERSION ULTRAVIOLET STUDIES OF ACTIVE CHROMOSPHERE G–K DWARFS

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ABSTRACT

We have obtained IUE ultraviolet echelle spectra of three late-type active-chromosphere dwarf stars—\(\chi^1\) Orionis (G0 V), \(\xi\) Bootis A (G8 V) and \(\epsilon\) Eridani (K2 V)—which we compare with previously published observations of the quiet chromosphere dwarfs \(\alpha\) Centauri A (G2 V) and \(\alpha\) Centauri B (K1 V). The first group exhibits surface fluxes in a wide range of species from \(\text{O i}\) and \(\text{Mg ii}\) (6000 K) to \(\text{C iv}\) (10\(^5\) K) which are up to an order of magnitude larger than those of the second group. Nevertheless, the shapes of the important emission features are remarkably similar between the bright-line dwarfs and the weak-fine dwarfs. Qualitatively the same behavior is seen on the Sun in comparisons between the ultraviolet emissions from regions of strong and weak magnetic field. Literal application of the “solar analogy” would suggest that the bright-line dwarfs are more heavily covered by solar-like magnetic active regions than the weak-line dwarfs. However, the weakening of \(\text{Si iii}\) \(\lambda 1892\) relative to \(\text{Si iv}\) \(\lambda 1394\) and \(\text{C iv}\) \(\lambda 1548\) in the bright-line dwarfs raises the possibility that the magnetic active regions on the two classes of stars differ in a more quantitative way, the mean pressures for example, than the qualitative similarity of their line shapes would seem to suggest. In addition, we find a power-law dependence with slope \(\approx 1.5\) between the high-excitation \(\text{C iv}\) \(\lambda 1548\) emission and the purely chromospheric \(\text{Mg ii}\) \(\lambda\lambda 2796, 2803\) flux; we confirm the tentative result of previous work that the \(\text{He ii}\) \(\lambda 1640\) intensity is linearly correlated with coronal soft X-ray emission; and we comment on the apparent steep relation of the high-temperature emission to stellar rotation rate.

I. INTRODUCTION

We present high-dispersion ultraviolet (1150–3000 \(\AA\)) spectra of five bright dwarf stars of spectral type early G to early K which span a wide range of chromospheric activity. The observations were obtained with the echelle spectrographs of the International Ultraviolet Explorer (Boggess et al. 1978). Our study is part of a continuing effort to provide high-quality ultraviolet line profiles of late-type stars to help determine the properties of layers of the stellar outer atmosphere analogous to the solar chromosphere \((T < 10^4 \text{ K})\), transition region \((T \approx 10^5 \text{ K})\), and corona \((T \approx 10^6 \text{ K})\). Our ultimate goal is to understand the origins of chromospheric and coronal activity throughout the cool half of the Hertzsprung-Russell (H-R) diagram, where virtually all stars spend some portion of their lives. In the present study we concentrate on main-sequence stars that are similar in temperature, gravity, mass, and chemical composition to the Sun.

Detailed studies of the Sun over the past several decades have revealed that the high-temperature chro-
OUTER ATMOSPHERES OF COOL STARS. XV

785

mospheric and coronal plasmas of the solar outer atmosphere are associated with magnetic activity, whose energy initially is supplied by vigorous subphotospheric convection and surface velocity fields (see, e.g., review by Athay 1976). The solar magnetic fields often are concentrated into "active regions" which are considerably brighter in coronal soft X-rays and other high-temperature emissions than the "quiet" regions where only the supergranulation magnetic fields are present. The number of magnetic regions, or equivalently the area they cover, increases and decreases with the well-known 11 year activity cycle of the Sun. Nevertheless, even at sunspot maximum the magnetic active regions cover only a small fraction of the solar surface (less than 10% according to a recent estimate by Cook, Brueckner, and Van Hoosier 1980). Consequently the Sun seen in integrated light always appears comparatively "quiet."

Ground-based and satellite surveys of nearby solar-like stars have revealed that many share the comparatively low level of chromospheric and coronal emissions typical of integrated solar disk measurements. However, these surveys also have revealed the existence of "active" dwarf stars whose chromospheric and coronal luminosities exceed those of the average Sun by an order of magnitude or more (e.g., Ayres, Marstad, and Linsky 1981; Vaiana et al. 1981). Such stars tend to be young, fast rotators for which magnetic generation mechanisms, like the dynamo (Parker 1970), may be more vigorous than in old, slowly rotating dwarfs such as the Sun (cf. Skumanich 1972).

It is tempting to generalize the behavior of the Sun seen over its magnetic cycle and propose that the active chromosphere dwarfs differ from the quiet dwarfs primarily in the surface coverage of magnetic regions: pervasive on the former, sparse on the latter. Since we cannot observe the surfaces of even the nearest active dwarfs, we must rely on high-dispersion spectroscopy to provide insight concerning the active regions on these stars. In particular, the line shapes of chromospheric and higher temperature species are sensitive to Doppler shifts arising from bulk flows, to small-scale nonthermal motions, and to opacity. Consequently, any differences in detailed profile shapes between the active and quiet dwarfs should reflect differences in the kinematics and geometry of their active regions.

II. OBSERVATIONS

a) Target Stars

We have obtained high-dispersion IUE spectra of the active chromosphere dwarfs χ¹ Orionis (G0 V), ξ Bootis A (G8 V), and e Eridani (K2 V), which we compare with previously published spectra of the solar-like, quiet chromosphere dwarfs, α Centauri A (G2 V) and B (K1 V) (Ayres et al. 1982). Because the chromospheric and transition-region emission lines are faint, our choice of targets was limited to stars of large apparent brightness in the far-ultraviolet region.

The early G dwarf χ¹ Orionis is a probable member of the young (age ≤10³ yr) Ursa Major Stream (Roman 1949). Boesgaard and Simon (1982) have analyzed a number of IUE low-dispersion spectra of χ¹ Orionis obtained during a single rotation (P = 5 days), and found substantial variations in the chromospheric and higher temperature line emission which may be associated with a spatially inhomogeneous distribution of emitting regions across the stellar surface.

The late G dwarf ξ Bootis A is the brighter component of the 150 year visual binary ADS 9413 (current separation ~ 8″). The secondary is about two magnitudes fainter in the visual, and somewhat cooler (K4 V). Spatially resolved low-dispersion (6 Å FWHM) spectra of the pair reveal Si II λ1815 and C IV λ1550 emission from both stars (Ayres, Marstad, and Linsky 1981). However, the emission lines of the primary are much brighter than those of the secondary (see also Hartmann et al. 1979), as would be expected if the chromospheric luminosities scale roughly as the bolometric luminosities. Ground-based studies of the ξ Boo primary in magnetically sensitive absorption lines (Robinson, Worden, and Harvey 1980; Marcy 1981) suggest that, at least occasionally, large portions of the visible hemisphere are covered by magnetic regions with field strengths comparable to those of sunspots (B ≥ 10³ G). The ξ Boo system likely also is a member of the Ursa Major Stream (Roman 1949), and therefore probably is as young as χ¹ Ori.

The early K dwarf e Eridani is the coolest and closest of the active stars of our sample. It is believed to be a single star, although van de Kamp (1974) reported evidence for a low-mass (~ 0.01 M☉) astrometric companion (P = 25 yr). Recent high-quality optical spectroscopy of e Eridani (Steenbock and Holweger 1981) indicates that the nonthermal broadening of photospheric absorption lines is about 40% larger than that of the average Sun, which the authors propose may be related to the enhanced chromospheric activity of the K dwarf.

The nearby α Centauri system provides an important link between the Sun and solar-like stars. In particular, α Cen A is similar in its stellar properties—radius, temperature, and mass—and far-ultraviolet emission to the Sun (Ayres and Linsky 1980a), while a detailed evolutionary study indicates that the system is comparable in age to the Sun (Flannery and Ayres 1978). Furthermore, Einstein soft X-ray images of α Centauri reported by Golub et al. (1982) show that the integrated coronal emission of the primary is comparable to that of the Sun at the minimum of its 11 year magnetic activity cycle. However, the X-ray luminosity of α Cen B is about a factor of 4 larger than that of the primary.

Detailed chromospheric models have been constructed for three of the dwarf stars: α Cen A and B
(Ayres et al. 1976) and e Eri (Kelch 1978; Simon, Kelch, and Linsky 1980). Some modeling of ξ Boo A has also been carried out by Kelch, Linsky, and Worden (1979). The important conclusion of these studies is that in the region of the chromospheric temperature inversion, the spatially averaged structure of the a Centauri stars is very similar to that of quiet Sun models, whereas the chromospheres of e Eri and ξ Boo A are more similar in structure to that of a typical solar plage.

Three of the stars, a Cen A, a Cen B, and e Eri, have been observed repeatedly with IUE, and changes in the chromospheric emission, presumably produced by rotation of long-lived active regions onto and off of the visible hemisphere, have been detected in all of them (Hallam and Wolff 1981). Previously, Stimets and Giles (1980) analyzed Wilson’s (1976) ground-based Ca II K line emission indices of χ Ori and ξ Boo A and found significant rotational modulations. Vaughan et al. (1981) discovered analogous modulations in the Ca II flux of e Eri. The rotational periods inferred in the independent monitoring efforts agree favorably with spectroscopic estimates of $V \sin i$ (cf. Smith 1979). The active stars of our sample tend to be fast rotators with periods of 12 days or less. The quiet dwarfs are slow rotators, perhaps even slower than the Sun ($P_{\text{rot}} \approx 28$ days).

Fundamental properties of the five dwarf stars are summarized in Table 1.

### b) IUE Exposures

One or more high-dispersion exposures in the short-wavelength (SWP camera; 1150–2000 Å) and long-wavelength (LWR camera; 2000–3000 Å) regions were taken of each target, through the large aperture ($10'' \times 20'$) in all cases. The short-wavelength band contains important chromospheric emission lines (e.g., H I λ1216 Lyα, O I λ1302, 1305, 1306, and Si II λλ1808, 1816, 1817) as well as lines from higher temperature species (e.g., Si iv λλ1394, 1403 and C iv λλ1548, 1551). The long-wavelength region contains the strong resonance lines of Mg ii (λλ2796, 2803) and Mg i (λλ2852).

SWP exposure times ranged from 120 minutes (a Cen A) to 952 minutes (ξ Boo A). We obtained the very long exposure by combining a UK and a US low-background radiation shift. LWR exposure times ranged from 1 minute (a Cen A) to 60 minutes (ξ Boo A). The latter was a deliberate overexposure of the Mg ii h and k emission features in an effort to reach the faint emission core of the Mg i λ2852 resonance line. (A comprehensive discussion of Mg ii and Mg i emission in late-type dwarfs can be found in the survey by Ayres, Rodgers, and Zarro 1983.)

Both a Cen A and a Cen B were acquired by blind offsets from a nearby ninth magnitude field star, since the current separation of the bright companions (about 23") precludes the normal acquisition sequence (see Ayres and Linsky 1980a). In the case of the ξ Boo system, the current separation is small enough to permit both stars to be included in the large aperture. At the time of the 16 hour ξ Boo exposure, the binary was aligned along the echelle dispersion direction of the large aperture. Consequently, the spectra of the pair are partially blended with an effective separation of $7''5 \approx 5$ pixels $= 40$ km s$^{-1}$.

The circumstances of the IUE high-dispersion exposures can be found in Table 2.

### c) Data Reduction

We reduced the echelle images, obtained from the extracted-spectrum (ESHI) file on the Guest Observer tapes, as follows:

We heavily smoothed the interorder signal with a 100 point running mean to eliminate reseau marks and bright cosmic ray hits but retain large-scale structure of the background such as curvature across the echelle order. We then subtracted the smoothed background from the gross spectrum and divided the result by an...
TABLE 2

<table>
<thead>
<tr>
<th>Target</th>
<th>Image Number</th>
<th>J.D. (mid-exposure)</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^1$ Orionis</td>
<td>SWP 13643</td>
<td>1697.10</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>LWR 10268</td>
<td>1696.95</td>
<td>15</td>
</tr>
<tr>
<td>$\alpha$ Centauri A</td>
<td>SWP 5541</td>
<td>1040.92</td>
<td>(120) (^b)</td>
</tr>
<tr>
<td></td>
<td>SWP 11017</td>
<td>1615.34</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>LWR 2093</td>
<td>737.66</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>LWR 2094</td>
<td>737.71</td>
<td>1</td>
</tr>
<tr>
<td>$\xi$ Bootis A</td>
<td>SWP 14792</td>
<td>1839.56</td>
<td>952 (^c)</td>
</tr>
<tr>
<td></td>
<td>LWR 11402</td>
<td>1839.15</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>LWR 11403</td>
<td>1839.20</td>
<td>15</td>
</tr>
<tr>
<td>$\alpha$ Centauri B</td>
<td>SWP 9036</td>
<td>1378.04</td>
<td>340.</td>
</tr>
<tr>
<td></td>
<td>LWR 2095</td>
<td>737.88</td>
<td>6</td>
</tr>
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<td></td>
<td>LWR 2096</td>
<td>737.90</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>LWR 2097</td>
<td>737.92</td>
<td>18</td>
</tr>
<tr>
<td>$\epsilon$ Eridani</td>
<td>SWP 13353</td>
<td>1687.12</td>
<td>447</td>
</tr>
<tr>
<td></td>
<td>LWR 10193</td>
<td>1686.96</td>
<td>10</td>
</tr>
</tbody>
</table>

\(^a\) All exposures high-dispersion through 10\(\text{"} \times 20\(\text{"}\) aperture in the echelle mode: SWP spectral range: 1150-2000 \AA; LWR spectral range: 2000-3000 \AA.

\(^b\) Effective exposure time 109 minutes (target was intentionally offset to one edge of large aperture to displace geocoronal Ly\(\alpha\) emission redward of interstellar D I Ly\(\alpha\) absorption feature).

\(^c\) Exposure obtained by combining UK and NASA shifts.

We calibrated the spectra by dividing the blaze-corrected fluxes by the exposure time and multiplying by a logarithmically interpolated inverse sensitivity curve for sharp-line emission sources proposed by Cassatella, Ponz, and Selvelli (1981). When several LWR exposures were available for a particular star, we constructed an exposure-time-weighted composite spectrum, excluding saturated regions from the sum.

The calibrated LWR spectra are compared in Figure 1, and the SWP spectra in Figure 2. For purposes of illustration, the monochromatic flux spectrum measured at Earth was divided by the stellar bolometric luminosity, measured at Earth (Table 1), and expressed in units compatible to the velocity scale of the abscissa. The normalized monochromatic fluxes are proportional to surface fluxes, and the integrated normalized flux of each line is equivalent to the fraction of the stellar bolometric energy flux that ultimately appears as the radiative power loss in that feature.

We determined line-shape parameters—emission centroids, FWHMs, and integrated fluxes—for each spectrum by a least squares Gaussian technique. We registered the velocity scale of each spectrum to the flux-weighted mean of the strong emission lines, since the large-aperture IUE spectra cannot be assigned an absolute velocity scale reliably (owing mostly to the positional freedom of the target in the aperture and thermal shifts of the echelle format). Nevertheless, the relative velocities should be reasonably accurate since the large-aperture dispersion constants are tied ultimately to small-aperture wavelength calibrations obtained, and updated periodically, by means of an onboard platinum hollow-cathode lamp. However, discussion of possible relative velocity shifts between...
Fig. 2.—Selected regions of the far-ultraviolet emission spectra of the program stars, plotted in the same manner as Fig. 1. In addition, shading indicates saturated pixels or regions affected by reseaux marks; "©" and "sa" denote portions of the Lyα emission profiles that are contaminated by geocoronal emission through the large and small apertures, respectively; and "#" symbols designate prominent particle radiation hits. The emission structure on the shortward edge of the ξ Boo A C IV λ1548 profile may be due to the secondary star.

high-excitation and low-excitation lines is deferred to a separate study (Ayres et al. 1983) that includes well-exposed spectra of giants and supergiants in addition to the dwarfs presented here.

A summary of line shape parameters is provided in Table 3. Note that measurements of the α Cen A spectrum longward of 1800 Å are based on the short exposure (120 minutes), because the rapidly rising photospheric continuum of the early-G dwarf saturates that region in the longer exposure. Even so, Si III λ1892 and C I λ1994 still are overexposed in the 120 minute observation.

III. ANALYSIS AND DISCUSSION

A preliminary analysis of the emission line fluxes and widths has been given by Jordan, Ayres, and Brown (1983), and a more detailed application of emission-measure techniques to the spectra of the five dwarfs currently is in progress (Jordan et al. 1983). At present we focus on the broad properties of the stars as inferred from correlations between different line strengths, and the gross behavior of the line shapes.

a) Line Strengths

The most obvious difference between the active and quiet dwarfs is the substantial increase in the normalized fluxes \( f_{\lambda} / I_{\text{bol}} \) of the former compared with the latter in virtually all of the prominent ultraviolet lines (see Figs. 1 and 2). A more subtle difference, demonstrated in Figure 3a, is that the C IV λ1548 flux ratio increases relative to the chromospheric Mg II doublet emission with a power-law slope steeper than unity, in fact roughly 1.5. The differential behavior of high-dispersion C IV λ1548 and Mg II h and k flux ratios among the solar-type dwarfs parallels that seen at low dispersion for the combined Si IV + C IV + N V flux against Mg II for a diverse sample of G–K dwarfs, giants, and supergiants (Ayres, Marstad, and Linsky 1981). Note also that the three active dwarfs have very similar \( f_{\lambda 1892} / I_{\text{bol}} \) and \( f_{\lambda 1548} / I_{\text{bol}} \) ratios despite the moderate spread in their stellar parameters, particularly rotation rate and surface temperature.

There are a few counter examples to the generally large increases in normalized line strengths from the quiet to active dwarfs. For example, the λ1892 inter-system line of Si III exhibits a smaller increase in strength.
### Table 3
IDENTIFICATIONS AND LINE SHAPE PARAMETERS

<table>
<thead>
<tr>
<th>Identification</th>
<th>Rest Wavelength</th>
<th>( \chi^1 ) Orionis G9 V</th>
<th>( \alpha ) Centauri A G2 V</th>
<th>( \xi ) Bootis A G8 V</th>
<th>( \alpha ) Centauri B K1 V</th>
<th>( \epsilon ) Eridani K2 V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( v_L )</td>
<td>FWHM</td>
<td>( f_L )</td>
<td>( v_L )</td>
<td>FWHM</td>
<td>( f_L )</td>
</tr>
<tr>
<td>Soft X-rays</td>
<td>3-80</td>
<td>...</td>
<td>...</td>
<td>310 ± 100b</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>H i Lyα</td>
<td>1215.668</td>
<td>-31</td>
<td>99</td>
<td>95</td>
<td>+3</td>
<td>165</td>
</tr>
<tr>
<td>O i</td>
<td>1306.029</td>
<td>+4</td>
<td>23</td>
<td>0.9 ± 0.2</td>
<td>-5</td>
<td>51</td>
</tr>
<tr>
<td>C II</td>
<td>1334.532</td>
<td>+1</td>
<td>54</td>
<td>2.0 ± 0.2</td>
<td>-2</td>
<td>65</td>
</tr>
<tr>
<td>Si IV</td>
<td>1393.755</td>
<td>+2</td>
<td>69</td>
<td>2.1 ± 0.3</td>
<td>+2</td>
<td>56</td>
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<tr>
<td>C IV</td>
<td>1548.185</td>
<td>+4</td>
<td>87</td>
<td>2.9 ± 0.8</td>
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<td>56</td>
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<tr>
<td>He II</td>
<td>1640.4</td>
<td>+0</td>
<td>53</td>
<td>2.0 ± 0.3</td>
<td>-11</td>
<td>18</td>
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<tr>
<td>Si II</td>
<td>1808.012</td>
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<td>33</td>
<td>2.7 ± 0.1</td>
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<tr>
<td>Si III</td>
<td>1816.928</td>
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<td>4.9 ± 0.1</td>
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<td>30</td>
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<td>C I</td>
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<td>25</td>
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<td>Mg II</td>
<td>1993.620</td>
<td>-1</td>
<td>46</td>
<td>1.5 ± 0.1</td>
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<tr>
<td></td>
<td>2795.528</td>
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<td>71</td>
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<td>83</td>
</tr>
<tr>
<td></td>
<td>2802.704</td>
<td>-2</td>
<td>66</td>
<td>120 ± 10</td>
<td>-5</td>
<td>95</td>
</tr>
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</table>

**Notes:** — \( v_L \) and FWHM are the emission centroid velocity and full width at half-intensity, respectively, in km s\(^{-1}\) obtained by least squares Gaussian fits. \( f_L \) is the line flux in 10\(^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) at Earth. The velocity scale of each image was registered to the flux-weighted mean of the prominent emission lines. The typical single-line measurement errors are ±3 km s\(^{-1}\) for \( v_L \) and ±7 km s\(^{-1}\) for FWHM in the well-exposed spectra of \( \alpha \) Cen A, \( \alpha \) Cen B and \( \epsilon \) Eri, but somewhat larger for the weaker exposures of \( \chi^1 \) Ori and \( \xi \) Boo A. These uncertainties, and the flux uncertainties cited explicitly in the table, are based on the RMS deviation of the fitted profiles from the observed line shapes, and the algorithms of Landman, Roussel-Dupre, and Tanigawa 1982 (see also Leckrone 1980). Brackets designate fluxes for which saturated pixels were included in the fits. Owing to interstellar absorption, the Lyα emission of \( \chi^1 \) Ori and \( \xi \) Boo A is largely geocoronal rather than stellar. Colons indicate uncertain measurements.

aKelly and Palumbo 1973. The He II feature consists of several components: the cited wavelength is a mean value obtained by weighting the individual components by the statistical populations.

bWalter et al. 1980.

cGolub et al. 1982.

dJohnson 1981.
Fig. 3.—(a) Comparison of the C IV λ1548 normalized flux ($f_{CIV}/f_{bol}$) with that of the Mg II doublet. The solid line is an eye-fitted power law with slope 1.5. (b) Comparison of the He II λ1640 Balmer-α emission with the normalized soft X-ray fluxes of the program stars. The solid line is the relationship predicted by Hartmann et al. (1979) using a photoionization-recombination model based largely on solar considerations.

compared with C IV λ1548, C II λ1335, or Mg II h and k. It is well known that the ratio of the Si III intersystem line to permitted lines formed at the same temperature is sensitive to density in the regime $n_e \geq 10^{11}$ cm$^{-3}$ (e.g., Doschek et al. 1978; Cook and Nicolas 1979). The empirical behavior of λ1892 demonstrates that not only do the “active” and “quiet” stars have different spatially-averaged electron densities, but also that $n_e$ must be $\geq 10^{11}$ cm$^{-3}$. The C I λ1994 intersystem line is pumped by the optically thick C I λ1657 multiplet (Jordan 1967), and because it is sensitive to the column density rather than to the emission measure, the ratio of the C I feature to chromospheric resonance lines like Mg II h and k also is sensitive to density. The behavior of C I λ1994 parallels that of Si III λ1892 between the quiet and active dwarfs, suggesting that the latter have uniformly higher densities throughout the chromosphere and transition region.

In contrast to the modest enhancement of the intersystem lines, the He II λ1640 emission increases even more rapidly relative to Mg II than does C IV λ1548. This behavior has been ascribed to photoionization of He II by coronal radiation (e.g., Zirin 1975; Avrett, Vernazza, and Linsky 1976) with He II Balmer-α being formed by recombination. Hartmann et al. (1979) suggested that the He II λ1640 flux therefore provides an indirect measure of the stellar coronal soft X-ray emission. Indeed, the stellar coronal soft X-ray flux also is observed to be a steeper function of increasing Mg II emission than is C IV (Ayres, Marstad, and Linsky 1981). Figure 3b shows the correlation between He II λ1640 and soft X-ray flux ratios for the five dwarfs of our sample (see Table 3). The solid line in Figure 3b is the He II–soft X-ray relationship predicted by Hartmann et al. using a model based largely on solar considerations (cf. Raymond, Noyes, and Stopa 1979). It can be seen that our measurements are consistent with the proposed scaling.

However, in the solar atmosphere recombination accounts for between one-third and one-half of the total He II flux (Kohl 1977), while the remainder comes from a combination of collisions and a high opacity in He II Lyβ. Because a steep temperature gradient may enhance the collisional component (Jordan 1975, 1980), it is possible that the apparent correlation between He II Ba and soft X-rays could be explained by a significant steepening of the temperature profiles of the transition regions of the active dwarfs compared with those of the quiet dwarfs. The relative importance of recombination and collisional excitation in the formation of the He II λ1640 feature will be considered in the detailed theoretical modeling of these stars (Jordan et al. 1983).

Whatever the formation mechanism may be, we stress the importance of obtaining high-dispersion spectra of the 1640 Å region when studying the He II Balmer emission. At low dispersion, He II Balmer can be blended with Fe II (multiplet 40) and, especially in low-gravity stars, with the intersystem line of O I (λ1641.3), which is pumped by the O I resonance triplet (Brown and Jordan 1980; Brown, Ferraz, and Jordan 1980). The effect of such blends can be seen in the low-dispersion survey by Ayres, Marstad, and Linsky (1981), where the slope of the He II-Mg II relation is flatter than that of X-ray–Mg II. Equally important, the width of the He II feature may be used to distinguish between the alternative excitation mechanisms. If He II is photoionized by strong...
X-ray radiation, then the Ba line will be formed at low temperatures \((T < 2 \times 10^4)\), whereas if collisionally excited, the Ba line will be formed at much higher temperatures \((\approx 10^5)\). The measured widths of the optically thin Si \([\text{III}]\) and C \([\text{IV}]\) features indicate that the nonthermal broadening in the stellar transition region increases rapidly with increasing temperature above \(5 \times 10^4\) K. Accordingly, we expect that the Ba feature will be as narrow or narrower than Si \([\text{III}]\) if recombination dominates, and as broad as C \([\text{IV}]\) if collisional excitation dominates. The observed widths would then suggest that recombination is the more important mechanism in the three active stars.

The differential behavior of Mg \([\text{II}]\), C \([\text{IV}]\), and coronal soft X-rays with increasing activity must be related to the balance between the heating mechanisms at different levels of the stellar outer atmosphere and the energy loss processes. In this respect, it is important to remember that the overall chromospheric emission is considerably larger than that of the transition region and corona, even in the most active G–K dwarfs. For example, the chromospheric Lyα feature of \(\epsilon\) Eri in Figure 2 (excluding the small geocoronal contribution) completely dominates the far-ultraviolet emission of the active dwarf, even without a correction for interstellar H \(_i\) absorption.

### b) Line Shapes

Despite the large enhancement of line strengths in the active dwarfs compared with the quiet dwarfs, there is no evidence for any substantial differences in line widths (except for He \([\text{II}]\) \(\lambda 1640\), as noted above) over the entire temperature range accessible to \(\text{IUE}\). Table 4 compares the flux-weighted mean FWHMs for the active dwarfs, as a group, against the mean for the \(\alpha\) Centauri stars. We have corrected the mean \(\text{IUE}\) widths for an instrumental FWHM \(\approx 30\) km s\(^{-1}\), assumed Gaussian. The adopted value is consistent with the apparent widths of Si \([\text{II}]\) \(\lambda 1808\) and C \([\text{I}]\) \(\lambda 1994\) in the quiet dwarfs \((\approx 32\) km s\(^{-1}\)) and the small intrinsic widths of these features in the solar spectrum \((\approx 10\) km s\(^{-1}\)).

### TABLE 4

**MEAN HIGH-TEMPERATURE LINE WIDTHS**

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>APPROXIMATE</th>
<th>FWHM ± s.e. (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(T_{\text{max}}) ((K))</td>
<td>Sun(^b)</td>
</tr>
<tr>
<td>C ([\text{II}])</td>
<td>1335, 36</td>
<td>3( \times 10^4)</td>
</tr>
<tr>
<td>Si ([\text{III}])</td>
<td>1892</td>
<td>5( \times 10^4)</td>
</tr>
<tr>
<td>Si ([\text{IV}])</td>
<td>1394</td>
<td>7( \times 10^4)</td>
</tr>
<tr>
<td>C ([\text{IV}])</td>
<td>1548, 51</td>
<td>1( \times 10^5)</td>
</tr>
</tbody>
</table>

**Notes.**—FWHM is the flux-weighted mean line width averaged over the available measurements for the two groups of stars; s.e. is the standard error of the mean. A Gaussian instrumental profile contribution of FWHM \(\approx 30\) km s\(^{-1}\) has been removed from the stellar mean widths.  

\(^a\)Sources for ion temperatures: Jordan 1969; Summers 1972; Baliunas and Butler 1980;  
\(^b\)White and Lemaire 1976;  
\(^c\)Optically thick;  
\(^d\)\(\alpha\) Cen B only; the \(\alpha\) Cen A Si \([\text{III}]\) feature is overexposed.
covered by solar-like plage regions than the quiet stars, but consistency is this case does not constitute a proof.

An additional consistency check for the hypothesis is provided by the higher temperature lines like C IV λ1548, 1551 which also do not exhibit a marked charge in line shape between the quiet and active dwarfs. In particular, Mouradian et al. (1982) have emphasized that the nonthermal widths of high-excitation lines in solar plages are the same as observed in “quiet” regions (where much of the emission is from the supergranulation network component). Indeed, the nonthermal motions observed in the solar atmosphere vary little between different regions such as coronal holes, the quiet Sun, and sunspots (Cheng, Doschek, and Feldman 1977; Feldman et al. 1976). The similarity in line shapes between the quiet and active dwarfs suggests that their magnetic active regions are not grossly different in terms of kinematic properties.

In contrast, active-chromosphere giant stars exhibit a rather dramatic broadening of the high-temperature species compared with the line widths observed in the dwarfs (Ayres et al. 1982). The behavior of the optically thin intersystem lines like Si III λ1892 and C III λ1909 indicates a substantial increase in the small-scale nonthermal motions of the emitting structures on the giant stars compared with those of the dwarf stars.

c) Rotation-Activity Relations

We discuss briefly the connection between stellar rotation and the chromospheric and coronal activity of the dwarfs of our sample. The range in chromospheric Mg II flux ratios ($f_{\text{Mg II}}/f_{\text{bol}}$) is of order 0.7 dex, while the range in coronal soft X-ray flux ratios ($f_{c}/f_{\text{bol}}$) is of order 2.5 dex (see Table 3). The rotation periods given in Table 1 cover a range of as much as 0.9 dex. The stellar radii are similar; therefore, the equatorial rotational velocities (and angular rotation rates) must span the same range. Consequently, chromospheric activity as measured by Mg II emission may have a nearly linear dependence on rotation rate (cf. Skumanich 1972), while the coronal rotation-activity relation must be described by a steeper power law, perhaps cubic in $V_{\text{rot}}$ (cf. Ayres and Linsky 1980b) if we compare the two early G stars, $\chi^1$ Ori and $\alpha$ Cen A, or parabolic (cf. Pallavicini et al. 1981) if we compare the three later type dwarfs, $\xi$ Boo A, $\alpha$ Cen B, and $\epsilon$ Eri. However, owing to our obviously limited sample, we cannot comment on the possibility of a change in the slope of the rotation-activity relations for periods near 10 days as proposed by Walter (1981; see also Vaughan and Preston 1980), and discussed recently by Dursey, Mihalas, and Robinson (1981) in the context of mode switching by the stellar magnetic dynamo.

IV. CONCLUSIONS

High-dispersion IUE spectra indicate a gross strengthening of chromospheric and transition-region line fluxes from quiet to active dwarf stars without a fundamental change in the line shapes. Qualitatively the same spectroscopic behavior is seen in detail on the solar surface between regions of strong and weak magnetic fields. We believe that the correspondence between the stellar and solar behavior is not accidental, but instead affirms that enhanced chromospheric and coronal emission on late-type main sequence stars is a result of increased surface coverage of magnetic active regions. Further analysis of these and future high-resolution spectra, combined with measurements of coronal X-ray luminosities and temperatures, should permit the analogies between solar magnetic active regions and active-chromosphere dwarf stars to be pursued in a more quantitative manner.

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