RED SHIFTS OF HIGH-TEMPERATURE EMISSION LINES IN THE
FAR-ULTRAVIOLET SPECTRA OF LATE-TYPE STARS

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ABSTRACT

High-dispersion IUE spectra of six late-type stars exhibit small but statistically significant differential redshifts of high-temperature emission lines, like Si IV and C IV, with respect to low-temperature lines like S I and O I. A well-exposed, small-aperture spectrum of the active chromosphere binary Capella (α Aurigae A: G6 III + F9 III) establishes that the high-temperature lines are redshifted in an absolute sense with respect to the accurately determined photospheric velocity of the system at single-fine phase 0.50.

We discuss several possible explanations for the stellar redshifts, including a warm wind (10^5 K) in which apparent redshifts are produced in optically thick lines by an accelerating outflow, and the downflowing component of a vertical circulation system for which the up-leg portion of the flow is too cool, too hot, or too tenuous to be visible in Si IV and C IV. If the second scenario is true, the stellar redshifts may provide an important phenomenological link to the downflows observed in 10^5 K species over magnetic active regions on the Sun.

Subject headings: stars: coronae — stars: individual — stars: late-type — stars: winds — ultraviolet: spectra

I. INTRODUCTION

Late-type supergiants exhibit low velocity, cool stellar winds with large mass loss rates (e.g., Cassinelli 1979). In contrast, the Sun exhibits a high velocity, hot coronal wind with a very small mass loss rate (e.g., Athay 1976a). The clear dichotomy in wind properties between late-type supergiants and dwarfs has inspired many attempts to elucidate the character of outflows in the intermediate luminosity yellow and red giants, even though the spectral signatures of circumstellar absorp-

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indicate the presence of a warm wind, but the signal-to-noise ratio in their published spectrum was not sufficient to measure the anticipated blueshifts of features formed near $10^5$ K.

Recently, the search for warm winds in the giant branch took an unexpected turn when Brown et al. (1983) found that the C IV λ1548, 1551, and other high-temperature emission lines in the far-ultraviolet spectrum of β Draconis (G2 Ib–II) are redshifted with respect to narrow, low-temperature features formed deeper in the atmosphere, presumably at, or close to, the rest velocity of the star. The same phenomenon had been noted previously by Ayres and Linsky (1980) in their analysis of high quality spectra of Capella (α Aurigae A: G6 III + F9 III) obtained near one of the single-lined phases.

The reported redshifts of high-excitation species in the far-ultraviolet spectra of β Dra and Capella have encouraged us to examine the existing IUE SWP high-dispersion observations of late-type stars for additional examples of the phenomenon. In addition, we undertook a critical test of the effect by obtaining a well-exposed small-aperture IUE echelle spectrum of Capella, in conjunction with an absolute wavelength calibration.

### II. OBSERVATIONS

We analyzed a number of high-dispersion, far-ultraviolet IUE spectra from several observing programs. The target stars, their physical properties, and the circumstances of the exposures are summarized in Table 1. The long exposures of β Dra (1273 minutes) and β Ceti (795 minutes) were obtained by us through NASA-UK and NASA-ESA joint observations, respectively. The β Dra exposure was, at the time, the longest taken with IUE, and was made possible by an unusually low particle background during the NASA No. 2 shift (see Brown et al. 1982, 1983).

Most of the spectra were taken through the large aperture ($10'' \times 20''$), because the far-ultraviolet emissions of late-type stars are quite faint, and the transmission of the small aperture (3') typically is less than 50%. Nevertheless, small-aperture spectra are important for Doppler shift studies because they can be assigned an accurate absolute velocity scale (see IUE Image Processing Information Manual Version 1.0, § 5.2.4). Fortunately, the active F-type secondary of the Capella system is bright enough in the far-ultraviolet (Ayres and Linsky 1980) to permit a high signal-to-noise ratio observation through the small aperture.

Accordingly, we obtained a 240 minute, small-aperture spectrum of Capella on 1982 March 29, followed immediately by a wavelength calibration exposure of the platinum hollow cathode emission-line lamp on board the satellite. We observed Capella exactly at the phase 0.5 conjunction, within the ±0.002 cycle uncertainty in the ephemeris (Batten, Fletcher, and Mann 1978: at the phase 0.5 conjunction the more active, but less massive, star [F9 III] is in front). At conjunction, the velocity frames of the primary and secondary coincide with that of the system center-of-mass (COM), and the composite spectrum is single-lined. Because the heliocentric radial velocity of the system ($V_r = 29.5 \pm 0.2$ km s$^{-1}$; Batten, Fletcher, and Mann 1978) is known very accurately, we are confident that we can determine the absolute velocities of the bright emission lines in the rest frame of the Capella secondary to the highest precision permitted by the resolution and signal-to-noise ratio of well-exposed

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**TABLE 1**

<table>
<thead>
<tr>
<th>Target</th>
<th>Spectral Type</th>
<th>$M/M_\odot$</th>
<th>$R/R_\odot$</th>
<th>log $g$</th>
<th>SWP Image No.</th>
<th>JD Exposure</th>
</tr>
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<tr>
<td>β Draconis .....</td>
<td>G2 Ib–II</td>
<td>~13</td>
<td>~100</td>
<td>1.6 ± 0.3</td>
<td>5437</td>
<td>028.84</td>
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<tr>
<td>β Ceti</td>
<td>G9.5 III</td>
<td>~2.5</td>
<td>8.9</td>
<td>2.9 ± 0.3</td>
<td>14786</td>
<td>836.59</td>
</tr>
<tr>
<td>α Aurigae Ab</td>
<td>F9 III</td>
<td>2.55</td>
<td>7.1</td>
<td>3.2 ± 0.2</td>
<td>13610</td>
<td>693.35</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Pt I, II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>16660d</td>
<td>1058.06</td>
</tr>
<tr>
<td>λ Andromedae</td>
<td>G8 III–IV + ?</td>
<td>1.8</td>
<td>6.2</td>
<td>3.1 ± 0.3</td>
<td>1058.16</td>
<td>1058.16</td>
</tr>
<tr>
<td>α Centauri A</td>
<td>G2 V</td>
<td>1.1</td>
<td>1.2</td>
<td>4.3 ± 0.2</td>
<td>11017</td>
<td>615.34</td>
</tr>
<tr>
<td>ε Eridani</td>
<td>K2 V</td>
<td>0.75</td>
<td>0.81</td>
<td>4.5 ± 0.1</td>
<td>13553</td>
<td>687.12</td>
</tr>
</tbody>
</table>

- *Sources of these stellar parameters are: β Draconis (Brown et al. 1983), β Ceti (Eriksson, Linsky, and Simons 1983), α Aurigae Ab (Ayres and Linsky 1980), λ Andromedae (Balurnas and Dupree 1979), α Centauri A (Ayres et al. 1976), and ε Eridani (Kelch 1978).
- SWP spectral range 1150–2000 Å.
- Orbital phase. Ephemerides based on those cited by Batten, Fletcher, and Mann 1978. In both cases, phase 0 is the conjunction with the spectroscopic primary in front. The uncertainty in the Capella ephemeris is comparable to the phase duration of the small-aperture exposure.
- Small (3'') diameter aperture; all others through large ($10'' \times 20''$) aperture.

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HIGH-TEMPERATURE EMISSION-LINE REDSHIFTS

III. DATA REDUCTION AND ANALYSIS

Line position measurements for several of the spectra have been reported elsewhere (Ayres et al. 1982, 1983; Brown et al. 1983; Ayres, Simon, and Linsky 1982). However, in order to apply measurement techniques uniformly, we have examined the entire body of spectra using the most recent procedures available at the IUE Regional Data Analysis Facility in Boulder. These include median-filtering and running-mean smoothing of the interorder backgrounds, an echelle blaze correction (Ahmad 1981) with optimum grating "constants" (Ake package (Tumrose, Thompson, and Bohlin 1981). The implementation of an upgraded image processing bration spectrum were obtained after the recent implementation of an upgraded image processing package (Turnrose, Thompson, and Bohlin 1981). We established differential velocity errors in images extracted according to the previous scheme will be significantly degraded. Furthermore, Leckrone (1980a) has demonstrated that velocity the relative velocities measured between lines within one echelle order, or in different orders, should be reliable.

We established line positions and fluxes by a least squares Gaussian fitting technique. In practice we smoothed the calibrated spectra, prior to fitting, by a three-point running mean (five points for the more finely sampled small-aperture spectra) to reduce the apparent noise levels and thereby aid the identification of weak stellar features. The fitting procedure incorporates provisions to avoid regions of the line profile that are affected by strong cosmic ray "hits," by camera artifacts ("hot" pixels), by structure at the emission peak (caused, for example, by interstellar absorption), or by overexposure.

We measured a standard group of 25 emission lines, where possible, in each of the spectra. We have sorted, somewhat arbitrarily, the reference lines into five categories as listed in Table 2: weak chromospheric, strong chromospheric, low transition region (TR), TR intersystem, and high-temperature permitted. The primary velocity reference in each large-aperture spectrum is the flux-weighted mean of the first group, which consists of narrow, weak features that presumably are formed deep in the chromosphere where the bulk motions probably are smallest. Accordingly, we assume that the mean velocity of the first group is close to the rest velocity of the stellar photosphere (as established by the optical absorption line spectrum). The strong chromospheric lines are very optically thick (O I triplet) or mildly optically thick (Si II triplet: see Tripp, Athay, and Peterson 1978) compared with the first group, and consequently should be formed at higher altitudes where systematic velocity fields might be larger. However, in the two dwarf stars these lines are much narrower and weaker than their counterparts in the giant stars, particularly the O I triplet, and therefore were included with the first category for the purpose of establishing a "zero" velocity.

The third group consists of the very optically thick C II multiplet near 1335 Å, and the optically thin He II λ1640 Balmer-α feature. In collisional equilibrium, the first species attains maximum abundance in the low transition region at temperatures of about 3 × 10^4 K, while the He II feature would be formed at much higher temperatures, perhaps 10^5 K. However, the He II emission is thought to be excited, in part, by a photoionization-recombination process involving the coronal EUV radiation field (e.g., Zirin 1975; Avrett, Vernazza, and Linsky 1976), and accordingly can be formed at much cooler temperatures, perhaps ≲ 2 × 10^4 K. The mean wavelength of the He II Balmer-α feature therefore will depend on the relative influence of collisional excitation and
TABLE 2

<table>
<thead>
<tr>
<th>GROUP</th>
<th>SPECTRUM</th>
<th>REST WAVELENGTH$^a$ (Å)</th>
<th>Relative Velocity$^b$ (km s$^{-1}$)</th>
<th>Flux Weight$^c$</th>
<th>Absolute Velocity ± s.e. [Pt]$^d$ (km s$^{-1}$)</th>
<th>Flux Weight$^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak chromospheric (6000 K)</td>
<td>S I</td>
<td>1295.653</td>
<td>-4.4</td>
<td>2.1</td>
<td>-4.3 ± 1.1(5)</td>
<td>0.5</td>
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<td></td>
<td></td>
<td>96.174</td>
<td>+7.8</td>
<td>1.3</td>
<td>+6.1 ± 3.2 f</td>
<td>0.3</td>
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<tr>
<td></td>
<td></td>
<td>1302.863</td>
<td>...</td>
<td>...</td>
<td>+4.3 ± 2.4 f</td>
<td>0.3</td>
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<tr>
<td></td>
<td>Cl I</td>
<td>1351.657</td>
<td>-2.8</td>
<td>2.4</td>
<td>+5.7 ± 2.7 f</td>
<td>0.6</td>
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<tr>
<td></td>
<td>O I</td>
<td>1355.598</td>
<td>+5.2</td>
<td>3.1</td>
<td>+12.0 ± 3.2 f</td>
<td>0.7</td>
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<tr>
<td></td>
<td>C I</td>
<td>1641.305$^c$</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1993.620</td>
<td>-3.7 ± 3.2 f</td>
<td>2.7</td>
<td>...</td>
<td>...</td>
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<tr>
<td>Weighted mean ± s.e.</td>
<td></td>
<td>+0.0 ± 2.4</td>
<td></td>
<td></td>
<td>+5.3 ± 2.9 f</td>
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<tr>
<td>Strong chromospheric (6000–10000 K)</td>
<td>O I</td>
<td>1302.169</td>
<td>...</td>
<td>...</td>
<td>+6.8 ± 2.7 f</td>
<td>3.5</td>
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<tr>
<td></td>
<td></td>
<td>04.858</td>
<td>+1.8</td>
<td>13.6</td>
<td>+4.9 ± 1.1(5)</td>
<td>4.2</td>
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<td></td>
<td></td>
<td>06.029</td>
<td>+5.4</td>
<td>12.6</td>
<td>+4.9 ± 1.1(5)</td>
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<tr>
<td></td>
<td>Si II</td>
<td>1808.012</td>
<td>+3.3</td>
<td>7.8</td>
<td>[+8.0 ± 2.0(6)]</td>
<td>[1.6]$^f$</td>
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<tr>
<td></td>
<td></td>
<td>16.928$^c$</td>
<td>...</td>
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<tr>
<td></td>
<td></td>
<td>17.451$^c$</td>
<td>...</td>
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<tr>
<td>Low transition region (2 × 10$^4$–3 × 10$^4$ K)</td>
<td>C II</td>
<td>1334.532</td>
<td>+2.1</td>
<td>17.9</td>
<td>+8.4 ± 1.1(3)</td>
<td>5.3</td>
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<td></td>
<td>35.708</td>
<td>+14.2</td>
<td>19.5</td>
<td>+19.8 ± 1.3(8)</td>
<td>5.3</td>
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<tr>
<td></td>
<td>He II</td>
<td>1640.4$^b$</td>
<td>+8.6</td>
<td>4.7</td>
<td>+22.3 ± 1.2(7)</td>
<td>2.3</td>
</tr>
<tr>
<td>TR intersystem (5 × 10$^4$ K)</td>
<td>O III [</td>
<td>1666.153</td>
<td>-3.9</td>
<td>2.0</td>
<td>+4.0 ± 1.2(7)</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Si III</td>
<td>1892.030</td>
<td>+3.9 ± 3.2 f</td>
<td>22</td>
<td>[+23.3 ± 1.4(4)]</td>
<td>[15]$^g$</td>
</tr>
<tr>
<td></td>
<td>C III</td>
<td>1908.734</td>
<td>+7.2 ± 3.2 f</td>
<td>8.8</td>
<td>[+13.7 ± 1.4(4)]</td>
<td>[15]$^g$</td>
</tr>
<tr>
<td>High-temperature permitted (7 × 10$^4$–2 × 10$^5$ K)</td>
<td>N v</td>
<td>1238.821(805)</td>
<td>+7.9</td>
<td>7.9</td>
<td>+18.6 ± 2.7(4)</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42.804(803)</td>
<td>-6.8</td>
<td>3.3</td>
<td>+3.7 ± 2.7(4)</td>
<td>0.8</td>
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<tr>
<td></td>
<td>Si IV</td>
<td>1393.755</td>
<td>+13.4</td>
<td>14.7</td>
<td>+21.5 ± 1.0(9)</td>
<td>3.4</td>
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<td>1402.770</td>
<td>+0.9</td>
<td>6.9</td>
<td>+11.1 ± 1.0(9)</td>
<td>2.1</td>
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<tr>
<td></td>
<td>C IV</td>
<td>1548.185(202)</td>
<td>+11.0</td>
<td>30.5</td>
<td>+17.5 ± 1.0(9)</td>
<td>8.5</td>
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<tr>
<td></td>
<td></td>
<td>50.774(774)</td>
<td>+12.6</td>
<td>17.2</td>
<td>+0.7 ± 1.0(4)</td>
<td>5.0</td>
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<tr>
<td>Weighted mean ± s.e. [N v + Si IV + C IV]</td>
<td></td>
<td>+9.9 ± 2.1</td>
<td></td>
<td></td>
<td>+16.7 ± 1.7 f</td>
<td></td>
</tr>
<tr>
<td>Weighted mean ± s.e. [Si IV + C IV only]</td>
<td></td>
<td>+10.9 ± 2.1</td>
<td></td>
<td></td>
<td>+17.1 ± 1.6 f</td>
<td></td>
</tr>
</tbody>
</table>


$^b$Velocity relative to flux weighted mean of weak chromospheric lines.

$^c$Integrated flux of fitted Gaussian in units of 10$^{-2}$ erg cm$^{-2}$ s$^{-1}$ at Earth. Note: the effective transmission of the small aperture was about 0.3 for the phase 0.5 exposure.

$^d$Standard error in mean Pt lamp line velocity for wavecal features in vicinity of stellar emission lines. The mean Pt velocities, typically of order +2 km s$^{-1}$, were subtracted from the stellar emission line velocities within the blocks of three echelle orders which were reduced for each wavelength region of interest. The number of individual Pt lines measured within each block is given in parentheses following the standard errors. The single-line measurement error for the stellar features is of order ± 5 km s$^{-1}$.

$^e$Feature badly blended or not visible in Capella spectrum, but measured in one, or more, of the other stars of sample.

$^f$Registration uncertainty between long and short exposure (standard error of flux-weighted mean velocity difference between 15 brightest lines common to the exposure pair).

$^g$Some pixels overexposed, or beyond top level of intensity transfer function.

$^h$The cited wavelength is a mean of the individual components of the feature weighted by the statistical populations.

recombination on the several components of the line (cf. Kohl 1977), in addition to any bulk motions that might be present in the layers from which the He II emission arises.

The fourth group consists of the intersystem lines of O III, Si III, and C III, which are optically thin in the intermediate temperature (5 × 10$^4$ K) plasma of the stellar transition region. Note, however, that both O III| λ1666 and Si III| λ1892 behave like “coronal” lines (i.e., $F_L - n_e^2$) for the density regime $n_e < 10^{13}$ cm$^{-3}$ thought to be appropriate for the transition regions of late-type dwarfs and giants (see, e.g., review by Doschek 1983), while C III| λ1909 is “density-sensitive” (i.e., $F_L - n_e$) in that regime. Consequently, the O III and Si III emission
will be more heavily weighted toward the denser structures of an inhomogeneous transition region than will the C III emission.

The final group consists of the resonance doublets of Li-like C IV and N V and Na-like Si IV, which reach maximum abundance in the temperature range 7 × 10^4 K to 2 × 10^5 K. These lines are thought to be optically thin in solar active regions, and probably also in the transition regions of other dwarf stars. Whether these features are optically thin or thick in the giant stars has not been established conclusively. Ayres et al. (1982) argued that the factor of 2 width increase of the Si IV and C IV resonance doublets compared with the Si III and C III emissions indicated that the former were "opacity broadened" and hence at least mildly optically thick (τ ≈ 10). Nevertheless, the Si IV and C IV features of Capella (cf. Ayres, Schiffer, and Linsky 1983) and of β Dra (Brown et al. 1982) do not exhibit self-reversed permitted fines is caused by a mechanism other than possible that the high-temperature resonance doublets do not depart greatly of Capella (cf. Ayres, Schiffer, and Linsky 1983) and of C IV transitions at 1548 Å for C IV do not depart greatly from the optically-thin 2:1 limit, at least within the uncertainties imposed by the limited signal-to-noise ratio of typical IUE spectra of those stars, and the uncertain continuum levels at 1550 Å. Accordingly, it is quite possible that the high-temperature resonance doublets in the active-chromosphere giants, and that the width dichotomy between the intersystem and permitted lines is caused by a mechanism other than opacity broadening, for example a steep rise in the turbulent broadening with increasing temperature.

The emission lines of the small-aperture spectrum of Capella were adjusted to the velocity frame of the IUE satellite using the even weighted mean positions of the emission calibration features (exclusively Pt II lines) in the blocks of three echelle orders which were reduced for each wavelength region of interest (see Table 2). The small-aperture spectrum of Capella then was registered to the velocity frame of the secondary star using heliocentric corrections for the Earth and satellite motion (Harvel 1980) and the system radial velocity.

For β Dra and Capella (phase 0.0), pairs of large-aperture spectra with a factor of 4 difference in exposure time were combined to permit the analysis of bright features longward of 1800 Å. The short exposures were registered to the longer exposures according to the flux-weighted mean velocity of the approximately 15 brightest features that appear in each pair.

Examples of the velocity and flux measurements are provided in Table 2 for the Capella exposures. Selected portions of the Capella small-aperture spectrum are illustrated in Figure 1, and the quality of the Gaussian fits is illustrated in Figure 2 for the C IV λ1548, 1551 profiles.

Figure 3 summarizes the velocity measurements for the entire sample of stars. For clarity, lines of the same species within individual groups have been combined into single symbols. The area of each circle is proportional to the line flux (or combined fluxes): the larger the flux, the more accurately the line centroid (or mean of the line centroids) can be established. The filled circles without error bars in each panel designate the features that establish the zero-velocity level. The hatched circles in the Capella panel refer to the phase 0.5 observations in the velocity frame of the secondary star. The error bars at the left-hand and right-hand sides of each panel indicate the flux-weighted mean velocity, and standard error of the weighted mean, for the zero velocity reference features and the Si IV + C IV doublets, respectively. In the latter cases (except for Capella phase 0.5), the uncertainty is the quadratic sum (square root of sum of squares) of the two independent standard errors to illustrate the uncertainty in the velocity differences.

It is apparent from Figure 3 that all of the stars of our sample exhibit a differential redshift between the high- and low-temperature features, although the results for β Ceti and α Cen A are significant only at the ≈ 2.5 σ level. The Capella small-aperture measurements confirm that the Si IV + C IV features are redshifted in an absolute sense, and reveal that even the low-temperature features are slightly redshifted with respect to the photospheric absorption line velocity of the secondary spectrum at phase 0.5. Furthermore, the agreement between the small-aperture spectrum of Capella at phase 0.5 and the large-aperture spectrum at phase 0.0 is excellent when the absolute redshift of the low-temperature lines in the former is taken into account. Because the differential redshift appears to persist in time and is the same for opposite orientations of the binary, it likely is a stellar, not a system, phenomenon. We also call attention to the agreement between the differential redshifts of the Capella secondary and λ Andromedae, both log g ≈ 3 giants, despite the large difference in spectral types and aspect angles; λ And is viewed at a high inclination (Balunñas and Dupree 1979), while Capella is viewed more nearly equator-on.

Finally, if one considers the differential velocity shift of Si IV + C IV with respect to the weak chromospheric species, the measurements summarized in Figure 3 suggest an inverse correlation between differential redshift and surface gravity, although any firm conclusions would be premature given the small sample of stars.

IV. DISCUSSION

It is clear that differential redshifts of high-temperature species relative to low-temperature species are common among the few late-type stars whose far-ultraviolet spectra have been measured with sufficient signal-to-noise ratios. Given the wide range of stellar types for which the redshifts are observed, it is important to consider possible origins and implications of the phenomenon. Potential sources of the differential redshifts...
Fig. 1.—(a) Selected 25 Å bands in the 1230–1357 Å region from a 240 minute small-aperture exposure of Capella at phase 0.5 (top tracing in each panel) and the platinum hollow cathode emission-line lamp (bottom tracing). The flux scale is relative because the small-aperture spectra cannot be calibrated reliably owing to the uncertainty in the effective transmission of the small slot at the time of observation (see text). Both spectra have been smoothed with a 5-point running mean, and the stellar spectrum has been registered to the velocity frame of the secondary star using the wavelength calibration and heliocentric corrections for the Earth and satellite motion and the system radial velocity. Selected stellar emission features and the Pt lamp wavecal standard lines are identified. Vertical ticks indicate the rest positions of the prominent emission features; cross hatching below the zero intensity line designates regions of the spectrum affected by reseau marks; and # symbols identify prominent particle radiation hits or camera artifacts. Interstellar absorption features can be seen in the 0 cm⁻¹ lower level lines of O i (λ1302) and C ii (λ1334), as well as a weaker feature in the 64 cm⁻¹ line of C ii (λ1336). The 200 cm⁻¹ lines of O i (λ1304,1306) show no evidence for interstellar absorption, as expected. (b) Same as Fig. 1a for 25 Å bands in the 1387–1660 region.
fall into two broad categories which we loosely describe as instrumental and atmospheric.

a) Instrumental Effects

In the preceding analysis we have adopted the standard deviation of individual line centroid velocities about the flux-weighted mean to characterize the uncertainty in a single profile measurement. We make the implicit assumption in this approach that lines within a particular group, the weak chromospheric features for example, are formed in essentially the same layers of the stellar outer atmosphere and thereby experience essentially the same velocity field. If this condition is obeyed, the standard deviation about the mean of the individual measurements should indicate the error introduced by the profile fitting technique, uncertainties in the laboratory wavelengths, distortions in the linearity of the assigned wavelength scale, and so forth. The standard errors ($= \sigma/\sqrt{n}$ for evenly-weighted samples) of the flux-weighted mean velocities obtained in this manner for the four components of the Si IV and C IV doublets
range from less than $\pm 1$ km s$^{-1}$ for the high signal-to-noise ratio spectrum of the sharp-line dwarf $\epsilon$ Eri to $\pm 8$ km s$^{-1}$ for the weak exposure of the broad-line giant $\beta$ Ceti. The error associated with the measurement of a single line would be roughly $\sqrt{4} = 2$ times larger than the standard error, and accordingly would range from about $\pm 2$ km s$^{-1}$ for $\epsilon$ Eri to $\pm 16$ km s$^{-1}$ for $\beta$ Ceti. Both of these empirical single-line measurement errors are smaller than the 30 km s$^{-1}$ instrumental resolution. Are the estimated errors plausible?

Recently, Landman, Roussel-Dupré, and Tanigawa (1982) have published algorithms for estimating the measurement errors associated with fitting least squares Gaussians to noisy data. For the sampling frequency appropriate to pre-1981 November IUE spectra, the random measurement error for the centroid velocity is:

$$8V \sim 2.5 \text{FWHM}^{1/2} (S/N)^{-1} \text{km s}^{-1},$$

(1)

where FWHM is the full width at half-peak intensity of the fitted Gaussian (in km s$^{-1}$) and $S/N$ is the ratio of the peak intensity of the fitted Gaussian to the rms noise level in the spectrum. For the broad C iv lines of the giants (FWHM $\leq$ 200 km s$^{-1}$) and the typical signal-to-noise ratio for a well-exposed point source ($S/N = 10$–30; Holm 1982), the predicted single-measurement error is $\leq 3.5$ km s$^{-1}$. For the narrow C iv lines of the dwarfs (FWHM = 50 km s$^{-1}$) and the same signal-to-noise ratio, the single-measurement error is $\leq 1.8$ km s$^{-1}$. These values are compatible with those obtained empirically. Furthermore, the difference in velocity between the well-exposed components of the C iv doublet of Capella is small in both the small- and large-aperture spectra, while the velocity differences between the components of the lower $S/N$ Si iv and N v doublets is larger as predicted by equation (1). Note, also, that the standard deviations about the mean velocity of the narrow, but weak, chromospheric lines of either the large- or small-aperture spectrum of Capella, $\sigma \approx m \times (s.e.) \approx 5$ km s$^{-1}$, is compatible with the single-line measurement error cited by Leckrone (1980a) based on studies of weak interstellar absorption lines, and is consistent with the low signal-to-noise ratio typical of the faint chromospheric emissions ($S/N \leq 4$). Only by taking the mean of several features can one improve the precision of a velocity measurement significantly beyond the single-measurement error.

Another source of “instrumental” error is uncertainty in the laboratory wavelengths. We have adopted Kelly and Palumbo (1973) as the source for line positions. The authors cite a typical uncertainty in the tabulated wavelengths of $\pm 0.002$ Å, which corresponds to a $\pm 0.4$ km s$^{-1}$ velocity uncertainty at the C iv doublet. Bockasten, Hallin, and Hughes (1963) have reported wavelengths for C iv (1548.202 $\pm 0.010$ Å) and N v (1238.805 $\pm 0.010$ Å) that are, respectively, $3.3 \pm 1.9$ km s$^{-1}$ larger and $3.9 \pm 2.4$ km s$^{-1}$ smaller than the wavelengths we have adopted here. We conclude that the uncertainty in the laboratory wavelengths is, at worst, comparable to the single-line measurement error. Accordingly, the significance of the small positive Doppler shifts of the high-excitation lines of the dwarf-star spectra may be in jeopardy, although the significance of the large positive shifts in the giant-star spectra is not in doubt.

A third source of instrumental error, which was recognized only recently, are small-amplitude nonlinearities in the extracted wavelength scales of IUE echellograms (R. Thompson 1982, private communication). The distortions appear to be random with a rms amplitude of less than 1 pixel and a correlation length of less than several pixels (1 pixel $\approx 8$ km s$^{-1}$ for the short-wavelength echelle). Their origin is not entirely clear, but they could induce artificial wavelength shifts. We have examined this possibility by comparing the small- and large-aperture spectra of Capella, assuming that the wavelength scale distortions would not be correlated between the exposures taken a year apart, on different portions of the SWP vidicon, and extracted using the different image processing schemes in effect at those times. The standard deviation of the velocity differences between the small- and large-aperture spectra range from about 3 km s$^{-1}$ for the strong chromospheric and high-temperature permitted lines up to 7 km s$^{-1}$ for the TR intersystem lines. The weak chromospheric line group...
Fig. 3.—Summary of differential Doppler shifts between high-excitation and low-excitation species. For clarity the Doppler shifts of individual features from similar excitation groups, such as O I λλ1356,1641 or O I λλ1302,1305,1306, have been combined into single symbols. The size of each circle is proportional to the combined fluxes of the particular features: the larger the flux, the more accurately the line centroid (or mean of the line centroids) can be established. Filled circles refer to the weak, narrow chromospheric features that were used to define the velocity zero for each spectrum, with the exception of the Capella phase 0.5 measurements (hatched circles) which are in the velocity frame of the secondary star (where zero velocity refers to the photospheric optical absorption spectrum). The error bars at the left-hand and right-hand sides of each panel indicate the flux-weighted mean velocity, and standard error of the mean, of the low-excitation species and the Si iv + C iv doublets, respectively. In the latter case (except for Capella phase 0.5), the error bar is the root-sum-square of the low-excitation and high-excitation standard errors to illustrate the uncertainty in the difference of the mean velocities.
has an intermediate value of 5 km s\(^{-1}\). The intersystem line comparison likely is prejudiced by overexposure of the Si \(\text{III}\) and C \(\text{III}\) emission cores in the 4 h small-aperture spectrum. These standard deviations are comparable to those expected solely on the basis of the single-line measurement errors cited previously. Accordingly, we believe that velocity uncertainties attributable to small departures from linearity in the extracted wavelength scales very likely are not larger than the single-line measurement errors, at least for the broad lines of the Capella spectrum. Nevertheless, the fidelity of the wavelength scales should be considered carefully in future investigations of this type, particularly for narrow-line spectra where the consequences may be most severe.

Finally, we consider the small positional freedom of the stellar image in the small aperture. Under optimum conditions, the target can be centered in the small aperture to an rms precision of about 0\(\text{\arcsec}\)27 (Holm 1982), which corresponds to an rms velocity error of about 1.4 km s\(^{-1}\), if the spatial offset is along the dispersion axis. By comparing the fluxes of well-exposed, isolated emission lines in the small- and large-aperture spectra of Capella, we can estimate the effective transmission of the small aperture for the particular observation and establish how well the target was centered. The O \(\text{I} \lambda 1305, 1306\) and C \(\text{IV} \lambda 1548, 1551\) features indicate an effective transmission of about 0.29, which suggests that the target may have been off center in the small-aperture observation, since the nominal point source transmission 0.53 ± 0.13 (Holm 1982). However, the most likely positional error was in the direction perpendicular to the dispersion axis (F. Schiffer 1982, private communication), and the inferred offset may therefore have introduced only a small effective velocity shift. Nevertheless, the significance of the slightly positive velocity of the weak chromospheric line group in the phase 0.5 spectrum may be in jeopardy, although the positive velocities of the Si \(\text{IV}\) and C \(\text{IV}\) doublets are large enough that their significance is not in doubt.

In summary, we have considered a number of instrumental effects, but conclude that none of these could explain the large positive Doppler shifts of Si \(\text{IV}\) and C \(\text{IV}\) seen in the giant stars in general, and in Capella in particular. We now consider how the stellar atmosphere itself might produce the differential redshifts of the Si \(\text{IV}\) and C \(\text{IV}\) doublets relative to the weak and narrow emissions of the lower chromosphere.

\textit{b) Atmospheric Effects}

Since all of the measured redshifts, aside from the small-aperture spectrum of Capella, are differential, the high-temperature lines could be at rest with respect to the stellar photosphere, while the narrow chromospheric lines that provide our zero velocity reference might be blueshifted. This possibility is a serious concern, because with the exception of O \(\text{I} \lambda 1356\), all of the other O \(\text{I}\), S \(\text{I}\), Cl \(\text{I}\), and C \(\text{I}\) multiplets are fluorescent lines, that are radiatively pumped by the strong emissions of O \(\text{I} (1305 \text{\AA} \text{triplet})\), C \(\text{I} (1657 \text{\AA} \text{multiplet})\) and C \(\text{II} (1335 \text{\AA} \text{multiplet})\) (see, e.g., Brown and Jordan 1980; Shine 1982). The pumping process could, in principle, induce small artificial wavelength shifts in the fluorescent emission profiles that might bias the differential velocity measurement. However, it is unlikely that the different radiative pumps would all produce spurious Doppler shifts of the same sense. Indeed, the mean velocity of the fluoresced lines in the small-aperture spectrum of Capella is 2 \(\sigma\) redward of the stellar rest velocity, and an unusually poor placement of the target in the aperture would have been required in order to hide a net blueshift of those features. Furthermore, the small-aperture spectrum demonstrates that the Si \(\text{IV}\) and C \(\text{IV}\) doublets are redshifted, in Capella at least, regardless of the velocities of the weak, fluorescent lines.

We therefore believe that the measured differential velocities indicate genuine absolute redshifts. Nevertheless, possible wavelength shifts of the fluorescent lines should be studied more thoroughly in future work by means of additional absolute velocity measurements and numerical simulations of the pumping process and associated radiative transfer effects.

We now address a more challenging question: what is the significance of the redshifts with regard to flows in the stellar atmosphere? We consider two very different possibilities: (1) warm (10\(^5\) K) winds of the type proposed by Hartmann, Dupree, and Raymond (1980, 1981), and Hartmann and McGregor (1980); and (2) the downflowing component of a vertical circulation system in which the up-leg portion of the flow is at a significantly different temperature or density than the downleg portion. The dichotomy in interpretation exists because inflows and outflows having large velocity gradients over the line formation region can produce similar apparent Doppler shifts in optically thick emission lines (Athay 1976b, and references therein). For example, the very optically thick O \(\text{I} 1305 \text{\AA} \text{triplet}\) lines of \(\alpha\) TrA (K4 II) appear to be redshifted owing to blueshifted circumstellar absorptions that mask the short-wavelength sides of the emission profiles (Hartmann, Dupree, and Raymond 1981). A similar effect has been noted in the far-ultraviolet spectrum of Arcturus (\(\alpha\) Boo, K2 III; see Ayres, Simon, and Linsky 1982). In both cases, the Mg \(\text{II} \lambda 2796, 2803\) lines also are heavily distorted by circumstellar absorption components. Nevertheless, if the line-forming region has a constant velocity with respect to the stellar photosphere, then a net redshift will result if the material is moving toward the star (away from the observer), and a blueshift if the material is moving away (toward the observer), regardless of the optical depth of the emission lines.

There are a number of complications in assessing the viability of warm winds in explaining the observed
differential redshifts of the Si IV and C IV doublets. The major impediment is that among the stars of our sample, there are no other spectroscopic signatures of winds, such as blueshifted circumstellar absorption features in Mg II h and k or infrared excesses. Consequently, we have no independent information concerning the terminal velocity of the flow or the mass loss rate, unlike the cases of α Aqr, β Aqr, and α TrA (Hartmann, Dupree, and Raymond 1980, 1981) or α Boo (Ayres, Simon, and Linsky 1982). We therefore cannot establish whether the wind itself is responsible for most of the observed high-temperature emission, or whether the flow instead is of secondary importance and merely shadows bright, static structures of the lower atmosphere. We therefore must resort to indirect arguments to test the plausibility of the warm-wind hypothesis.

We suspect, for example, that the wind cannot be responsible for the majority of the high-temperature emission on active chromosphere giant stars and at the same time be highly extended (in the sense that most of the emission from the wind arises in a volume with $r_w \gg R_*$. In particular, studies of RS CVn systems like HR 1099 at opposite quadratures in the orbit (maximum velocity separation) indicate that the Si IV and C IV emission is gravitationally bound to the active subgiant star, not to the center of mass of the system as an extended wind would be (Ayres and Linsky 1982). Additional evidence that the wind cannot be highly extended and also provide most of the emission measure ($\int n_e^2 dV$) at $10^5$ K comes from the study by Hartmann, Dupree, and Raymond (1981) of the early-K bright giant α TrA. The authors constructed models of a warm wind, using the formalism developed by Hartmann and MacGregor (1980), to match the terminal velocity of the circumstellar absorptions in Mg II h and k, and to explain the velocity widths of Si III, C III, and C IV. However, owing primarily to the low densities required by a highly extended flow, the models predicted a surface flux for the “density-sensitive” C III λ1909 line more than an order of magnitude larger than observed, and even the fluxes of permitted lines like C IV were several times larger than observed. Within our sample of giant stars, the ratio of C III emission to the permitted lines of Si IV and C IV is somewhat larger than the equivalent ratio for the dwarf stars, but not grossly different (e.g., Ayres et al. 1982). The observed ratios are consistent with somewhat lower densities in the regions of large emission measure in the atmospheres of the giants compared with those of the dwarfs. The observed ratios, however, are not compatible with the very small densities required by the geometrically-extended warm-wind models, unless the wind is not responsible for the majority of the emission measure at $10^5$ K.

A second possibility is that the warm wind is compact, in the sense that the emission scale height is small compared with the stellar radius. A wind will be compact in Si IV and C IV if the maximum temperature, assumed to be near $10^5$ K, occurs close to the star and the velocity law beyond $T_{\text{max}}$ decreases less rapidly than $r^{-1}$. If opacity effects and a wind are to explain the apparent redshifts of the Si IV and C IV features in the active giant stars, then the flow must be accelerating outward in the region of line formation. Consequently, the condition on the velocity law is satisfied, and the wind will be compact only if the $10^5$ K region occurs close to the star. However, in this event the optically thin lines O III λ1666, Si III λ1892 and C III λ1909 must be blueshifted. (Note: in a highly extended wind, the optically thin lines should appear near their rest velocities since both hemispheres of the expanding flow are visible to the external observer. The interstellar lines will be broadened by an amount that depends on the expansion velocity in the region of line formation [see Hartmann, Dupree, and Raymond 1981]).) The measured velocities of the optically-thin lines summarized in Figure 3 provide no convincing evidence for blueshifts on the order of the redshifts of Si IV and C IV. We conclude that a compact, warm wind of large emission measure is not a likely explanation for the redshifted Si IV and C IV features of the active chromosphere giant stars.

A final possibility for a warm wind is a highly extended flow of low emission measure that, nevertheless, is optically thick in the Si IV and C IV resonance lines. Such a wind could obscure the short-wavelength edges of high-temperature emission features from bright, static structures of the lower atmosphere, analogous to coronal active regions on the Sun, for example. Since the column opacity of a permitted transition is directly proportional to the height integral of the density, while the emission is proportional to the volume integral of the square of the density, it is possible to find a combination of density law and geometrical extension to produce significant absorption, while contributing negligible emission, to the blue side of the C IV profile, for example. In this situation, the strong, permitted lines would appear to be redshifted owing to the short-wavelength absorption by the wind; the optically thin lines of O III and Si III would be found close to the intrinsic velocity of the structures of high emission measure in the lower atmosphere (since these inter system lines behave like permitted transitions for $n_e \leq 10^{11}$ cm$^{-3}$); while the “density-sensitive” C III feature might be slightly blueshifted with respect to the other optically thin lines. The latter condition is the principal test of the hypothesized configuration of the warm wind. Unfortunately, the difference velocity of C III λ1909 and Si III λ1892, for example, is dominated in our IUE observations by the quadratic sum of the individual single-measurement errors, which likely is no smaller than $\pm 5$ km s$^{-1}$. We therefore cannot rule out the possibility of an extended warm wind of low emission measure to explain the
apparent redshifts of the Si iv and C iv doublets of the active-chromosphere giant stars. However, even in that situation we must contend with the possibility that the surface structures of the high emission measure themselves may have an internal redshift, in addition to the opacity effects produced by the hypothesized wind, since the mean velocities of the optically thin intersystem lines in all of the giant stars are at least slightly positive.

We therefore consider the alternative class of conditions that can produce apparent redshifts in the high-temperature permitted lines, namely mass motions in the stellar atmosphere which are predominantly downward in the layers in which the Si iv and C iv doublets are formed. Downflows would produce apparent redshifts of these features if the lines are optically thin, or if the motion is uniform throughout the region of line formation, regardless of the optical depth of the emission lines.

The downflow hypothesis is attractive for two important reasons.

First, the Si iv and C iv features probably are at worst only marginally optically thick in the layers that contribute most of the 10^5 K emission measure, based on the arguments outlined in § III, above, and by Brown et al. (1982, 1983). In short, the densities inferred from intersystem line ratios, and the emission measures derived from the permitted lines, imply that the regions of line formation must be quite thin (Δr < 10^{-3} R_☉), like those on the Sun, unless the outer atmospheres of the giant stars are extremely inhomogeneous and the surfaces are covered sparsely by highly elongated (Δr = R_☉) structures. (For fixed emission measure and mean electron density, both the vertical extent and optical depth of emitting structures are inversely proportional to the surface covering fraction.) We consider this possibility to be unlikely, although we cannot rule it out on the basis of available data. For example, Walter, Gibson and Basti (1982) have studied the X-ray emission of the RS CVn system AR Lac during primary and secondary eclipse and have discovered an extended (Δh = R_☉) component of the corona (10^6–10^7 K) associated with the active K-giant, in addition to a more compact (≤ 0.02 R_☉), inner component.

Second, downflows of material at Si iv and C iv temperatures are known to occur in magnetic active regions on the Sun (e.g., Brueckner 1981, and references therein). The velocities of the solar downflows measured from high spatial resolution spectrometers range from 5 to 20 km s^{-1} over plages and the supergranulation network (Doschek, Feldman, and Bohlin 1976; Feldman, Cohen, and Doschek 1982). Rousset-Dupré and Shine (1982) have detected a similar range of redshifts in spatially averaged, quiet-Sun profiles of C iv and Si iv, which presumably are dominated by the network component. Doschek and Feldman (1977) have measured smaller downflows (≤ 5 km s^{-1}) in the self-reversed cores of the chromospheric Mg ii h and k emission features over supergranulation network boundaries. Recently, Athay et al. (1983) have summarized the results of a Doppler-shift investigation of C iv λ1548 using the Solar Maximum Mission. Their study supports the existence of a net redshift of C iv over magnetic active regions, indicates a strong correlation of the line FWHM with the magnitude of the shift, and provides some corroboration for a previously suggested correlation between the redshift and intensity of the C iv line (although many counterexamples to the latter phenomenon were cited). We stress, however, that none of these high-spatial resolution investigations has established whether the disk-average profile of the solar C iv λ1548 emission would exhibit a systematic net redshift.

Several explanations for the downflows in the solar transition region have been proposed. The flows may be produced by coronal material that is cooling, becoming denser, and falling back down to the footpoints of a magnetic loop following the interruption of the internal heating source (Rosner, Tucker, and Vaiana 1978). The downflows may be part of a circulation system within magnetic loops for which the up-leg portion of the flow is too cool (spicules, for example) to be visible in C iv (Pneuman and Kopp 1977). It is even possible that material is flowing upward at C iv temperatures more rapidly than it is flowing downward because the decrease in density required by mass conservation will greatly reduce the visibility of the upward moving gas (since F_l ∼ n_e^2, if the column path lengths are the same (Doschek, Feldman, and Bohlin 1976).

In this regard, it is worth noting that the O i resonance lines appear to be slightly redshifted, and the C ii features are significantly redshifted, in the giant stars of our sample. The apparent shifts in the chromospheric and low transition region features that are very optically thick might indicate an accelerating outflow of material in those layers which is in fact the up-leg portion of the hypothesized circulation system. If the rising gas is mechanically heated rapidly to coronal temperatures, the visibility in C iv will be much less than during a subsequent radiative cooling phase where substantial emission by C iv is a natural by-product of the importance of the Li-like ions in the plasma cooling function near 10^5 K (cf. Cox and Tucker 1969). Furthermore, the smaller redshifts of the optically thin intersystem lines of O iii, Si iii, and C iii compared with those of the Si iv and C iv doublets may imply that the downflow attains its highest velocity in the 10^5 K layers, and decelerates substantially below that level, as is thought to be the case for the solar flows (Dere 1982).

Finally, we consider whether the hypothesized downflows, particularly the inferred velocities, are consistent with our assumption of optically thin emission, namely Δh ≪ R_☉. If the redshifts are produced by free falling material or gravitational settling (Rousset-Dupré and Beerman 1981), we can set a lower limit to the vertical extent of the acceleration region. The acceleration
region, itself, very likely will be larger than the line-forming layer if the gas is cooling from coronal to transition-region temperatures during the acceleration period. The lower limit to the vertical extent of the acceleration region is:

$$\Delta h_{\text{min}} = \frac{1}{2} V_*^2 / g_*,$$

where $V_*$ is the plasma velocity and $g_*$ is the stellar surface gravity. The measured redshifts, to the extent that they indicate $V_*$, do not vary greatly among the giant stars, but the surface gravity does. Accordingly, we expect that $\beta$ Dra will present the most extreme case. Using $V_* = 20 \text{ km s}^{-1}$ and the surface gravity cited in Table 1, we obtain $\Delta h_{\text{min}} \approx 10^{-2} R_*$ for $\beta$ Dra, while using $V_* = 10$ we obtain $\Delta h_{\text{min}} = 10^{-2} R_*$ for $\lambda$ And and the Capella secondary. The latter estimate is compatible with the "thin" corona ($\Delta h \approx 10^{-2} R_*$) derived by Mewe et al. (1982) for the Capella secondary using an emission-measure analysis of the soft X-ray flux from the system. (In the solar outer atmosphere, the emission scale height of coronal material typically greatly exceeds that of Si IV and C IV.) The stellar downflow velocities therefore predict a minimum acceleration zone thickness that is compatible with the assumption that the Si IV and C IV features are not very optically thick. Even if the line-forming region were as large as the acceleration zone, and the latter were an order of magnitude larger than $\Delta h_{\text{min}}$, owing to viscosity and ram pressure effects for example, the high-temperature resonance lines very likely still would not be very optically thick ($\tau_* \lesssim 50$). On the other hand, our chain of reasoning is based on a number of unproven assumptions, for example, that the measured redshift indicates the magnitude of the downflow directly. Accordingly, the argument must be considered tentative and certainly not conclusive.

Nevertheless, the importance of a possible phenomenological link between the differential redshifts of Si IV and C IV in the IUE spectra of several active chromosphere giant stars and the downflows at $10^5 \text{ K}$ seen over magnetic active regions on the Sun would be difficult to ignore.

IV. SUMMARY AND FUTURE WORK

We have measured what we believe are statistically significant differential redshifts of high-excitation lines, like Si IV $\lambda1394$ and C IV $\lambda1548$, with respect to low-excitation species like O I and S I in the IUE spectra of a number of active chromosphere giant stars, and possibly in two dwarf stars as well. In the case of the binary Capella, observed in conjunction with a wavelength calibration spectrum, we have established that the low-excitation species are close to the rest velocity of the stellar photosphere, and that the Si IV and C IV features truly are redshifted. The redshifts in the giant stars of the sample could be produced by an outflow (wind) at $10^5 \text{ K}$ that has low emission measure but high opacity in the Si IV and C IV doublets, and which selectively absorbs the blue edges of emission lines from bright, static structures of the lower atmosphere. Alternatively, the redshifts may be generated within the lower atmosphere itself by downflows like those seen over magnetic active regions on the Sun. In either case, the dynamical consequences of the flows may be essential to the energy balance of the stellar outer atmosphere (e.g., Hartmann and MacGregor 1980; Pneuman and Kopp 1977).

Accordingly, the importance of accurately characterizing the dynamical properties of stellar outer atmospheres should be clear. Unfortunately, the limitations from an observational point of view imposed by even the highest quality IUE observations are equally clear. The only means for reducing the influence of the large single-measurement errors for the critical diagnostics like C IV $\lambda1548$, Si III $\lambda1892$, and C III $\lambda1909$ is to obtain repeated high signal-to-noise ratio spectra, assuring that the proper observing procedures are followed to permit the assignment of an accurate velocity scale. The amount of observing time required by such an effort, even if restricted to the handful of brightest late-type stars, is quite formidable.

In fact, significant progress in this area likely cannot be made until the Space Telescope era. In particular, the High Resolution Spectrograph (HRS) (Leckrone 1980b) will permit very precise velocity measurement in a large, unbiased sample of cool stars. Furthermore, the great sensitivity of the HRS will permit the detection of weak, density-sensitive lines in the far-ultraviolet region (cf. Dere and Mason 1981) which cannot presently be observed, but whose aid is critical for inferring the density structure of the stellar transition region so that the powerful techniques of emission-measure analysis (cf. Jordan and Wilson 1971) can be applied to diagnose the geometry and energy balance.

At the same time, it would be essential to continue theoretical modeling of warm winds, such as the work of Hartmann and MacGregor, as well as to examine the consequences of downflows for the energy balance of transition regions on giant stars, such as the recent study by Wallenhorst (1981) in the spirit of the previous solar models by Pneuman and Kopp (1978). In these modeling efforts, it would be vitally important to predict the emission profiles of optically thin and optically thick species in the flows, in order to compare with empirical line shapes from spectra obtained using IUE and future spectroscopy missions. Ultimately, one hopes that such comparisons will remove the fundamental ambiguity presented by observations of Doppler-shifted lines in stellar spectra (Athay 1976b): one knows with certainty that the plasma is moving, but not necessarily the direction of the flow.

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