THE SOLAR OUTPUT AND VARIABILITY VIEWED
IN THE BROADER CONTEXT OF STELLAR ACTIVITY

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The sun is most likely a unique star only by virtue of its proximity, but the consequences of its closeness are far-reaching indeed. Because of its proximity the sun appears to be $10^{10}$ times as bright visually as the brightest stars and subtends a solid angle $10^8$ that of the largest stars. Also the solar radiative flux is essentially unattenuated by intervening matter (except for the terrestrial atmosphere), whereas interesting stellar emissions shortward of 912 Å and in the cores of ultraviolet resonance lines are heavily attenuated. As a consequence, many phenomena routinely studied on the sun have not been observed in stars where they are presumably present, and the opportunity for cross-fertilization between solar and stellar research has heretofore not presented itself despite the similarity of physical processes and diagnostic techniques available to understand them. The phenomena observed on the sun thus tend to be considered solar phenomena, rather than examples of stellar phenomena seen on the sun.

I. PERSPECTIVE

In classical terms, stellar atmospheres are usually assumed to be homogeneous, plane-parallel, and static envelopes which are in local thermodynamic equilibrium (LTE), radiative and/or convective equilibrium, and hydrostatic equilibrium, and which have no magnetic fields. In recent years, stellar models have been constructed that incorporate radiatively driven winds, extended geometries, and departures from LTE. What I refer to as solar-type phenomena are those that depart further from these assumptions through considerations of nonradiative heating, magnetic fields, and small-scale or dynamic structures governed by nonradiative heating and magnetic effects. Praderie (1973) and Doherty (1973) have reviewed the observational basis for stellar chromospheres and for nonradiative heating therein, as it was known in 1972. At that time the only evidence for solar-type phenomena in stars was evidence of chromospheres, of flares in dMe stars, and of stellar winds in supergiants and M-type stars.
More recently, evidence has been presented for other solar-type phenomena in stars, as will be described below; and theoretical and semiempirical models for stellar chromospheres, coronae, and flares have been computed. This recent activity has resulted from new satellite and rocket instruments, able to observe cool stars (spectral classes F-M) in the ultraviolet and X-ray portions of the spectrum, and also from the development of spectroscopic diagnostic techniques to interpret spectral features, such as the Ca II H and K lines, that are observed frequently but have not yet been properly analyzed. This trend should accelerate in the next few years as more powerful space experiments become available (International Ultraviolet Explorer, HEAO-B, Large Space Telescope), as ground-based spectra of fainter stars are obtained, and as the diagnostic techniques are further developed and applied systematically to a wide range of stars. For this reason it is useful to assess where we stand in this field, to delineate some important problems to be solved, and to suggest how they might be solved.

It is important to emphasize that the study of solar-type phenomena in the sun and stars is a two-way street. Perhaps it is more obvious that our understanding of solar-type phenomena on the sun is important to the study of similar stars. Our experience in studying the sun naturally suggests what phenomena to search for in stars and how best to search for them. For example, the λ 1175-1600 Å emission line spectrum of Capella (G8III+F?) is similar to that of a solar plage (Vitz et al., 1976; Haisch and Linsky, 1976); thus the stellar spectrum may reasonably be interpreted in terms of a transition region similar to that in a solar plage. Conversely, when a stellar ultraviolet emission line spectrum differs qualitatively from that seen in the sun, as in the case of Arcturus (K2 III) (Weinstein, Moos, and Linsky, 1976), then the atmospheric structure of the star must differ considerably from that of the sun.

The opposite case—what we can learn about the sun by studying stars—may not be as obvious, but it is important and has several aspects.

First, we have only a tiny temporal baseline (compared to the age of the sun) from which to study the variability of solar radiative output and phenomena that modulate this output. One way to study long-term variability is to study stars similar to the sun but of different ages. In particular, it is important to ascertain whether the statistical trend of decreasing chromospheric activity with age seen by Wilson (1963), Wilson and Skumanich (1964), and Skumanich (1972) is applicable to the solar chromosphere and corona.

Second, we will probably not understand many solar phenomena in detail unless we can investigate the effects of changing basic parameters such as gravity, convective generation of wave modes, and background radiation fields. This may only be possible by studying stars.

Third, we are still quite ignorant about the underlying causes of solar variability, presumably because these phenomena are not readily apparent owing to their long time scale or small amplitude near the surface of the sun. I have in mind
here large-scale circulation patterns, causes of sunspots and the solar magnetic cycle, and the global properties of the solar wind. In stars with more active outer atmospheres, these phenomena may be more apparent and easier to study.

Until now I have spoken of the sun as one star with a wide range of phenomena and structures. For our purposes it might be more instructive to speak of the sun as many stars coexisting in the same gravitational field with the same effective temperature and chemical composition. Below we will identify a number of different solar chromospheres, transition regions, and coronae identifiable by their emission spectra produced by differing pressure and temperature structures. These differences in physical properties, in turn, can probably be traced back to characteristic magnetic field structures. It is likely that these differences in structures on the sun are prototypes for the range of phenomena in cool stars, and the best way to understand the range of stellar "activity" is first to understand the range of solar "activity." We will endeavor below to quantify the word "activity."

Finally, I mention that, most conveniently, the sun has a near twin close by. This twin is α Cen A at a distance of only 1.33 parsec and an apparent visual magnitude of \(m_V = -0.01\). Table 1 summarizes the parameters for the two stars taken from Ayres et al. (1976). It is important to note that α Cen A appears to be twice as old as the sun, on the basis of its location in the Hertzsprung-Russell diagram, and thus may be indicative of the direction in which the sun is evolving. Consequently, this star should be studied in detail for evidence of solar-type phenomena, as described in the next section, and for variability in its radiative output.

Table 1

<table>
<thead>
<tr>
<th>STELLAR PARAMETERS</th>
<th>α Cen A</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Type</td>
<td>G2 V</td>
<td>G2 V</td>
</tr>
<tr>
<td>Mass/Mass (θ)</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>L/L (θ)</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>(10 \times 10^9)</td>
<td>(5 \times 10^9)</td>
</tr>
<tr>
<td>Assumed Metal abundance</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>(T_{\text{eff}}) (K)</td>
<td>5700</td>
<td>5770</td>
</tr>
<tr>
<td>(\log g) (cm s(^{-1}))</td>
<td>4.25</td>
<td>4.27</td>
</tr>
</tbody>
</table>
II. A SURVEY OF SOLAR-TYPE PHENOMENA IN THE SUN AND EVIDENCE FOR SUCH PHENOMENA IN COOL STARS

We now consider in turn a number of solar-type phenomena, giving a description of the phenomena on the sun, some of the useful diagnostics for identifying and characterizing these phenomena, and evidence (if any) for these phenomena in cool stars.

A. NONRADIATIVE HEATING IN THE UPPER PHOTOSPHERE

Except in unusual circumstances, radiative equilibrium model atmospheres are characterized by a decrease in temperature with height. The addition of nonradiative heating of any sort to such an atmosphere will tend to make the decrease less steep. Then, at some height where the densities and radiative cooling rates are sufficiently small, the nonradiative heating will force the temperature to increase with height. For clarity we refer to the region where $dT/dh < 0$ as a nonradiatively heated "photosphere" and the region where $dT/dh > 0$ as a "chromosphere," but the question is more complex and interesting than stated here (Praderie, 1973; Underhill, 1973).

The identification of nonradiative heating in the upper portion of a photosphere is important because it is evidence for the violation of a classical assumption and because it can affect the emergent spectrum. In stars like the sun an increase in the upper photosphere temperature distribution at $10^{-2} < \tau_{5000} < 10^{-4}$ would manifest itself in significantly increased flux in the far infrared continuum (10-200 \(\mu\)m), ultraviolet continuum (1200-2000 Å; see Vernazza, Avrett, and Loeser, 1976), the inner wings of the strong resonance lines, and in the cores of some strong absorption lines.

The evidence for nonradiative heating in the solar upper photosphere is presently in dispute. Vernazza, Avrett, and Loeser (1976) have computed a photosphere-chromosphere model to best fit the existing infrared and ultraviolet continuum data, explicitly treating non-LTE effects in H I, Si I, C I, Mg I, and A I I. Their model has a temperature minimum of 4150 K located at $\tau_{5000} = 3 \times 10^{-4}$, and their data, they claim, are consistent with a minimum temperature in the range 4050-4250 K. This result is somewhat sensitive to the line-blanketing assumptions and absolute calibration errors.

The inner wings of the Ca II and Mg II resonance lines are also formed in the upper photosphere. Using the partial redistribution (PRD) technique (see Appendix A) for solving the transfer equation in the wings of these lines, Milkey and Mihalas (1974) and Shine, Milkey, and Mihalas (1975a) estimate a minimum temperature of 4400-4450 K; Ayres and Linsky (1976) derive detailed models with a temperature minimum of 4450 K located at a mass column density (measured inward) of 0.05 g cm$^{-2}$, corresponding to $\tau_{5000} = 2 \times 10^{-4}$. The latter result is sensitive somewhat to errors in the atomic abundances, line broadening, and
absolute intensity calibration. The Ayres-Linsky models are hotter than the Vernazza-Avrett-Loeser model over the range $2 \times 10^{-4} < \tau_{5000} < 5 \times 10^{-2}$.

The important question is whether the semiempirical models are consistent with, or significantly hotter than, radiative equilibrium models. On the basis of a radiative equilibrium, line-blanketed model including a representative sample of non-LTE lines, Athay (1970) derived an upper photosphere boundary temperature of $4330 \pm 150$ K. Kurucz (1974) has computed a radiative equilibrium model blanketed with $1.7 \times 10^{6}$ lines with a boundary temperature of 4300 K. Compared to these radiative equilibrium models, the semiempirical model by Vernazza, Avrett, and Loeser appears cooler in the upper photosphere, possibly indicative of an unknown cooling process; and the Ayres-Linsky models appear hotter, indicative of nonradiative heating. The question is thus not yet resolved. An additional consideration is that in plages the inner wings of the Ca II lines are clearly brighter than for the quiet sun (Shine and Linsky, 1973), indicative of nonradiative heating or backwarming by chromospheric radiation (Underhill, 1973).

An important point is that in the upper photosphere the densities are sufficiently high that a temperature excess of 100-200 K over radiative equilibrium corresponds to a radiative loss (due mainly to $\text{H}^{-}$) that could be as large as $1 \times 10^{9}$ ergs cm$^{-2}$ s$^{-1}$ (Ayres, 1975). This corresponds to 2 percent of the solar luminosity and is far in excess of the radiative losses of $4.6 \times 10^{6}$ ergs cm$^{-2}$ s$^{-1}$ estimated by Athay (1976) for the solar chromosphere and corona.

Shine, Milkey, and Mihalas (1975b) have computed theoretical PRD models for solar-type stars with log $g = 4.44$ and 2.0. They find that for the lower gravity star the inner wings of strong chromospheric resonance lines are much darker despite the same (scaled) temperature distribution, demonstrating that PRD diagnostics must be employed to empirically derive an accurate temperature distribution for the upper photosphere.

So far only three stars have been studied for evidence of photospheric nonradiative heating by comparisons among the semiempirical temperature distributions obtained from PRD analyses of the Ca II line wings and line-blanketed radiative equilibrium model atmospheres. In two cases, Procyon (F5 IV-V) studied by Ayres (1975), and $\alpha$ CEN A studied by Ayres et al. (1976), there seems to be evidence for nonradiative heating. In the third case, $\alpha$ CEN B (K1 V) studied by Ayres et al. (1976), the lack of evidence may be due to omission in the radiative equilibrium model of CO line-blanketing, which should be important for stars having an effective temperature near 5000 K (Johnson, 1973).

**B. CHROMOSPHERES**

As noted above, the question of how to define a chromosphere is an interesting one. I feel, however, that given the rudimentary state of our understanding of stellar chromospheres, it is premature to define a chromosphere very rigorously. Instead, I will adopt as a working definition for a chromosphere that region of a
stellar atmosphere where dT/dh > 0 (dT/dm < 0) and where the energy balance is dominated by radiative and nonradiative (wave-dissipation) heating terms and radiative losses. Specifically excluded are conductive and stellar wind terms characteristic of transition regions and coronae. Praderie (1973) has argued that a net mass flux is necessary for nonradiative heating and is thus required for a chromosphere. In the sun the chromosphere covers the approximate temperature range from 4500 to 30,000 K, but it is incorrect to identify any stellar atmospheric region having this range of temperatures as a "chromosphere" without first considering the energy balance equation.

At the present time no detailed models of solar or stellar chromospheric regions have been constructed on a completely theoretical basis, that is, purely on the basis of computed wave dissipation and energy-balance considerations. Instead, chromospheric models have been constructed semiempirically to match one or more observed spectral lines or continua. Such spectral features are referred to as diagnostics. Diagnostics are useful to the extent that they uniquely define some physical parameters of the atmosphere such as the distribution of temperature, pressure, and velocities, or a background radiation field. Clearly, the accuracy of the semiempirical models is intimately tied to the usefulness of the diagnostics and the accuracy of the physical basis for these diagnostics.

In Appendix A we consider in detail the various chromospheric diagnostics in use, their physical basis, the data available, and models of solar and stellar chromospheres computed by means of these various diagnostics. The reader is also referred to the earlier review by Praderie (1973). Here we give a broad outline of the various diagnostics, their usefulness, and what is being learned about solar and stellar chromospheres with them. The various available diagnostics are readily divided into a number of categories:

(1) Collisionally Dominated Resonance Lines. In this category are such lines as the H (λ 3968) and K (λ 3933) lines of Ca II, the h (λ 2803) and k (λ 2796) lines of Mg II, and the Lyman-alpha (λ 1216) line of H I. Under conditions that exist in solar chromospheres and probably also in a wide range of stellar chromospheres, these lines are collisionally dominated (Thomas and Athay, 1961) and of sufficient optical thickness that their cores are thermalized above the temperature minimum (Avrett and Hummer, 1965). Thus the emission cores of these lines are useful diagnostics of the lower and middle chromosphere temperature and density structure. Milkey and Mihalas (1973) showed the importance of incorporating coherency effects into the transfer equation for these lines; and Shine, Milkey, and Mihalas (1975a) were able to resolve the long-standing question of limb darkening in the Ca II lines by using this new PRD formulation. Essentially all of the recent work in constructing semiempirical models of stellar chromospheres as described below is based on these lines by using the PRD formulation. Other potentially useful lines in this category are Ca I (λ 4226), Na I (λ 5890,
(2) Resonance Lines of Uncertain Formation. The resonance lines of He I (λ 584) and He II (λ 304) are potentially useful diagnostics of chromospheric structure, but have not been utilized since the process of formation, even in the sun, is in dispute. Various authors have proposed excitation by electron collisions, by recombination following photoionization by the coronal XUV radiation field, and by mixing- and diffusion-type processes. Depending on the method of formation, the strengths of these emission lines could be diagnostics of the coronal radiation field or of the upper chromosphere and transition-region temperature structure.

(3) Collisionally Dominated Subordinate Lines. To fall in this category, a line must respond to a change in chromospheric temperature structure or density by changing in core intensity. The infrared triplet lines of Ca II (λ 8542, λ 8498, λ 8662) fall in this category for the solar chromosphere and many stellar chromospheres, while the Balmer-alpha line in dMe stars and subordinate lines of He I (λ 10830, λ 5876) and He II (λ 1640) may be useful under certain conditions (see Appendix A). These lines have not been utilized (except λ 8542) in conjunction with the Ca II resonance lines.

(4) Spectral Lines Responsive to Radiation Fields. The central intensities of a number of lines are sensitive to continuum or line radiation fields and thus can be used as diagnostics for these radiations, but not directly for other chromospheric properties. Examples include the Balmer-alpha and epsilon lines of H I which are sensitive to the Balmer and Paschen radiation fields, the O I resonance lines (λ 1302, λ 1304, λ 1306), which are pumped by the H I Lyman-beta line, and subordinate lines of He I (λ 10830, λ 5876) and He II (λ 1640), which may be excited by the coronal XUV radiation field.

(5) Other Diagnostics. In this category are the Balmer continuum (which is in emission in T Tauri stars and occasionally in solar flares), the hydrogen free-free continuum in the far infrared, and the Si bound-free continuum (λ < 1525 Å) and other continua in the ultraviolet. These features are sensitive to the temperature distribution at the base of the solar chromosphere (Vernazza, Avrett, and Loeser, 1973; 1976). Also the CO fundamental vibration-rotation band in K giants may show emission owing to a chromosphere (Heasley and Milkey, 1976).

Table 2 summarizes the solar and stellar chromospheric models that have been constructed using the above diagnostics, mainly category (1). The table includes the minimum temperature (T_{min}) and the pressure and mass column density at the location of the temperature minimum. As originally suggested by Thomas and Athay (1961), the temperature rises very steeply when the H I Lyman continuum
Table 2

<table>
<thead>
<tr>
<th>Structure</th>
<th>Paper</th>
<th>Diagnostic</th>
<th>( t_{\text{min}} ) (s)</th>
<th>( P(t_{\text{min}}) ) (dynes/cm²)</th>
<th>( n(t_{\text{min}}) ) (g/cm³)</th>
<th>( \rho(t_{\text{LYC}}=1) ) (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet Sun</td>
<td>Vernazza et al. (1973)</td>
<td>Continua</td>
<td>4130</td>
<td>5 \times 10⁶</td>
<td>0.02</td>
<td>4 \times 10⁶</td>
</tr>
<tr>
<td></td>
<td>Vernazza et al. (1976)</td>
<td>Continua</td>
<td>4150</td>
<td>1.4 \times 10⁷</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shine et al. (1975a)</td>
<td>Ca II PRD</td>
<td>~4450</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ayres and Linsky (1976)</td>
<td>Ca II, Mg II PRD</td>
<td>4450</td>
<td>1.6 \times 10⁷</td>
<td>0.06</td>
<td>5.6 \times 10⁶</td>
</tr>
<tr>
<td>( \alpha ) CEN A (G 2v)</td>
<td>Ayres et al. (1976)</td>
<td>Ca II PRD</td>
<td>4490</td>
<td>3.0 \times 10⁷</td>
<td>0.016</td>
<td>5 \times 10⁶</td>
</tr>
<tr>
<td>( \alpha ) CEN B (K 1V)</td>
<td>Ayres et al. (1976)</td>
<td>Ca II PRD</td>
<td>3730</td>
<td>1.9 \times 10⁷</td>
<td>0.063</td>
<td>3 \times 10⁶</td>
</tr>
<tr>
<td>Procyon (F5 IV-V)</td>
<td>Ayres et al. (1974)</td>
<td>Ca II Mg II PRD</td>
<td>5200</td>
<td>1.1 \times 10⁸</td>
<td>0.11</td>
<td>1 \times 10⁷</td>
</tr>
<tr>
<td></td>
<td>Ayres et al. (1976)</td>
<td>Ca II Mg II PRD</td>
<td>5200</td>
<td>1.1 \times 10⁸</td>
<td>0.11</td>
<td>1 \times 10⁷</td>
</tr>
<tr>
<td>Arcturus (K2 III)</td>
<td>Ayres and Linsky (1976a)</td>
<td>Ca II, Mg II PRD</td>
<td>3150</td>
<td>9 \times 10⁷</td>
<td>1.8</td>
<td>3 \times 10⁵</td>
</tr>
<tr>
<td>Solar Flare (3)</td>
<td>Machado and Linsky (1975)</td>
<td>Ca II PRD</td>
<td>5030</td>
<td>1.1 \times 10⁸</td>
<td>0.4</td>
<td>3 \times 10⁵</td>
</tr>
<tr>
<td>T Tau (d05e)</td>
<td>Dumont et al. (1973)</td>
<td>Hα</td>
<td>4 \times 10⁵</td>
<td></td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

becomes optically thin owing to the loss of a major source of cooling. As a result, the mass column density at \( \tau(\lambda = 911 \text{ Å}) = 1 \) is a convenient benchmark for the top of the lower chromosphere.

Table 3 summarizes parameters for various structures in the solar chromosphere. These parameters are based on the chromospheric models described in Table 2 and some guesses where models are not yet available. The various structures are arranged in order of increasing chromospheric "activity" as measured by the emission strength of the K line. Note that this sequence is also a sequence of increasing \( P_0 (\tau_{\text{LYC}} = 1) \) and \( dT/dh \) between the temperature minimum and the location where \( \tau_{\text{LYC}} = 1 \). The reason for the increase in emission with increasing \( P_0 \) and \( dT/dh \) is that at each K-line optical depth the temperature \( T_e (\tau_K) \) and Planck function \( B \big( \tau_K \big) \) are larger, which increases the ionization of hydrogen and the metals so that the Ca II line source functions are more thermalized by collisions.

Table 4 summarizes the evidence for stellar chromospheres in different classes of stars and according to different diagnostics. The symbols are N (no emission), W (weak emission), S (strong emission), and VS (very strong emission). The stars are also listed approximately in order of increasing visibility of the chromospheric diagnostics, but visibility is not synonymous with absolute flux as described below because the background flux is a strong function of stellar effective temperature.

We consider now what can be said concerning the energy balance in solar and stellar chromospheres. Athay (1976) has recently summarized the various radiative losses from the spatially averaged solar chromosphere. He estimates a total loss of about \( 4 \times 10^6 \) ergs cm\(^{-2}\) s\(^{-1}\) in which the dominant contributors are Lyman alpha in the upper chromosphere, the Balmer continuum, Balmer-alpha, Mg II, Ca II, \( \alpha \) CEN A (G 2v), and Ca II Mg II PRD.
### Table 3

**SOLAR CHROMOSPHERES**

<table>
<thead>
<tr>
<th>STRUCTURE</th>
<th>SCALE (M&quot;)</th>
<th>$P_{0}(\text{luc}^{-1})$ (dynes/cm²)</th>
<th>dT/dh ($^\circ$K/km)</th>
<th>B (gauss)</th>
<th>LIFETIME (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMBRA</td>
<td>15</td>
<td>?</td>
<td>?</td>
<td>3300</td>
<td>$10^6-10^7$</td>
</tr>
<tr>
<td>PENUMBRA</td>
<td>10</td>
<td>?</td>
<td>?</td>
<td>1900</td>
<td>$10^6-10^7$</td>
</tr>
<tr>
<td>PROMINENCE</td>
<td>100</td>
<td>0.02 small</td>
<td>5 -50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPIQUE</td>
<td>1x10</td>
<td>0.15 small</td>
<td>25 -50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QUIET REGION</td>
<td>300x2</td>
<td>0.15 small</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NETWORK</td>
<td>1</td>
<td>?</td>
<td>?</td>
<td>$10^2-10^3$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Cell</td>
<td>30</td>
<td>?</td>
<td>?</td>
<td>$\leq 1$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>PLAGUE</td>
<td>60x1</td>
<td>2</td>
<td>3.0</td>
<td>$10^2-10^3$</td>
<td>$10^6-10^7$</td>
</tr>
<tr>
<td>FLARE (SF-3)</td>
<td>10x0.6</td>
<td>8-80</td>
<td>3.5-4.3</td>
<td>10³</td>
<td>10²</td>
</tr>
</tbody>
</table>

### Table 4

**EVIDENCE FOR STELLAR CHROMOSPHERES**

<table>
<thead>
<tr>
<th>CLASS</th>
<th>EXAMPLES</th>
<th>H I</th>
</tr>
</thead>
<tbody>
<tr>
<td>A STARS</td>
<td>yBOO</td>
<td>W N N N N N</td>
</tr>
<tr>
<td>EVOLVED F-M IV-V</td>
<td>αCMi</td>
<td>W S S N N N S ? W N</td>
</tr>
<tr>
<td>Quiet Sun</td>
<td>W S S N N N S ?</td>
<td></td>
</tr>
<tr>
<td>Young F-M V</td>
<td>θERI</td>
<td>VS VS VS S S N N VS</td>
</tr>
<tr>
<td>Active Sun</td>
<td>VS VS VS N N N N VS</td>
<td>S N</td>
</tr>
<tr>
<td>G-M GIANTS</td>
<td>αBOO, βGEM</td>
<td>S VS VS N W N W W N</td>
</tr>
<tr>
<td>G-M SUPERGIANTS</td>
<td>αORI</td>
<td>S VS VS N N N W N</td>
</tr>
<tr>
<td>Long Period Var.</td>
<td>αCET</td>
<td>VS S</td>
</tr>
<tr>
<td>dG - dM e-e</td>
<td>GM AUR</td>
<td>VS S S S S S</td>
</tr>
<tr>
<td>SPEC. BINARIES</td>
<td>αAUR, λAND</td>
<td>VS VS VS VS VS</td>
</tr>
<tr>
<td>T Tau</td>
<td>T Tau</td>
<td>VS S W S S</td>
</tr>
<tr>
<td>Turned On</td>
<td>Fu ORI, v1057 CYG</td>
<td>VS S S S S</td>
</tr>
<tr>
<td>Nova (Principals) (Nebular)</td>
<td>T CRB, T PYX</td>
<td>VS S S S S W</td>
</tr>
<tr>
<td>Flare Stars</td>
<td>Sun</td>
<td>VS VS VS VS S W VS S S S S VS S S</td>
</tr>
<tr>
<td>UV CYG, AD LEO</td>
<td>VS VS S S W VS S S W N</td>
<td></td>
</tr>
<tr>
<td>SS CYG, U GEM</td>
<td>VS VS S S VS VS S S S S VS S S</td>
<td></td>
</tr>
</tbody>
</table>
and Fe I in the middle chromosphere, and H\textsuperscript{−} in the low chromosphere.

At present we cannot completely estimate the radiative losses from the solar chromosphere, much less from stars, but we can compare the losses in a few important lines formed at different chromospheric layers. Table 5 summarizes the data now available for the Lyman alpha, Mg II, and Ca II lines. These data are of necessity very heterogeneous. One unresolved question is whether the chromospheric losses in the Ca II and Mg II lines are measured by the emergent flux between, say, $k_{1R}$ and $k_{1V}$ (e.g., Ayres, Linsky, and Shine, 1974; Ayres and Linsky, 1975a) or by the flux above an estimated "photospheric" absorption line profile (e.g., Dravins, 1976; Blanco et al., 1974; 1976; Kondo et al., 1976b; Kondo, Morgan, and Modisette, 1976b; Kondo et al., 1976a). Despite the heterogeneity of the data, several trends clearly appear:

1. There is a strong trend in all the lines of decreasing emission with decreasing stellar effective temperature (later spectral type).
2. The emission does not appear to depend on stellar luminosity.
3. The sun does not appear to be anomalous to this sample of 17 stars.
4. The Mg II lines are the strongest chromospheric emitters, as originally suggested by Kandel (1967). The star $\alpha$ CMI may not be an exception to this rule since the Ca II and Mg II line fluxes were estimated differently as described above. Thus it may be possible to roughly estimate the total chromospheric radiative loss as five times the Mg II flux (the solar ratio).

Dravins (1976) and Blanco et al. (1974; 1976) have measured Ca II K line fluxes (above the estimated "photospheric" absorption line profile) for a wide range of late-type stars. Dravins finds that the K line absolute fluxes measured this way are approximately constant between spectral classes F0 and K0. An important result obtained by Blanco et al. (1974; 1976) is that the ratio of the K line flux to the integrated Planck function goes through a maximum at $T_{\text{eff}} = 4500$ K for giants and at 5000 K for main-sequence stars. This trend is not found in the theoretical mechanical flux calculations of de Loore (1970) based on the mixing-length theory of convection. As a consequence, either the calculations are in error or the fraction of the total mechanical flux available that is eventually emitted in the Ca II lines depends on spectral type. There is no evidence in Table 5 that the latter is true.

In addition to de Loore (1970), Kuperus (1965), Ulmschneider (1967), and Nariai (1969), among others, have computed the mechanical energy flux generated by convective zones and available to heat the outer atmospheres of stars. Athay (1976) and de Jager (1976) have recently discussed this work and have pointed out the large uncertainties in the mechanical flux generation that results from uncertainties in the mixing-length theory. There is the further point that by far the largest amount of this energy may be dumped in the photosphere (cf. §11A) and not in the chromosphere or corona, so that it is premature to compare these calculations with the estimated chromospheric radiative losses.
Table 5

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
<th>Assumed Angular Diameter ( \Omega ) (°)</th>
<th>Assumed Interstellar ( N_H ) (cm(^{-2}))</th>
<th>( L_H )</th>
<th>( Mg\ II ) ( n_H )</th>
<th>( Ca\ II ) ( n_H )</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Cas</td>
<td>F2 IV</td>
<td>0.0059</td>
<td></td>
<td></td>
<td>4.2x10(^{6}) (^{(1)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α Ori</td>
<td>F5 IV-IV</td>
<td>0.0057</td>
<td>0.03</td>
<td></td>
<td>5.7x10(^{5}) (^{(2)})</td>
<td>1.5x10(^{6}) (^{(3)})</td>
<td></td>
</tr>
<tr>
<td>η Per</td>
<td>F5 Ib</td>
<td>0.0030</td>
<td></td>
<td></td>
<td>2.6x10(^{4}) (^{(4)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Sun</td>
<td>G2 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.2x10(^{8}) (^{(5)})</td>
<td>1.2x10(^{5}) (^{(6)})</td>
</tr>
<tr>
<td>Solar Flare</td>
<td>G2 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.1x10(^{6}) (^{(7)})</td>
<td>3.6x10(^{5}) (^{(8)})</td>
</tr>
<tr>
<td>α Aur</td>
<td>G8 III+??</td>
<td>0.0094</td>
<td>0.01</td>
<td></td>
<td>4.2x10(^{10}) (^{(10)})</td>
<td>1.2x10(^{10}) (^{(11)})</td>
<td></td>
</tr>
<tr>
<td>c Gem</td>
<td>G8 IIIb</td>
<td>0.0085</td>
<td></td>
<td></td>
<td>2.1x10(^{10}) (^{(12)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α Uma</td>
<td>K0 IIII</td>
<td>0.0081</td>
<td></td>
<td></td>
<td>1.5x10(^{9}) (^{(13)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α Gem</td>
<td>K0 IIII</td>
<td>0.0105</td>
<td>0.10</td>
<td></td>
<td>4.1x10(^{8}) (^{(14)})</td>
<td>1.2x10(^{8}) (^{(15)})</td>
<td></td>
</tr>
<tr>
<td>ε Eri</td>
<td>K2 IIII</td>
<td>0.0026</td>
<td>0.10</td>
<td></td>
<td>6.0x10(^{8}) (^{(16)})</td>
<td>1.1x10(^{8}) (^{(17)})</td>
<td>4.3x10(^{8}) (^{(18)})</td>
</tr>
<tr>
<td>α Boo</td>
<td>K2 IIII</td>
<td>0.022</td>
<td>0.10</td>
<td></td>
<td>5.2x10(^{8}) (^{(19)})</td>
<td>1.7x10(^{8}) (^{(20)})</td>
<td>1.3x10(^{8}) (^{(21)})</td>
</tr>
<tr>
<td>c Peg</td>
<td>K2 IIIb</td>
<td>0.014</td>
<td></td>
<td></td>
<td>1.0x10(^{9}) (^{(22)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α Hyi</td>
<td>K3 IIII</td>
<td>0.014</td>
<td></td>
<td></td>
<td>4.8x10(^{8}) (^{(23)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ω Eri</td>
<td>K4 IIII</td>
<td>0.014</td>
<td></td>
<td></td>
<td>3.8x10(^{7}) (^{(24)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α Tau</td>
<td>K5 IIII</td>
<td>0.022</td>
<td>0.10</td>
<td></td>
<td>2.6x10(^{8}) (^{(25)})</td>
<td>6.9x10(^{7}) (^{(26)})</td>
<td>1.1x10(^{7}) (^{(27)})</td>
</tr>
<tr>
<td>α And</td>
<td>M0 IIII</td>
<td>0.039</td>
<td></td>
<td></td>
<td>1.3x10(^{7}) (^{(28)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α Sco</td>
<td>M1 IIIb</td>
<td>0.062</td>
<td></td>
<td></td>
<td>4.8x10(^{7}) (^{(29)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α Ori</td>
<td>M2 Iib</td>
<td>0.060</td>
<td></td>
<td></td>
<td>1.7x10(^{6}) (^{(30)})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Kondo et al. (1976a); (2) Evans et al. (1975); (3) Ayres et al. (1974); (4) Kondo et al. (1976b); (5) McClintock et al. (1975b); (6) Ayres and Linsky (1975); (7) Ahay (1976); (8) Dupree et al. (1973); (9) Landrue and Skumanich (1973); (10) Shine and Linsky (1974); (11) Dupree (1975); (12) Kondo et al. (1976a); (13) Doberty (1972b); (14) McClintock et al. (1975a); (15) Blanco et al. (1974); (16) Ayres and Linsky (1975a); (17) Bernat and Lambert (1976).

Given the abundance of diagnostics available, the large and growing set of observations, and the few pioneering model chromospheres computed; it is important to state some realistic goals for future studies of chromospheres.

Specific lines such as the Balmer-alpha line of H I, the \( \lambda \) 5876 and \( \lambda \) 10830 lines of He I, and the \( \lambda \) 1640 and \( \lambda \) 4686 lines of He II will be of great use, when these diagnostics are better understood, in probing regions of the chromosphere above where the Ca II and Mg II lines are formed.

It is important to determine the region of the Hertzsprung-Russell diagram where chromospheres exist, including both the high and low temperature limits, if any.

The difference between active and quiet chromospheres in the sun and stars in terms of temperature and density structures as well as energy balance remains to be studied. One question to be resolved is whether atmospheric extension produces the bright emission spectra in spectroscopic binaries and in T Tauri stars—and if so, why.

It is important to know the extent to which the solar chromosphere models are reliable prototypes, in terms of the general temperature structures and energy balance, for the range of stellar chromospheres.
C. TRANSITION REGIONS

The term "chromosphere-corona transition region" or "transition region," TR for short, applies to the region in the sun where the energy balance is determined by conductive heating from the corona, radiative losses, and possibly also dynamical terms. Typically the temperature range is from $3 \times 10^4$ to $1 \times 10^6$ K. For the present we apply this term also to stellar structures where the energy balance equation appears roughly to apply, but the energy balance may be more complex than usually assumed, even for the solar TR.

Pottasch (1964) and Athay (1966) originally showed that the solar TR temperature gradient is consistent with thermal conduction heating from the corona. Subsequent semiempirical (e.g., Dupree, 1972) and theoretical models (Moore and Fung, 1972; Shmeleva and Syrovatskii, 1973) have either derived or assumed a thermal conduction temperature distribution. Withbroe and Gurman (1973) then showed that a sequence of TR models for coronal holes, quiet sun, and active regions is a sequence of increasing temperature gradient and downward conductive flux. Since the solar TR appears typically to be thin compared to a pressure scale height, it appears reasonable to set $P_{\text{TR}} = P_{\text{tr}}$, the pressure at the top of the chromosphere. Table 6 summarizes a number of solar TRs and their properties.

<table>
<thead>
<tr>
<th>Structure</th>
<th>$P_0$ (dynes/cm$^2$)</th>
<th>$n_0 T_0$ (K cm$^{-3}$)</th>
<th>$f_c$ (ergs/cm$^2$/s)</th>
<th>Thickness (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunspot</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>&gt;30,000</td>
</tr>
<tr>
<td>Prominence</td>
<td>0.02</td>
<td>$8 \times 10^{13}$</td>
<td>$3 \times 10^4$</td>
<td>5,400</td>
</tr>
<tr>
<td>Hole</td>
<td>0.09</td>
<td>$3.6 \times 10^{14}$</td>
<td>$1.2 \times 10^5$</td>
<td>1,400</td>
</tr>
<tr>
<td>Spicule</td>
<td>0.15</td>
<td>$6.0 \times 10^{14}$</td>
<td>$1.2 \times 10^5$</td>
<td>135</td>
</tr>
<tr>
<td>Quiet Region</td>
<td>0.15</td>
<td>$6.0 \times 10^{14}$</td>
<td>$1.2 \times 10^6$</td>
<td>135</td>
</tr>
<tr>
<td>Cell</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Network</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Active Region</td>
<td>1.4</td>
<td>$5.4 \times 10^{15}$</td>
<td>$6 \times 10^6$</td>
<td>30</td>
</tr>
<tr>
<td>Flare (SF-3)</td>
<td>8-80</td>
<td>$3 \times 10^{16-3}$</td>
<td>$3 \times 10^{17}$</td>
<td>large/small</td>
</tr>
<tr>
<td>CMR (Evans et al., 1975)</td>
<td>0.006-0.05</td>
<td>$2.0 \times 10^{13-1.7 \times 10^{14}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aAUR (Haisch and Linsky, 1974)</td>
<td>1.5</td>
<td>$5.6 \times 10^{15}$</td>
<td>$3 \times 10^6$</td>
<td></td>
</tr>
</tbody>
</table>
Before proceeding we summarize the assumptions that are included in the models just described: (1) plane-parallel geometry, (2) constant pressure, (3) no magnetic fields, and (4) an energy balance consisting solely of conductive heating and radiative losses. These assumptions are now being questioned from several directions. One deduction from (4) is that \( dT/dz \propto P \) for any assumed temperature dependence of the radiative cooling function (e.g., Haisch and Linsky, 1976). Withbroe and Gurman (1973) find empirically, however, that in the sun \( dT/dz \propto P^{1.8} \). This discrepancy could be resolved by an additional local heating term such as wave dissipation (Munro and Withbroe, 1972; Boland et al., 1973; Kopp, 1972), an additional loss term due to the solar wind (Noci, 1973), or a non-plane-parallel geometry defined by magnetic flux tubes (Kopp and Kuperus, 1968). An additional consideration suggested by McWhirter, Thonemann, and Wilson (1975) is that the pressure exerted by sound waves may be comparable in magnitude to the hydrostatic pressure (cf. Flower and Pineau des Forêts, 1974).

One typically determines TR models by inferring the run of emission measure \( (\int n_e^2 \, dh) \) with temperature from the intensities of collisionally excited resonance lines in the ultraviolet. Such lines as Si III (\( \lambda 1206 \)), Si IV (\( \lambda 1394 \) and \( \lambda 1403 \)), C III (\( \lambda 977 \)), N V (\( \lambda 1238 \) and \( \lambda 1242 \)), Ne VII (\( \lambda 465 \)), and Mg X (\( \lambda 610 \) and \( \lambda 625 \)) have been very useful. Also ratios of lines in the beryllium isoelectronic sequence have been proposed as electron-density diagnostics (Munro, Dupree, and Withbroe, 1971). The use of such diagnostics may lead to considerable error, however, when the atomic rates are poorly determined, where photoionization is ignored (Nussbaumer and Storey, 1976), when the geometry is unknown, or when local time-independent ionization balance is invalid owing to a wind or to diffusion (Shine, Gerola, and Linsky, 1975; Kjeldseth Moe, 1976).

The identification of transition regions in stars requires the measurement of line intensities from several ions so as to determine whether thermal conduction from a corona plays a role in the energy balance. Two stars have been analyzed to date. From measurements of the Lyman-alpha, Si III (\( \lambda 1206 \)), and O VI (\( \lambda 1032 \)) lines in \( \alpha \) CMi; Evans, Jordan, and Wilson (1975) showed that a solar-like TR may set in at a temperature of 100,000 K, and that this TR is thicker and less dense \((1.7 \times 10^{14} > n_e T_e > 2.0 \times 10^{13})\) than the solar TR \((n_e T_e \approx 6 \times 10^{14})\). Observations of lines of Si II-IV, C II-III, N V, and O VI in \( \alpha \) AUR by Vitz et al. (1976) and Dupree (1975) have led to a TR model in the \( \alpha \) AUR primary star with \( n_e T_e = 5.6 \times 10^{15} \) (Haisch and Linsky, 1976; Dupree and Baliunas, 1976), similar to pressures in solar active regions (Dupree et al., 1973). Haisch and Linsky (1976) state that these lines are formed in a TR rather than a corona because the line flux ratios are similar to those in the sun. Also the wind speed is about 0.2 times the sound speed at the O VI (\( T \approx 300,000 \) K) level, and this flow should affect the energy balance.
D. CORONAE AND WINDS
The term "corona" has come to imply that region of the solar outer atmosphere where $T > 1 \times 10^6$ K. A far better definition might be given in terms of an energy balance between nonradiative heating due to wave dissipation or magnetic annihilation (Tucker, 1973; Sheeley et al., 1975) and losses due to radiation, wind, and conduction into the TR and out to space. The sun has at least four coronae, and there is a close correlation of coronal base pressure and temperature (see Table 7). As pointed out by Adams and Sturrock (1975), among others, the divergence of the magnetic field lines in coronal holes increases the solar wind energy loss, resulting in lower coronal temperatures and densities. Conversely, closed magnetic field structures, which characterize active regions, result in decreased energy loss by the wind and higher densities and temperatures. Thus the magnetic field geometry plays a crucial role in the solar corona and presumably in stellar coronae as well. As mentioned above, purely theoretical models of stellar coronae are highly uncertain owing to uncertainties in the mechanical flux generation rates. As a result we concentrate on observations and semiempirical models.

One can argue that if a transition region has been identified in a star, then a corona must exist surrounding the TR; accordingly, coronae must exist in $\alpha$ CMi and $\alpha$ AUR. But only the coronal base pressure and a minimum value of the coronal temperature can be determined in this way. For more information the detection of a coronal line is necessary.

The coronal forbidden red and green lines of $[\text{Fe X}]$ and $[\text{Fe XIV}]$ have not been detected in any nonexploding star, presumably because of their relative faintness when seen against the stellar disk. An exception is the star AS 295 B (Herbig and Hoffleit, 1975) which shows these lines together with $[\text{Fe XI}] \lambda 7891$ and $[\text{Ar X}] \lambda 5533$, suggesting a corona of at least $1.25 \times 10^6$ K. This star may have been a recent nova, however, and novae often show a coronal spectrum (McLaughlin, 1960). Another diagnostic of coronae in the visible may be continuum polarization, which in white dwarfs may be due to cyclotron emission (Ingham, Brecker, and Wasserman, 1976).

In the ultraviolet, Gerola et al. (1974) have observed the O V ($\lambda 1218$) intercombination line in $\beta$ GEM, which they state is far too strong to be formed in a

<table>
<thead>
<tr>
<th>Structure</th>
<th>$P_0$ (dynes/cm²)</th>
<th>$T_{\text{COR}}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole</td>
<td>0.09</td>
<td>$1.0 \times 10^6$</td>
</tr>
<tr>
<td>Quiet Region</td>
<td>0.15</td>
<td>$1.6 \times 10^6$</td>
</tr>
<tr>
<td>Active Region</td>
<td>1.4</td>
<td>$2.8 \times 10^6$</td>
</tr>
<tr>
<td>Flare (SF-3)</td>
<td>8-80</td>
<td>$8 \times 10^5$</td>
</tr>
</tbody>
</table>
TR. Instead, they suggest that the line is formed in a cool corona at $T \approx 260,000$ K. This observation, however, has not been confirmed and could be spurious. In $\alpha$ CMI (Evans, Jordan, and Wilson, 1975) and $\alpha$ AUR (Dupree, 1975; Vitze et al., 1976), and O VI ($\lambda$ 1032) line has been observed; but in both cases the line may be formed in a TR rather than a corona. From the upper limits of the ultraviolet emission line, assuming that the coronal base pressure equals the pressure at the top of the chromosphere, Weinstein, Moos, and Linsky (1976) conclude that the coronal temperature of $\alpha$ BOO is unlikely to be in the range 20,000-350,000 K. They suggest however that the coronal pressure may be overestimated owing to a thick transition region, in which case a wide range of coronal temperatures is possible. Riegler and Garmire (1975) have searched for 140-430 Å emission from four stars including $\alpha^3$ CMA (K3 lab) without success.

Recent X-ray observations of several stars have revealed positive evidence for coronae. The star $\alpha$ AUR has been observed at 0.25 keV (Mewe et al., 1975; 1976) and with a 0.2-1.6 keV broadband channel (Catura, Acton, and Johnson, 1975). These observations do not imply a unique coronal temperature, but rather a range of possible temperatures and pressures. In particular, if we assume a pressure of 1.5 dynes cm$^{-2}$ from the Haisch and Linsky (1976) TR model, then the Mewe et al. (1975) data imply a coronal temperature of $2 \times 10^5$ or $10^8$ K for a homogeneous isothermal corona. Upper limits on the X-ray flux from a number of late-type stars have been given by Mewe et al. (1975; 1976), Margon, Mason, and Sanford (1974), Crudace et al. (1975), and Vanderhill et al. (1975). The white dwarfs $\alpha$ CMA B (Mewe et al., 1975; 1976) and possibly HZ 43 (Hearn et al., 1976; Lampton et al., 1976) have been detected at soft X-ray wavelengths and in the extreme ultraviolet, but the emission may be photospheric rather than coronal (Shipman, 1976; Durisen, Savedoff, and Van Horn, 1976).

Oster (1975) has reviewed radio observations relevant to the question of stellar coronae and has pointed out that no coronae similar to the quiet solar coronae have yet been discovered. On the other hand, nonthermal and highly variable emission has been detected from $\alpha$ ORI and $\alpha$ SCO (cf. Oster, 1971), and UV Ceti-type flare stars have been detected during flares (see below). Altenhoff et al. (1976) have recently published observations and upper limits on a number of stars.

The detection of winds would provide indirect evidence for stellar coronae in late-type stars even if there is no direct spectroscopic evidence for ions at coronal temperatures. A severe problem in using this method, however, is that if downward motions of chromospheric or TR material are correlated with brighter emission, as is apparently true for the sun, then a net red shift in a stellar emission line will give a false mass loss signal (Doschek, Feldman, and Bohlin, 1976). Dupree (1975) measured a blue shift of $20 \pm 7$ km s$^{-1}$ in the O VI ($\lambda$ 1032) line of $\alpha$ AUR which corresponds to a mass loss of $(1.2 \pm 0.4) \times 10^{-8}$ solar masses y$^{-1}$ (Haisch and Linsky, 1976) if the blue shift accurately measures the net doppler motion. With the same caveat, the asymmetric Mg II and Ca II lines of $\alpha$ BOO (Chiu et al., 1976)
imply a mass loss of $8 \times 10^{-9}$ solar masses $\gamma^{-1}$, but this loss may be only occasional.

Hills (1973) has proposed that the integrated soft X-ray emission from a corona is related to the stellar mass loss. On the basis of this theory Craddock _et al._ (1975) and Margon, Mason, and Sanford (1974) have estimated upper limits to the mass loss for several bright late-type stars.

Hearn (1975) has developed a theory to predict coronal temperature and mass loss given the stellar mass, radius, and coronal base pressure. The theory is based on the assumption that the most likely coronal configuration is one in which the total loss for a given base pressure is a minimum. The physical basis underlying the minimum flux assumption is unclear because it is unstable. A slight decrease in temperature increases the total energy loss from the corona, leading to a further decrease in temperature and thermal runaway. This point needs to be studied, but in the meantime the minimum flux assumption leads to a straightforward method of computing coronal properties which yields realistic values for the sun. Using this theory with some modification, Haisch and Linsky (1976) estimate for $\alpha$ AUR a coronal temperature of $1.2 \times 10^{6}$ K and mass loss of $2 \times 10^{-8}$ solar masses $\gamma^{-1}$, close to the value derived using the wavelength shift of the O VI ($\lambda$ 1032) line. Mullan (1976) has computed coronal models for dwarfs and giants using the minimum flux theory and the assumption that the fraction of the total stellar luminosity used to heat the corona is the same as for the sun. He finds for main-sequence stars that the coronal temperature should increase with effective temperature. In G and K giants (like $\alpha$ AUR and $\alpha$ BOO) he estimates coronal temperatures well under $10^{6}$ K and detectable winds. Also he suggests that the transition region in $\alpha$ BOO may be thick, as independently suggested by Weinstein, Moos, and Linsky (1976).

I. MAGNETIC FIELDS AND STELLAR CYCLES

Since solar chromospheric activity is related to the solar magnetic cycle, several observers have searched for stellar cycles by attempting to measure the longitudinal magnetic fields of late-type stars. In their search Severny (1970) and Borra and Landstreet (1973) report a measurable magnetic field only in $\gamma$ CYG (F8 Ib), and this field appears variable. Boesgaard (1974) has observed 8 F0-K0 dwarfs thought to be young on the basis of strong Ca II emission, high lithium content, or high rotation velocities. In this sample, $\gamma$ VIR N (F0 V) appears to have a small variable magnetic field, and $\xi$ BOO A (G8 V) and 70 OPH (K0 V) show marginal evidence for fields. Further work to confirm these not wholly convincing observations and expand our information on magnetic fields in late-type stars would be very helpful.

Since 1967, Olin Wilson has been systematically observing main-sequence stars to search for variability in the Ca II H and K line emission as evidence of stellar cycles. Stellar rotation would also be evidenced by the appearance of plages on the disk. His approach (described in Wilson, 1968) is to measure the flux in 1 Å bands centered on H and K and divide the sum by the flux in two continuum bands.
separated by about 250 Å on either side of the H and K region. The results of this work are to be published in 1977. Wilson has now found several stars of a spectral type later than G0 V with completed cycles. Figure 1 is one such example (shown with his permission), of the star HD 32147, a K5 dwarf. Wilson finds no evidence for periodicity in stars hotter than spectral type G0 V or in cooler stars with very strong H and K emissions. These latter, presumably younger, stars are very "noisy" in Ca II emission without much evidence for periodicity.

**F. FLARES, STARSPO T S, AND PLAGES**

A complete description of stellar flares is beyond the scope of the present paper and the reader is referred to the excellent reviews of Ambartsumian and Mirzoyan (1975), Kunkel (1975), and Gershberg (1975). We will dwell here briefly on only a few possible analogues of solar phenomena in flare stars.

There is considerable evidence that flares in UV Ceti-type stars are similar to the chromospheric aspects of solar flares. As summarized by Gershberg (1975), the similarities include light curves in emission lines, confinement to small areas in

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*Fig. 1* Time variation of the flux from the star HD 32147 in 1-Å bands centered on the H and K lines, divided by the flux in two continuum bands separated by about 250 Å on either side of the H and K spectral region (cf. Wilson, 1968). These are unpublished observations kindly supplied by Olin Wilson.
the disk, sympathetic flares, the emission line spectra, plasma temperatures and densities, and motions in excess of 100 km s⁻¹. However, Kunkel (1970) finds that the energies in these flares can exceed by at least a factor of 100 the total energy of solar class 3+ flares. Hard X-ray emission has been predicted (Grindlay, 1970) and 1-7 keV X-rays have been detected (Heise et al., 1975) from YZ CMi.

Many flare stars (BY Dra is the prototype here) show quasiperiodic brightness variations suggestive of cool starspots rotating on and off the disk. These spots may be 500-1500 K cooler than the stellar photosphere (Torres and Ferroz-Mello, 1973; Bopp and Evans, 1973), but Vogt (1975) has suggested bright plage regions as an alternative (cf. Fix and Spangler, 1976). An interesting point made by Gershberg (1975) is that stellar flares, like solar flares, tend to occur when the continuum flux is low (i.e., when the starspots are on the disk); thus the starspots may be the seat of flare activity (cf. Bopp, 1974). On theoretical grounds, Mullan (1974) has estimated magnetic fields of ~2 × 10⁴ gauss for these spots, and he suggests that the energy for stellar flares is the missing energy in the starspots (Mullan, 1975a). An unequivocal measurement of the magnetic fields in these spots would confirm or disprove the theory (cf. Anderson, Hartmann, and Bopp, 1976). There is also evidence (Kunkel, 1975) that, as in the sun, the lifetime for individual active regions is months and that long-term cycles on the order of one or several decades (like the solar cycle) may exist. Mullan (1975b) has proposed that W UMa-type stars also have magnetic starspots and cycles.

There is evidence for nonthermal processes during stellar flares. Flares may be heated by fast electrons (Bopp and Moffett, 1973). Spangler and Moffett (1976) and Spangler, Rankin, and Shawhan (1974) conclude on the basis of polarization and intensity measurements that the radio emission is nonthermal, possibly as a result of a coherent process (Robinson, Sée, and Little, 1976). Also the radio emission lags the optical emission, suggestive of a disturbance propagating outward in the stellar corona.

III. BASIC QUESTIONS AND POTENTIAL EXPERIMENTS

We conclude this survey of solar-type phenomena in the sun and late-type stars by posing a number of fundamental questions and suggesting experiments, both observational and theoretical, that may help in answering these questions.

What is stellar activity? I think that we have skirted this fundamental question long enough. It appears to me that the most productive approach is to ask why the sun has so many chromospheres, transition regions, and coronae, loosely described as varying “activity,” coexisting in the same gravitational field. To answer this we should first assess the energy balance in these various structures semiempirically and then question how it is that the various magnetic field structures lead to the various energy balance regimes. With this insight, we can productively begin to inquire
into stellar activity.

What are the various energy balance options that occur in the outer atmospheres of late-type stars? This question may be resolved into questions concerning non-radiative heating, radiative losses, winds, and conduction. I suggest that purely theoretical approaches, computing the generation and dissipation of mechanical energy, are not sufficiently accurate to yield very much insight into this question. Instead, it may be more productive to derive semiempirically the radiative losses and temperature structures in the various outer layers (including photospheres) of different kinds of stars and to use this information as a guide for future theoretical calculations. This suggests a major effort to obtain high-resolution spectra in the ultraviolet, visible, and X-ray portions of the spectrum. Even more important is the development and application of diagnostics to obtain reliable information and models from these data (Linsky, 1976).

What might be the long-term variation in solar activity and the solar radiative output? One approach is to seek out statistical effects, such as the decline of chromospheric emission with age (Skumanich, 1972; Blanco et al., 1974; Blanco, Catalano, and Marilli, 1976) and the properties of stellar cycles. Another approach is to study closely pairs of stars which are identical except for their outer atmospheres and estimated ages. From the differences in the temperature structure and energy balance of such star pairs, one may obtain insight into evolutionary effects. In particular, the α CEN A - sun pair should be closely studied.

Finally, what is the significance for its outer atmosphere of whether a star is a part of a binary or multiple system? Observationally we know that close spectroscopic binaries tend to have bright chromospheric and probably also coronal emission spectra (α AUR may be the prototype). It is commonly thought that when stars form they lose excess angular momentum by forming either a planetary system or a multiple star system. If so, the internal angular momentum distribution and convective envelopes of stars may depend on their past history in complex ways. Also, the existence of nearby stars will produce Roche lobes about stars which could be significantly filled, and tidal coupling may alter the generation and transport of mechanical energy in stars (Young and Koniges, 1976). This is a particularly intriguing question.

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APPENDIX A: CHROMOSPHERIC DIAGNOSTICS

In this appendix we consider in detail the various chromospheric diagnostics that are available—their physical bases and the chromospheric models that have been constructed using them.

Ca II
The Ca II resonance lines H (λ 3968) and K (λ 3933) have proved to be the most useful chromospheric diagnostics because Ca II is the most abundant ion in the chromosphere with resonance lines in the visible spectrum and because these lines are collisionally excited and thermalized in the low chromosphere (Linsky and Avrett, 1970). As a result the positive chromospheric temperature gradient (dT/dh > 0) produces emission cores in these lines.

Until recently, chromospheric models were derived by matching the observed line profiles with theoretical profiles computed in the complete redistribution (CRD) approximation (e.g., Linsky and Avrett, 1970). This approach was able to match line profiles at the center of the solar disk, but was unable to account for limb darkening of the whole line profile (Zirker, 1968; Athay and Skumanich, 1968). Milkey and Mihalas (1973) and Shine, Milkey, and Mihalas (1975a) subsequently showed that taking account of coherency effects in the inner line wings (via the partial redistribution or PRD formulation) is more realistic on physical grounds and can account for limb darkening as well. This approach is now in general use, although CRD is entirely adequate to explain the H and K line cores (but not the H I and K I minima features) and the entire profiles of the subordinate triplet lines at λ 8498, 8542, and 8662 (Shine, Milkey, and Mihalas, 1975b).

A number of solar chromospheric models have now been constructed that are based on the Ca II lines (see Table 2) to describe the quiet sun (Ayres and Linsky, 1976), plage regions (Shine and Linsky, 1974), and the chromospheric portions of flares (Machado and Linsky, 1975). These models are parameterized in terms of the temperature minimum (T_{\text{min}}) and pressure [P(T_{\text{min}})], or the mass column density [m(T_{\text{min}}) = P(T_{\text{min}})/\gamma] at the base of the chromosphere, and the mass column density at the layer where the hydrogen Lyman continuum (λ 911) has unit optical depth, m_0 = m(T_{\text{LYC}} = 1). Since the temperature corresponding to m_0 is about 8300 K for quiet and active regions on the sun (Noyes and Kalkofen, 1970), and since T(m) rises very steeply above this layer (Thomas and Athay, 1961; Vernazza, Avrett, and Loeser, 1976), these solar models and the stellar models described below assume this upper chromosphere temperature distribution. Between m(T_{\text{min}}) and m_0 these models generally assume for convenience that dT/d log m is a constant, but there is no independent evidence for this and Vernazza, Avrett, and Loeser (1976) suggest a nonlinear structure for the quiet sun. It is possible that the assumption that dT/d log m is constant leads to errors in the derived chromospheric microturbulent velocities.
As noted above, the sun has a number of chromosphere structures. We list these in Table 3, which gives the horizontal (or both horizontal and vertical) scales in megameters, typical magnetic fields, and lifetimes. Shine and Linsky (1974) are able to explain enhanced H and K emission in plages simply by increasing $m_0$ and thus $P_0$ about a factor of 10, which steepens the average value of $dT/dh$ in the chromosphere about 50%. This change in the model parameters results in enhanced emission because at each K line optical depth $T_e$ ($\tau_K$) and $B_\nu$($\tau_K$) are larger, which increases the ionization of hydrogen and the metals so that the Ca II line source functions are more thermalized. Machado and Linsky (1975) find that H and K emission in solar flares can similarly be explained by further increasing $P_0$ to 8 dynes cm$^{-2}$ for subflares and up to 80 dynes cm$^{-2}$ for Class 3 flares. This increase in $P_0$ and K line emission is presumably due to enhanced heating. The different solar chromospheres are listed in Table 3 in order of increasing $P_0$ according to computed models; where models have not yet been computed, the values are estimated.

A considerable literature now exists concerning stellar observations in the H and K lines, and Bidelman (1954) has compiled a very useful bibliography of the various stellar types that exhibit emission in these lines. H and K emission is occasionally seen in F stars, is usually seen in G stars, and is especially ubiquitous in K and M stars. The earliest stars seen with Ca II emission include the F0 V star $\gamma$ Vir N (Warner, 1968), and the F0 Ib star $\alpha$ CAR (Warner, 1966); occasionally Ca II is seen in the A7 III star $\gamma$ BOO (Le Contel et al., 1970). One important unanswered question is whether chromospheres exist in A-type stars, where it is commonly assumed that they should not occur because of the thinness of the convective zones in these stars. A search is presently under way by Chiu, Linsky, and Maran for chromospheric filling in of the K-line core in A-type stars.

A second question is whether chromospheres extend to the coolest low-gravity stars, the M giants and supergiants. Dyke and Johnson (1969), Jennings and Dyke (1972), and Jennings (1973) find an inverse correlation in these stars between K-line emission and polarization and infrared excess, both indicative of grains in a cool outer atmosphere. They interpret this empirical result as suggesting that when the grain density is high, the grains cool the gas and dissipate the nonradiative energy input to the outer atmosphere, which would otherwise be cooled by emission lines like H and K.

Table 4 lists various groups of stars or structures on the sun in rough order of increasing chromospheric emission. Listed under each diagnostic is an indication of whether the diagnostic appears weak or strong as measured against the background continuum, with the symbols N (not present), W (weak), S (strong), VS (very strong), and blank (unknown). H and K emission is seen in a number of interesting star types including T Tauris (e.g., Kuhi, 1965), classical cepheids on the rising branch (e.g., Kraft, 1960; Hollars, 1974), carbon stars (Richer, 1975), eclipsing variables (Odgens and Wright, 1965), and is especially strong in close
spectroscopic binaries (Eilek and Walker, 1976; Young, 1976). The emission is often variable even in single stars that do not show continuum variations (Griffin, 1964; Deutsch, 1967; Liller, 1968; Chiu et al., 1976), indicating that, like the sun, stellar chromospheric structures change with time and rotate on and off the disk. But in stars that are cooler and have lower gravity than the sun, the changes are of greater magnitude and the structures of larger size (Schwarzschild, 1975; Chiu et al., 1976).

Wilson and Bappu (1957) began a systematic study of H and K emission in cool stars at a dispersion of 10 Å mm\(^{-1}\). They characterized their K-line intensities on a scale, the so-called Wilson-Bappu intensities (WBI), from 0 (no detectable emission) to 5 (emission stronger than the continuum). On this scale, the quiet sun would be 0, plages 1-2, and solar flares 4-5. They also characterized the line widths from direct measurements of the plates at this dispersion by means of a width index W (km s\(^{-1}\)), indicative of the width somewhere between the K\(_2\) emission peak and the K\(_1\) minimum beyond the emission peaks (cf. Wilson, 1976). Wilson (1968) has extended this observing program and now obtains photoelectric observations of the H- and K-line cores. Warner (1969) has also applied the program to southern-hemisphere stars.

Several interesting empirical correlations have come from this program. Wilson and Bappu (1957) found that \(W \sim L^{1.6}\) (cf. Wilson, 1966a). Unfortunately the great interest in interpreting and extending this width-luminosity relationship (the so-called Wilson-Bappu effect) has so dominated the study of stellar chromospheres that other, possibly more interesting, empirical results have not been studied to the extent they merit. The fundamental question in interpreting the Wilson-Bappu effect is whether the width W refers to the doppler core or the damping wing. In the former case one is led to the conclusion that chromospheric turbulent velocities increase with stellar luminosity (Goldberg, 1957; Fosbury, 1973; Reimers, 1973; Wilson, 1957b). An alternative approach is that W refers to a feature in the damping part of the line profile, in which case Ayres, Linsky, and Shine (1975) showed that \(W \sim L^{1.6}\) naturally follows from the increase in mass column density above the temperature minimum needed to retain the same H\(^{-}\) optical depth as the gravity of a star decreases (cf. Lutz, Furenlid, and Lutz, 1973). This question remains unresolved. In the meantime other width-luminosity relations have been found for Balmer-alpha (Kraft, Preston, and Wolfe, 1964; Fosbury, 1973; Reimers, 1973), the Mg II resonance lines (Kondo, Morgan, and Modisette, 1976a; McClintock et al., 1975a), and Lyman-alpha (McClintock et al., 1975a).

Wilson (1963; 1966a), Wilson and Skumanich (1964), and Wilson and Woolley (1970) have found statistically that the relative strength of the Ca II K\(_2\) emission decreases with age as stars evolve off the main sequence, and Skumanich (1972) has derived an evolutionary time scale for this decay. Similar decreases with age in the rotational velocity of main-sequence stars (Wilson, 1966b; Kraft, 1967) and lithium depletion with age (e.g., Herbig, 1965) have suggested the picture (Wilson,
that stars with well-developed convective envelopes (spectral types F and later) have chromospheres, winds, and magnetic fields as a result of dynamo processes. The loss of angular momentum by the wind in time (Brandt, 1966) then brakes the star, decreasing the dynamo and resultant magnetic fields, the dissipation of acoustic energy (somehow related to the magnetic field), and ultimately the Ca II emission. This picture has considerable plausibility, especially since magnetic field strength and Ca II emission are well correlated in the sun (e.g., Frazier, 1971), but the picture has never really been tested. In particular, the correlation of decreasing Ca II emission with age may only be true statistically as α CEN A and the sun have similar Ca II emission but α CEN A is probably twice as old (Ayres et al., 1976). Also, high-luminosity evolved stars often have strong emission, and the strength of emission in spectroscopic binaries appears to be a function of the filling of one star’s Roche lobe rather than of age (Young, 1976).

Stellar chromospheric models have now been constructed for α CMI (F5 IV; Ayres et al., 1974), α BOO (K2 IIIp; Ayres and Linsky, 1975a), α CEN A (G2 V; Ayres et al., 1976), and α CEN B (K1 V; Ayres et al., 1976). One important trend seen in these models is that despite the 2250 K range in effective temperature and the factor-of-600 range in gravity among these quiet chromosphere stars, the values of $m_0$ are all within a factor of 3 and $10^{-5}$ g cm$^{-2}$. It is important to determine what causes this small range in $m_0$ and whether $m_0$ is much larger in active chromosphere stars than it is in solar plages and flares.

In addition to the H and K lines, five subordinate lines of Ca II are potentially useful chromospheric diagnostics. The so-called infrared triplet lines $\lambda$ 8498, 8542, and 8662 couple the $4^2P$ states (upper states of H and K) with the $3^2D$ metastable states. These lines are less opaque than H and K, but they are also collisionally dominated and are formed in the solar chromosphere (Vernazza, Avrett, and Loeser, 1976). Spectroheliograms in these lines (Title, 1966) show the chromospheric network and plages as bright regions, and self-reversed emission features appear in the line cores in strong plages (Shine and Linsky, 1973) and flares (Machado and Linsky, 1975). Shine and Linsky (1974) have shown that plage models that match the H- and K-line profiles also match the infrared triplet line profiles, including the observation that the weakest of the triplet lines ($\lambda$ 8498) is the first to exhibit a clear emission feature as one goes from weak to strong plages. Thus these lines should be good chromospheric diagnostics. Also Shine, Milkey, and Mihalas (1975a, b) have shown that CRD diagnostics are entirely adequate in analyzing these lines, at least in solar-type stars.

The infrared triplet lines are typically in absorption in late-type stars, the exceptions being long-period variables near maximum light (Kraft, 1957; Merrill, 1934; 1961), T Tauri stars, and the peculiar binary AX MON (Wallerstein, 1971; Herbig and Rao, 1972; cf. Andrivat and Swings, 1976). Anderson (1974) has searched for emissions in the core of $\lambda$ 8498 without success, but he observed only
one active chromosphere star, β DRA (G2 II), and the λ 8498 profile of this star is shallow, presumably filled in by weak chromospheric emission. Linsky, Hunt, and Sowell (1976) are searching for core emission or filled-in profiles of the λ 8542 line, with emphasis on active chromosphere stars including spectroscopic binaries, to establish the usefulness of this line as an empirical test for active stellar chromospheres.

The 4 $^2$S ground state of Ca II is connected to the metastable 3 $^2$D states by quadrupole transitions at λ 7291 and λ 7324. These very weak lines, which Lambert, Mallia, and Warner (1969), and Schorn, Young, and Barker (1975) have observed in the sun, will be useful diagnostics of chromospheres in low-gravity, late-type stars.

**Mg II**

The Mg II resonance lines h (λ 2803) and k (λ 2796) are similar to H and K in that they are collisionally excited emission lines that are thermalized in the solar chromosphere. In the quiet sun they appear as stronger emission lines with peak residual intensities of, typically, 0.3, compared to 0.07 for H and K, in part because they are measured against a darker background and in part because they are thermalized higher in the chromosphere at slightly hotter temperatures. This is because magnesium is about 14 times more abundant than calcium; its ionization potential is larger (15.03 eV for Mg II compared to 11.87 eV for Ca II); Lyman-alpha photoionizes Ca II but not Mg II from the metastable 3 $^2$D states. In absolute flux units, however, the k-line emission core is only slightly stronger than K (2.24 X 10$^5$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for k in a ±0.60-Å bandpass compared to 1.56 X 10$^5$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for K in a ±0.275-Å bandpass; Ayres and Linsky, 1976). Also the Mg II lines appear bright in plage regions and the chromospheric network (Fredga, 1969; Lemaire and Skumanich, 1973).

As for the Ca II resonance lines, h and k should be synthesized using PRD codes rather than CRD codes (Milkey and Mihalas, 1974; Milkey, Ayres, and Shine, 1975). An important difference in synthesizing the Mg II lines is that, unlike Ca II, there are no intermediate metastable states between the resonance line upper and lower states and thus no finite minimum value of the incoherence fraction. As a result the inner wings of the Mg II lines are more nearly pure coherent scattering and thus can be darker. Milkey, Ayres, and Shine (1975) show that the inner wings of the Mg II lines in solar-type stars should darken considerably as the stellar gravity decreases.

Milkey and Mihalas (1974) have computed PRD Mg II line profiles using the HSRA model atmosphere (Gingerich et al., 1971). They were able to closely match the quiet sun line cores observed by Lemaire and Skumanich (1973), but with the HSRA model (T$_{\text{min}} = 4170$ K) they naturally compute k-line inner wings which are lower than observed. As a result they suggest that T$_{\text{min}}$ must be raised considerably. Previously Lemaire and Skumanich (1973) have computed Mg II for
several chromosphere models using CRD diagnostics and have compared these theoretical profiles with their observations of quiet and plage regions.

Using PRD diagnostics, Ayres and Linsky (1976) have derived a quiet chromosphere model by matching computed profiles with the observed profiles obtained by Kohl and Parkinson (1976) at two positions on the disk. The Ayres-Linsky Mg II model is slightly hotter in the upper photosphere than their Ca II model, and both models are characterized by $T_{\text{min}} = 4450$ K. The Mg II lines thus appear to be useful chromospheric diagnostics for deriving models for different chromospheric structures; this can be done with the aid of OSO-8 observations, for example.

Many stellar observations in the Mg II lines are now being acquired by space experiments. Doherty (1972a) has given integrated Mg II line fluxes for eight late-type stars obtained from the 25-Å photometry of OAO-2. Gurzadyan (1975) has also observed several late-type stars at 25-Å resolution. Kondo et al. (1972) and Kondo, Morgan, and Modisette (1975) have observed a number of late-type stars at 0.25-Å resolution with their balloon-borne stellar spectrometer. They found Mg II emission in stars as early as βCAS (F2 IV), and in α ORI (M2 lab) they noted asymmetrical emission in the k line which Modisette, Nicholas, and Kondo (1973) have interpreted as due to Fe I (λ 2795) absorption, possibly circumstellar. Observations with a new, higher resolution balloon-borne spectrometer are now underway.

Several groups have been using the Princeton spectrometer on Copernicus for Mg II chromospheric observations. In a study of O- and B-type stars, Kondo, Modisette, and Wolf (1975) and Kondo, Morgan, and Modisette (1976b) have obtained observed emission in γ ARA (B1 Vek) and βCEN (B1 II) and possible emission in λ ORI (O8 III), α VIR (B1 IV), α GRU (B7 IV), and βLIB (B8 V). If confirmed, these observations may be evidence for chromospheres in stars hotter than heretofore thought, although the heating mechanism(s) for these chromospheres could be different from that of the sun. Evans, Jordan, and Wilson (1975) have obtained Mg II profiles for α CAR (F0 Ib) and α CMI (F5 IV-V). Dupree and Baliunas (1976) have reported on strong Mg II emission from the α AUR primary (G8 III) and Baliunas, Dupree, and Lester (1976) find asymmetrical Mg II emission lines with no self-reversal and four times the solar surface flux from the spectroscopic binary λ AND (G8 III-IV). Moos et al. (1974) and McClintock et al. (1975a, b) have been studying K-type stars of all luminosity classes. They have found Mg II stellar surface fluxes that range from 0.05 to 0.16 that of the sun for giants and supergiants to the solar value for ε ERI (K2 V). They also find asymmetric emission in α BOO (K2 IIIp) and possibly also in α TAU (K5 III), indicative of significant mass loss. Finally, Bernat and Lambert (1976), in their study of the M stars α ORI and α SCO, find the k line asymmetric and h line symmetric (cf. Kondo et al., 1972), suggestive of circumstellar absorption by Fe I and Mn I as proposed by Modisette, Nicholas, and Kondo (1973).

Mg II observations have now been utilized in constructing stellar chromospheric
models for $\alpha$ CMI (Ayres, Linsky, and Shine, 1974) using the Kondo et al. (1972) data and for $\alpha$ BOO (Ayres and Linsky, 1975a) using the Moos et al. (1974) data.

HI
A number of spectral features of hydrogen are potentially useful chromosphere diagnostics including Lyman-alpha, Balmer-alpha, Balmer-epsilon, and the Lyman and Balmer continua. The Lyman-alpha ($\lambda\alpha$) line, like the Ca II and Mg II resonance lines, is collisionally dominated and thermalized in the solar chromosphere. Due to the larger abundance of hydrogen, however, $\lambda\alpha$ is formed higher in the chromosphere and, as suggested by Vernazza, Avrett, and Loeser (1973; 1976), the core of $\lambda\alpha$ is formed in a plateau of about 160 km width and a temperature near 20,000 K. The existence of this plateau remains to be confirmed by analyses of other lines of other species. Milkey and Mihalas (1973), following an earlier suggestion of Vernazza, have shown that PRD diagnostics are needed to analyze the inner wings of $\lambda\alpha$.

In the sun, spectroheliograms of $\lambda\alpha$ clearly show the bright plage and chromospheric network regions (Prinz, 1973) and in the preliminary OSO-8 data they also weakly show polar coronal holes. Basri et al. (1976) point out, however, that in images with high spatial resolution $\lambda\alpha$ does not show precisely the same chromospheric structure as other lines, such as Balmer-alpha and Ca II, presumably owing to its higher level of formation.

Despite its clear usefulness as a chromospheric diagnostic, $\lambda\alpha$ has not been effectively employed yet in model building. The exceptions have been the early analysis of Morton and Widing (1961) and the CRD analysis of OSO-4 and OSO-6 quiet chromosphere profiles by Vernazza, Avrett, and Loeser (1973; 1976) that led to the suggestion of a 20,000 K plateau noted above. Basri et al. (1976) have recently begun a PRD analysis of the $\lambda\alpha$ wings and core using the one-arcsec-resolution Brueckner spectra. They are interested in deriving temperature structures over the range 6,000-25,000 K in active and quiet chromosphere structures.

Stellar observations of $\lambda\alpha$ are feasible only for stars nearer than about 30 parsec due to strong interstellar absorption. Even for the nearby stars it is difficult to disentangle interstellar absorption from stellar or circumstellar self-reversals at line center. Evans, Jordan, and Wilson (1975) have obtained Copernicus spectra of $\lambda\alpha$ in $\alpha$ CMI with a line surface flux comparable to the sun. Dupree (1975), Dupree and Baliunas (1976), and Vitz et al. (1976) find the line surface flux in $\alpha$ AUR to be about 1.5 times stronger than the sun. Baliunas, Dupree, and Lester (1976) report that in the spectroscopic binary $\lambda$ AND the line surface flux is three times that of the sun and the red emission peak is stronger than the blue, suggestive of strong mass loss. The $\alpha$ BOO line flux has now been observed by several rockets and Copernicus (Rottman et al., 1971; Moos and Rottman, 1972; Moos et al., 1974; McKinney, Moos, and Giles, 1976; Weinstein, Moos, and Linsky, 1976) with clear evidence for variability. The $\alpha$ BOO $\lambda\alpha$ profile, like that of $\lambda$ AND, exhibits
a stronger red than blue emission peak, suggestive of mass loss. McClintock et al. (1975a, b) have measured L line fluxes in several other K-type stars. No L measurements of M-type stars have yet been reported, and none of the data just described have yet been analyzed.

The Balmer-alpha (Hα) line is also chromospheric and accessible to ground-based observing but is more difficult to use as a diagnostic of chromospheric densities and temperatures as it is typically photoionization-dominated in the sun (Gebbie and Steinitz, 1974). Hα spectroheliograms do show significant intensity variations, however, with the chromospheric network, plage regions, and especially flares appearing bright. Gebbie and Steinitz (1973; 1974) proposed that intensity contrasts in the quiet sun are due to lateral changes in the shape of the absorption profile, while in plages and flares the electron densities may be sufficiently large that the line is collision-dominated. The use of Hα as a spectroscopic diagnostic has not been vigorously pursued because of the typical photoionization-dominated nature of the line, except for M dwarfs (Fosbury, 1974), and because solutions of the transfer equation with the R1 redistribution function (Mihalas, 1970) have not yet been attempted. Computations of model atmospheres on the basis of eclipse line intensities have been done (e.g., Thomas and Athay, 1961). Also, Schoolman (1972) has computed Hα CRD line profiles for various atmospheric models and Canfield (1974) has done so for models of flares.

Hα profiles have been obtained for 33 late-type stars by Fosbury (1973), who extended the work of Kraft, Preston, and Wolfe (1964) and Lo Presto (1971), and have related line widths to stellar luminosity, chromospheric velocity fields, and acoustical energy flux. Dumont et al. (1973) have shown that for 20 T Tauri stars the Hα emission flux is consistent with a chromospheric origin, the observed Paschen and Balmer continua, and a photoionization-dominated source function. Herbig and Rao (1972) have compiled a list of Hα emission-line stars. Further studies of this line as a diagnostic in active chromosphere stars might be quite productive.

The Balmer-epsilon (Hε) line is located +1.6 Å from the core of the Ca II H line and thus is measured against a very dark background in cool stars. In the sun, Hε is in absorption on the disk but in emission in flares. In late-type stars and especially in K and M giants (Wilson, 1957a) Hε is often in emission while other members of the Balmer series are in absorption, suggesting that the dark background against which it is measured is an important aspect of Hε appearing in emission. Hε emission is also seen in active chromosphere stars (spectroscopic binaries, dMe, T Tauris, flare stars), long-period variables, and novae.

Fosbury (1974) argues that Hε should be photoionization-dominated in late-type stars such as the sun and K giants, but in M dwarfs chromospheric electron densities may be sufficiently high to produce a collision-dominated line whose emission is indicative of a chromosphere temperature rise. He concludes that the
He emission clearly seen in α BOO by Griffin (1968) results from the line excitation temperature (due to the hydrogen-continuum radiation fields) exceeding the local radiation temperature (dark H line wing) and is thus not indicative of a chromosphere. Ayres and Linsky (1975b) have made detailed calculations of the He line profile for the sun and α BOO. They find that the line, as expected, is insensitive to the chromospheric model for the sun; but the contrary is true for α BOO because the relative contribution to τ(He) by the chromosphere is large in stars with cool photospheres. Thus, although He remains photoionization-dominated (controlled by the Balmer-continuum radiation field) in K giants, it is largely formed in the chromosphere and is indirectly sensitive to chromospheric properties. It is therefore a good candidate for a chromospheric diagnostic in these stars and M dwarfs.

Since the Lyman continuum is probably not readily observable in any star other than the sun owing to interstellar absorption, we conclude this discussion of hydrogen chromospheric diagnostics by considering emission in the Balmer and Paschen continua. In the sun the only features that show this emission are white-light flares. A number of suggestions have been made that this emission is photospheric because of heating by flare X-rays (Rust and Hegewer, 1975; Somov, 1975) or by nonthermal ions and electrons (Svestka, 1973; Najita and Orrall, 1970). Alternative suggestions are that the emission is indeed chromospheric, originating either in a layer where T = 8500 K, which has been pushed down to a region of high density by the flare (Machado and Rust, 1974), or in a layer where T ≈ 20,000 K and the Lyman lines are formed (Machado, 1976).

Evidence for chromospheric hydrogen bound-free emission has not yet been presented for most types of late-type stars. Possible exceptions include the T Tauri stars (Kuhi, 1974; Dumont et al., 1973; but see Kuan, 1975), Herbig-Haro objects (Bohm, Schwartz, and Siegmund, 1974), and flare stars (e.g., Kunkel, 1970; Moffett, 1975).

He I and He II

We treat these two ions together because their similar energy level diagrams and spectra are likely produced by similar mechanisms and should be amenable to similar diagnostics. The bound-free continuum (λ < 504 Å for He I and λ < 228 Å for He II) and resonance lines (λ 584 for He I and λ 304 for He II) have been studied in the sun, but they may not be observable except for the very closest stars. The visible and infrared lines of He I (λ 5876, λ 10830) and He II (λ 4686) have been observed, however, in stars and should prove to be very interesting diagnostics because of the large excitation energies of these levels. Also the λ 1640 (Hδ) line of He II may be a useful diagnostic.

Three mechanisms have been proposed for the formation of the ultraviolet spectra of these ions: (a) excitation and ionization by electron collisions (Athay, 1966); (b) recombination following photoionization by coronal XUV emission and
the $\lambda$ 304 line in the case of He I (Hirayama, 1972; Zirin, 1975); (c) enhancement of collisional excitation by mixing of hot and cold plasma (Jordan, 1975), for example, by diffusion (Shine, Gerola, and Linsky, 1975).

In quiet-sun regions the color temperature of He II Lyman continuum is about 13,000 K (Linsky et al., 1976) and the He I continuum 11,500 K (Vernazza and Reeves, 1976). These cool temperatures are indicative of formation in the chromosphere by the second mechanism, and detailed computations by Linsky et al. (1976) and Avrett, Vernazza, and Linsky (1976) confirm this. The resonance lines, however, are observed to be much stronger than computed using mechanisms (a) and (b) (Jordan, 1975; Avrett, Vernazza, and Linsky, 1976), unless considerably more material exists in the solar transition region than presently accepted models allow (Milkey, Heasley, and Beebe, 1973; Dupree, 1972). This discrepancy has led to suggestions of mixing or diffusion, but it could also imply errors in our transition region models. In any case, the $\lambda$ 304 and $\lambda$ 584 lines are collisionally dominated in the quiet sun, but they may be formed over a wide temperature range in the chromosphere and transition region (Avrett, Vernazza, and Linsky, 1976). In late-type giants, however, the recombination mechanism may dominate because of low chromospheric densities, in which case the He I and He II spectra may be diagnostics of coronae rather than of chromospheres.

The formation of the subordinate lines $\lambda$ 5876 (D3) and $\lambda$ 10830 of He I and $\lambda$ 4686 of He II has not yet been clarified because the necessary calculations including all the above mechanisms have yet to be performed. Milkey, Heasley, and Beebe (1973) state that $\lambda$ 10830 should be a pure scattering line in the quiet sun and that the He I triplet states should be populated by both mechanisms (a) and (b). In Zirin's (1975) analysis there is sufficient coronal radiation at $\lambda < 504\AA$ to account for the observed quiet-sun $\lambda$ 10830 absorption, but Linsky et al. (1976) point out that energetically this mechanism cannot work because most of this coronal radiation will be absorbed by H I rather than He I.

Spectroheliograms show $\lambda$ 10830 and $\lambda$ 5876 absorption in plages and the chromospheric network and decreased absorption in supergranule cells and coronal holes (e.g., Harvey et al., 1975). The He II $\lambda$ 4686 line may also appear as weak absorption above plages. Zirin (1975) interprets the appearance of dark bands in $\lambda$ 5876 and $\lambda$ 4686 at 1150 km and 1500 km above the disk, respectively, as evidence for excitation of He I and He II low in the chromosphere and thus for mechanism (b). The shape of the He II $\lambda\alpha$ line profile $\lambda$ 1640 in the quiet sun, however, is very suggestive of formation by collisional rather than recombination processes (Fieldman et al., 1975; Kohl, 1976). It should therefore be clear that until the formation mechanisms for the He I and He II subordinate lines are sorted out, these lines will not be useful diagnostics.

A considerable number of stellar observations in the $\lambda$ 10830 line have been obtained by Vaughan and Zirin (1968), Zirin (1976), and Andrillat and Swings (1976). They find variability in many stars, and often the line is seen in emission
or with emission components. One interesting result is that \( \lambda 10830 \) absorption or emission is not tightly correlated with K-line emission as would be expected if \( \lambda 10830 \) were a coronal diagnostic [mechanism (b)]. Spectroscopic binaries typically exhibit very strong \( \lambda 10830 \) absorption, as they do K-line emission. M giants and supergiants usually do not show \( \lambda 10830 \) absorption or emission, possibly indicating weak or nonexistent coronae in these stars.

The \( \lambda 5876 \) line is typically weaker in stars than in the sun but a few observations have been presented (Pasachoff and Lepleur, 1972). This line is seen in spectroscopic binaries like \( \lambda \) AND (Pasachoff and Lepleur, 1972), dMe stars (Worden and Peterson, 1976), novae (McLaughlin, 1960), flare stars (Joy, 1960), and presumably T Tauri stars. Observations of the \( \lambda 4686 \) line have been reported for novae and flare stars. No chromospheric models have yet been attempted on the basis of stellar He I or He II data.

\( \text{O I} \)

Neutral oxygen is interesting because it is an example of a fluorescence spectrum; that is, a spectrum largely excited by a strong emission line in another species. Bowen (1947) pointed out that the H I Lyman-beta (L\( \beta \)) line is coincident with an O I transition from the ground state to the 3d \( ^3D^0 \) level, which then cascades to give lines at \( \lambda 11287 \), \( \lambda 8446 \), and the resonance lines \( \lambda 1302 \), \( \lambda 1305 \), and \( \lambda 1306 \). Strong \( \lambda 11287 \) and \( \lambda 8446 \) emission is indeed often seen in H II regions, Be stars, and novae as well as various peculiar stars (Andrillat and Swings, 1976).

In the sun, \( \lambda 11287 \) and \( \lambda 8446 \) appear in absorption and the \( \lambda 1302 \) triplet is in emission, as are the \( \lambda 1355 \) and \( \lambda 1358 \) intercombination lines (Dupree et al., 1973). In \( \alpha \) Aur the resonance triplet lines have about eight times the solar surface brightness (Vitz et al., 1976) and in \( \alpha \) Boo (Weinstein, Moos, and Linsky, 1976) the resonance triplet and the \( \lambda 1355 \) and \( \lambda 1358 \) lines are about equal to the solar surface brightness and are anomalously bright compared to other lines formed in the lower chromosphere.

The anomalous character of the O I lines in \( \alpha \) Boo results from the Bowen fluorescence mechanism. Haisch et al. (1976) calculated the O I spectrum in \( \alpha \) Boo using the Ayres and Linsky (1975a) chromospheric model. They find that Lyman-beta pumping enhances the resonant triplet flux a factor of 25 above the collisional excitation value, can explain the ultraviolet line fluxes, and can account for measured equivalent widths in \( \lambda 8446 \) and other near infrared lines in the Griffin (1968) atlas. Shine et al. (1976) find similar factor-of-30 enhancements in the O I resonant triplet in the quiet sun. Clearly the O I ultraviolet and near-infrared lines are diagnostics for the Lyman-beta flux and thus indirectly for chromospheric properties near \( T = 20,000 \) K.

\( \text{OTHER SPECTRAL LINES} \)

Other potentially useful chromospheric diagnostics include the resonance lines of
C II at 1334 and 1335 Å and Si II at 1260 and 1264 Å. These lines have been measured in α AUR (Vitz et al., 1976) and are being studied by Shine et al. (1976) in the sun. Heasley and Milkey (1976) have suggested that emission in the cores of the CO fundamental vibration-rotation bands should be a diagnostic of chromospheres in late-type giants.

ULTRAVIOLET AND INFRARED CONTINUA
In the sun the continuum originates in the chromosphere for λ < 1525 Å (the Si I edge) and λ > 150 μm (hydrogen free-free opacity) (Vernazza, Avrett, and Loeser, 1976), and in other stars we might expect to see chromospheric emission at somewhat different wavelengths, depending on the atmospheric models. The Wisconsin experiment on OAO-2 observed a number of late-type stars in broad-band channels down to 1900 Å with no clear evidence for chromospheric emission (Doherty, 1972). Parsons and Peytremann (1973), however, show evidence for chromospheric emission in HR 2786, a G0 II star, in the U3 (1620 Å) channel of the Smithsonian experiment on OAO-2. Evidence of chromospheric emission in other cool stars may be available in the OAO-2 Celeste data. At 20 μm no excess emission clearly ascribable to a chromosphere has been detected (Morrison and Simon, 1973) other than a 0.3 magnitude excess for α Lyr (A0 V), which the authors tentatively call chromospheric.

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