STELLAR CHROMOSPHERES

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I. INTRODUCTION

Important progress in our understanding of stellar chromospheres has occurred in the past few years as a result of new observations, developments in spectral line formation theory, and the application of that theory to the construction of detailed model chromospheres. Significant trends are beginning to emerge from such analyses, and we are on the threshold of a meaningful confrontation between purely theoretical models and the data. The range of stars thought to possess chromospheres may be widening, and we now have a better understanding of the enigmatic problem of why the Wilson-Bappu relation between Ca II emission core widths and stellar absolute visual magnitudes actually works.

An important element in this progress has been the realization that much can be learned by studying the outer atmospheres of the Sun and a wide range of stars in the same context, and that such an approach is a two-way street. Not only are the theoretical techniques for analyzing spectra, modeling atmospheric structures, and computing the consequences of different heating processes the same, but also the wide variety of structures and phenomena seen on the Sun with high spatial and spectral resolution may be useful prototypes for stellar atmospheric structures and phenomena that we cannot hope to resolve but whose existance is implied by indirect evidence. Needless to say, our understanding of the Sun can be strengthened by studying phenomena in stars that have values of gravity, rotational velocity, chemical composition, and luminosity very much different from those of the Sun.

Despite the importance of solar-stellar cross fertilization, it is unwise to pursue solar analogies too far. At some point most and perhaps all of the solar analogies will fail to explain observables for certain stellar chromospheres. When we run into such situations, as I think we have in several cases, we are in a position to make important advances in our understanding of underlying physical processes operating in stars.

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https://doi.org/10.1017/S0252921100075436 Published online by Cambridge University Press

The general topic of stellar chromospheres has been reviewed recently by Linsky (1977, 1979, 1980), Praderie (1977), Ulmschneider (1979), and Snow and Linsky (1979). Important earlier reviews include those of Praderie (1973), Doherty (1973) and Kippenhahn (1973) in the proceedings of the IAU Colloquium on Stellar Chromospheres held in 1972 (Jordan and Avrett 1973), which the reader is encouraged to pursue. Recent reviews and monographs on the solar chromosphere include Athay (1976) and Withbroe and Noyes (1977). Because of the extensive review literature in this field and the rapid advances made most recently and presently under way, I will adopt a nonstandard approach here. I will not specifically discuss plasma diagnostics since this topic has been reviewed by Praderie (1973), Linsky (1977), and Ayres and Linsky (1979). However, several interesting developments in our understanding and use of chromospheric diagnostics are described below under the relevant headings.

II. WHAT TRENDS ARE EMERGING FROM SEMIEMPIRICAL CHROMOSPHERIC MODELS OF SINGLE STARS?

During the past several years two important developments have greatly facilitated the computation of semiempirical models of stellar chromospheres. The first is the acquisition of absolute flux profiles of important diagnostics such as Ca II H and K, the Ca II infrared triplet, He I λ10830, and Hα from the ground; and Mg II h and k, Lα, and the resonance lines of C II, Si II, and Si III from space experiments, particularly IUE. The second development is the refinement in our understanding of optically thick resonance line formation. We now have increased confidence in the use of these diagnostics to probe can provide insight into the gross properties of stellar chromospheres.

The various diagnostics used in building semiempirical model chromospheres have been reviewed by Linsky (1977), Ulmschneider (1979), Linsky (1979), and Ayres and Linsky (1979). The usefulness of different spectral features for identifying chromospheres has been reviewed by Praderie (1973, 1977). Here I will describe some recent developments in the field, identify interesting trends that are emerging, and call attention to uncertainties in the conventional analyses.

First, I will mention important observational programs that are producing chromospheric line profiles, calibrated in absolute flux units, which are the backbone of model chromosphere studies. Linsky *et al.* (1979a) have obtained 120 mÅ spectra of the Ca II H and K lines in a wide variety of stars later than spectral type F0, using the Kitt Peak 4 m echelle spectrograph. These data were calibrated in absolute flux units at the stellar surface based on Willstrop's (1972) narrow band photometry and the Barnes and Evans (1976) relation for deriving stellar angular diameters. Giampapa (1979) is extending the program to dMe stars. Blanco *et al.* (1974, 1976) have published absolute K line fluxes for F5-G8 dwarfs and G2-M5 giants, and Blanco et al. (1978) have presented absolute fluxes and brightness temperatures for the H_1 and K_1 features in 21 late-type stars. Echelle spectra of λ And obtained with the Mt. Hopkins Kron camera system have been discussed by Baliunas and Dupree (1979). Anderson (1974) and Linsky et al. (1979b) have obtained spectra of the Ca II infrared triplet lines, and Young (1979) is obtaining spectra of these features in RS CVn-type systems and other active chromosphere stars using the KPNO CID system. The Balmer lines in dMe flare stars have been studied by many observers, most recently by Worden et al. (1979). Zirin (1976) has obtained He I λ10830 equivalent widths for some 200 stars later than F5, and in several stars such as R Aqr, T Tau, and 12 Peg that have circumstellar envelopes. O'Brien and Lambert (1979) are studying λ10830 with an echelle-reticon system at McDonald Observatory. They find λ10830 emission in α Boo and α^1 Her and are presently studying nearly 60 F-M stars, with monitoring programs on several particularly interesting objects.

A number of important observing programs are under way in the ultraviolet. Surveys of Mg II emission fluxes include the Copernicus observations of 49 stars by Weiler and Oegerle (1979), BUSS observations with 0.1 Å resolution (e.g. Kondo et al. 1979; de Jager et al. 1979; van der Hucht et al. 1979), and IUE observations by Pagel and Wilkins (1979), Basri and Linsky (1979), Carpenter and Wing (1979), Stencel and Mullan (1979), and several other groups. The 1175-2000 Å short wavelength spectral region of IUE permits the study of prominent chromospheric resonance lines of H I, O I, C I, Si II, C II, and Si III, and transition region lines of C III, Si IV, C IV, N V, and O V. Initial observations of cool stars in the short-wavelength region include Linsky et al. (1978), Linsky and Haisch (1979), Ayres and Linsky (1979b,c), Dupree et al. (1979a), Hartmann et al. (1979), Brown et al. (1979), Carpenter and Wing (1979), and Bohm-Vitense and Dettmann (1979).

Table 1 summarizes semiempirical chromospheric models that have been constructed to match various diagnostic features observed in quiet and active regions on the Sun and in stars cooler than spectral type F0 V. For the most part these models were constructed to fit the Ca II and Mg II emission cores and damping wings using partial redistribution (PRD) radiative transfer codes, although prior to 1975 only the less accurate complete redistribution (CRD) codes were available. Because the Ca II and Mg II lines are formed in chromospheric layers cooler than 8000 K, these models may have validity only below that temperature. The Lyman and millimeter continua are useful for extending the models to 10,000 K, but suitable data are available only for the Sun. Other diagnostics of the 6500-8000 K temperature range include Si II λλ1808, 1817, 1265, and 1553 and the damping wings of Lα. Tripp et al. (1978) have described the formation of the Si II lines in the quiet Sun, while Basri et al. (1979) have used Lα wing observations to construct quiet and active solar models. However, the accuracy of the Lα diagnostic is compromised by the uncertain amount of frequency redistribution beyond the Doppler core. Because the Si II lines and Lα wings can be observed in stars by IUE, these diagnostics are

TABLE 1. SEMIEMPIRICAL CHROMOSPHERIC MODELS

Stars or Solar Features	Diagnostics Used	Approximations Used	Chromospheric Temperature Range	References
	Solar Models			
Quiet Sun (one comp.)	H, H^-, C I, Si I, IR continua	nonLTE	4100-25,000	Vernazza *et al.* (1973)
Quiet Sun (one comp.)	Mg II h + k, Ca II H + K	PRD	4450-5320	Ayres and Linsky (1976)
Quiet Sun (one comp.)	UV and IR continua	nonLTE	4150-5360	Vernazza *et al.* (1976)
Quiet Sun (one comp.)	C II λλ1334, 1335; Lyman lines Lyman continuum	CRD	6884-57,000	Lites *et al.* (1978)
	Si II λ1816, 1265, 1533; Si III 1206	CRD	VAL (1973)	Tripp *et al.* (1978)
Plage	Ca II H + K, λ8498, λ8542, λ8662	CRD	4200-8000	Shine and Linsky (1974)
Plage	Mg II h + k, Ca II H + K	PRD	4600-8000	Kelch and Linsky (1978)
4 Component Sun	Lα, Lyman and mm continua	PRD	4460-25,000	Basri *et al.* (1979)
6 Component Sun	UV and IR continua	PRD	4150-25,000	Avrett (1979)
Flares	Ca II H + K	CRD	5000-8400	Machado and Linsky (1975)
Flares	Ca II K, UV continua	PRD	4890-6100	Machado *et al.* (1978)
	Main Sequence and Subgiant Stars			
α CMi (F5 IV-V)	Ca II K, λ8542	CRD	4750-8000	Ayres *et al.* (1974)
α Cen A (G2 V), α Cen B (K1 IV)	Ca II K	PRD	3650-8000	Ayres *et al.* (1976)
70 Oph A (K0 V), ε Eri (K2 V)	Ca II K, Mg II h + k	PRD	3850-8000	Kelch (1978)
γ Vir N (F0 V), θ Boo (F7 IV-V), 59 Vir (F8 V), HD 76151 (G4 V), 61 UMa (G8 V), ξ Boo A (G8 V), EQ Vir (dK 7e), 61 Cyg B (dM0)	Ca II H + K	PRD	3000-8000	Kelch *et al.* (1979)
dMe stars	Hα, Hβ, Hγ	CRD	3000-15,000	Cram and Mullan (1979)
ε Eri (K2 V)	Mg II h + k, C II, Si II, Si III	PRD, CRD	3850-30,000	Simon *et al.* (1979)

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Table 1. (continued)

Stars or Solar Features	Diagnostics Used	Approximations Used	Chromospheric Temperature Range	References
		Giants		
α Boo (K2 III)	Ca II H + K, λ8542; Mg II h + k	CRD, PRD wings	3200-8000	Ayres and Linsky (1975)
β Gem (K0 III), α Tau (K5 III)	Ca II K, Mg II h + k	PRD	2700-8000	Kelch et al. (1978)
		Supergiants		
β Dra (G2 II)	Ca II K, Mg II k, C II	PRD	4800-16,000	Basri (1979)
ε Gem (G8 Ib), α Ori (M2 Iab)	Ca II K, Mg II k	PRD	2730-7000	Basri (1979)
		RS CVn-Type Systems		
α Aur (G6 III + F9 III)	Ca II K, Mg II h + k	PRD	4700-8000	Kelch et al. (1978)
λ And (G8 III-IV) α Aur (G6 III + F9 III)	Ca II K, Mg II k, Hα	PRD	3800-10,000	Baliunas et al. (1979)
HR 1099 (G5 V + K1 IV), UX Ari (G5 V + K0 IV)	Mg II k, C II, Si II, Si III	PRD, CRD		

potentially very important. In dMe stars, Hα and other Balmer series members go into emission and are useful diagnostics of the 8000-15,000 K temperature range (Fosbury 1974; Cram and Mullan 1979).

Vernazza et al. (1973) have proposed that the solar upper chromosphere has a plateau near 20,000 K with small temperature gradients, presumably produced when Lα becomes optically thin and an efficient radiator. Such a plateau can be studied by analyzing the Lα core. However, interstellar H I absorption prevents the observation of the Lα core in any star other than the Sun, or perhaps a few short period binary systems for which the orbital motions are large enough to unmask the stellar Lα core from the saturated interstellar absorption feature. Instead, one can study the C II λλ1334, 1335 and Si III λλ1206, 1892 lines which are also formed in the plateau (Lites et al. 1978; Tripp et al. 1978). These features, except Si III λ1206, can be observed even in faint stars by IUE at low dispersion, and chromospheric models of the 20,000 K region have now been constructed for several stars (e.g., Simon et al. 1979; Basri 1979; Simon and Linsky 1979).

Before discussing the general trends emerging from these models, I should bring to your attention their inherent limitations:

(1) All of the stellar models assume one-component atmospheres, whereas the Sun exhibits an embarrassingly rich variety of chromospheric structure. Inhomogeneities must also be important in many other stars as indicated by Wilson's (1978) observations of time variability in K line emission. (Such variations are likely produced in part by the appearance and temporal evolution of plage regions on the visible hemispheres of stars.) The important question is whether a one-component analysis is sufficient for an assessment of critical auxiliary quantities, for example nonradiative heating rates, or for comparison with purely theoretical chromospheric models. This question will be deferred to the next section, but it is clear that the chromosphere of at least one cool giant -- Arcturus (K2 III) -- is structured enough to make models based on diagnostics such as Ca II or Mg II, which are representative of the hotter atmospheric components, inconsistent with observations of diagnostics such as the CO fundamental vibration-rotation bands, which are sensitive to the cooler components (cf. Heasley et al. 1978).

(2) Models based on optically thick chromospheric resonance lines are uncertain to the extent that frequency redistribution in the line wings is not properly treated. The redistribution problem is most accute for estimating temperatures near the stellar temperature minimum. In these low density layers, scattering in the Ca II and Mg II resonance lines is nearly coherent at and beyond the K_1 minima, consequently the monochromatic source functions are strongly decoupled from the Planck function. For the Ca II resonance lines, radiative transitions to the $3d^2D$ metastable levels provide a lower limit of roughly 0.05 to the incoherence fraction. However, Mg II lacks analogous subordinate levels between the upper and lower states of the resonance lines, and the lower limit to the incoherence fraction Λ is only

10^{-4} (Basri 1979). Supergiants provide the most extreme examples of nearly pure coherent scattering in the Ca II and Mg II wings, owing to the low hydrogen densities and correspondingly reduced collisional redistribution. In fact, Basri (1979) finds that the largest sources of incoherence in such situations are radiative transitions to other levels. As described below, highly coherent scattering can even lead to self-reversed profiles with K_1 minimum features in isothermal models. Finally, the disagreement in solar chromospheric temperature structures based on the Ca II and the Mg II lines (Ayres and Linsky 1976) is a clear warning either that our understanding of the underlying atomic physics of the scattering process in resonance lines may be lacking in some important respect, or more likely, that single-component, homogeneous models are not a satisfactory description of the solar outer atmosphere.

(3) Baliunas et al. (1979) have shown that steep temperature gradients relatively deep in the chromospheres of active stars such as λ And (G8 III-IV) and Capella (G6 III + F9 III) can produce high pressures in the upper chromospheres and Ca II and Mg II resonance line cores with small K_2-K_3-K_2 contrasts or no central reversals at all, consistent with observations. Their approach takes advantage of properties of the line cores that were ignored in constructing earlier models (e.g. Kelch et al. 1978). While the Baliunas et al. approach may be a reasonable way to model active chromosphere stars, it is important to recognize that other processes are equally effective in filling in the line core; in particular, rotation and intermediate scale turbulence (mesoturbulence; see e.g. Shine 1975; Basri 1979). Baliunas et al. (1979) also show that the usual approach of assuming a steep temperature rise beginning at 8000 K, as appears to be valid in quiet and active regions of the Sun, is an overly restrictive assumption.

Bearing these problems in mind and the nonunique aspects of the diagnostics, it is nonetheless important to consider the basic trends that are surfacing from the modeling effort. In some cases, such trends may not be overly sensitive to the uncertainties of the modeling process:

(1) In most cases studied, temperatures in the stellar upper photosphere inferred from the K line wings are hotter than predicted by radiative equilibrium models, implying nonradiative heating in the photosphere itself. This result is sensitive to uncertainties in the PRD theory, but such uncertainties are least for the Ca II lines in dwarfs, and solar active regions show temperature enhancements of at least 400 K (Chapman 1977; Morrison and Linsky 1978) compared with quiet Sun models below the temperature minimum. If active chromosphere stars, that is stars with chromospheric line surface fluxes comparable to or brighter than solar plages, are at all analogous to solar plages, then such stars should also have photospheres with temperatures significantly hotter than radiative equilibrium models predict. In fact, enhanced photospheric temperatures are common even for nonactive chromosphere stars (Kelch 1978; Kelch et al. 1978, 1979).

(2) Kelch et al. (1979) have presented evidence that the temperature minimum in dwarfs moves outward to smaller mass column densities with decreasing nonradiative heating. (The nonradiative heating is measured by the apparent radiative cooling rate in the Ca II resonance lines.) Furthermore, there is some evidence that the T_{min}/T_{eff} ratio decreases with age among main sequence stars (Linsky et al. 1979a) as might be expected if the nonradiative heating rate decreases with age.

(3) Active chromosphere dwarf stars have larger chromospheric radiative loss rates and steeper chromospheric temperature rises than quiet chromosphere stars. The latter result is depicted in Fig. 1, where the chromospheric temperature gradients for plages (Shine and Linsky 1974; Kelch and Linsky 1978) and flares (Machado and Linsky 1975) are compared to those of 13 dwarf stars (Kelch et al. 1979). The correlation of increasing temperature gradients with increasing nonradiative heating rates is as expected. Kelch et al. (1979) and Cram and Mullan (1979) have shown that Hα emission, which distinguishes dMe stars from normal M dwarfs, can be simply explained by the steep chromospheric temperature rises implied by the bright K line emission characteristic of dMe stars.

(4) For quiet chromosphere dwarfs and giants, Kelch et al. (1979) found a correlation between the mass column density at the 8000 K level of the chromosphere (m_0) and stellar gravity (see Fig. 2). However, Baliunas et al. (1979) argue that the Kelch et al. relation is not valid for RS CVn stars. In addition, the relation does not hold for solar plages and flares, where m_0 can be several orders of magnitude larger than typical quiet Sun values. Furthermore, based on an analysis of the Mg II, Si II, Si III, and C II lines, Simon et al. (1979) find that the active

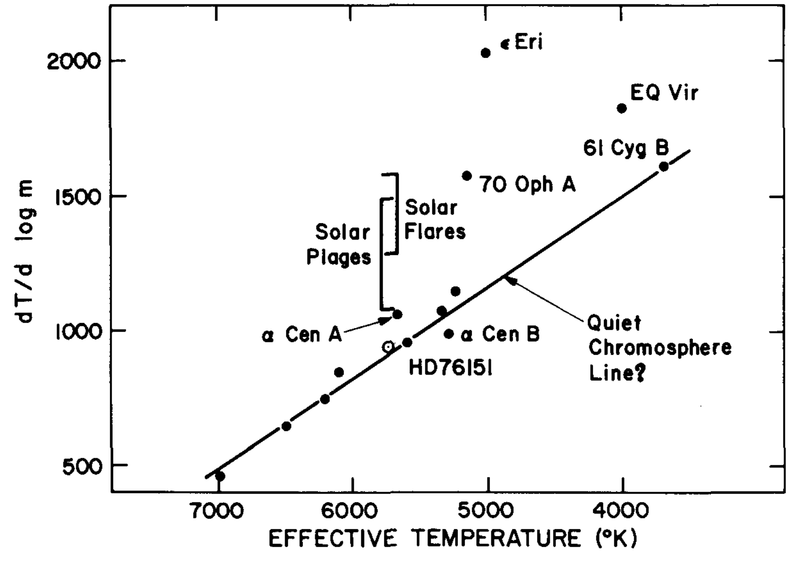

Figure 1. Temperature gradients in chromospheres of main sequence stars (Kelch et al. 1978).

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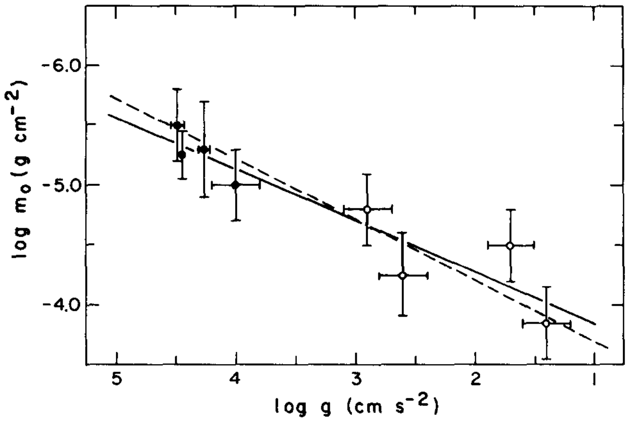

Figure 2. log m_0 versus log g (Kelch et al. 1978).

chromosphere star ε Eri (K2 V) has a value of m_0 a factor of 6 larger than predicted by the quiet chromosphere relation.

(5) A chromospheric temperature plateau near 20,000 K in the Sun (Vernazza et al. 1973), or near 16,500 K as suggested by Lites et al. (1978), may be a real feature of other stars. For example, Simon et al. (1979) propose that ε Eri (K2 V) has such a plateau. Furthermore, Basri et al. (1979) suggest that the plateau decreases in geometrical thickness with increasing brightness of Lα in the Sun.

Clearly much work remains to be done to better understand the available chromospheric diagnostics and to extend chromospheric modeling to other groups of stars. In particular, further studies of supergiants, RS CVn stars, dMe stars, F stars, and T Tauri stars are needed, as well as the extension of chromospheric models to transition regions using IUE spectra. The study of transition regions and coronae per se is beyond the scope of this review, but they are relevant to chromospheres since hydrostatic equilibrium, if valid, requires vertical pressure continuity between the top of the chromosphere and the base of the transition region. In this regard I would like to stress the following points: (1) The most reliable means of deriving pressures at the top of a chromosphere is to analyze diagnostic lines formed near 20,000 K such as the Lα core (useful primarily for the Sun), C II λλ1334, 1335 and Si III λλ1206, 1892. The Ca II and Mg II resonance lines are formed deeper in the chromosphere where the pressures are typically much larger than at the top, consequently the emission cores of these lines are not unique diagnostics. (2) Doschek et al. (1978) have proposed that the Si III λ1892/C III λ1909 line ratio, which is easily observed by IUE, is a useful diagnostic for densities at the base of the transition region. However, Simon et al. (1979) find that if a chromospheric plateau is present near 20,000 K, then Si III λ1892 is formed primarily in the plateau. Under these circumstances the Si III line is sensitive to the plateau thickness and the Si III/C III line ratio is a poor density diagnostic. Other prominent density diagnostics accessible to IUE include Si IV λ1403/C III λ1909 (Cook and Nicolas 1979) and C III λ1176/λ1909 (Raymond and Dupree 1978). However, one must keep in mind that such ratios can be sensitive to systematic flows (Raymond and Dupree 1978; Dupree et al. 1979b). Alternatively one can derive transition region pressures from emission measures, using an auxiliary relation such as constant conductive flux (e.g. Evans et al. 1975; Haisch and Linsky 1976; Brown et al. 1979). However, the validity of this approach is questionable. For example, Ayres and Linsky (1979) have argued against a conduction-heated transition region in the specific case of Capella B because that scenario requires pressures a factor of 30-50 times larger than those estimated from transition region density diagnostics, coronal emission measures, and the Mg II lines.

III. ARE THEORETICAL MODELS OF CHROMOSPHERES BECOMING REALISTIC?

Despite the rapidly growing number of spectroscopic observations of stellar chromospheres and the semiempirical models computed to match these data, we cannot claim that we understand chromospheres without first identifying the important heating mechanism(s), and second computing ab initio theoretical chromosphere models based on these heating mechanisms which accurately match the available data and semiempirical models. This particular goal of understanding stellar chromospheres has not yet been achieved, but considerable progress has been made recently.

Stein and Leibacher (1974) and Ulmschneider (1979) have described the different types of hydrodynamic and magnetohydrodynamic waves that are thought to exist in the solar atmosphere and are candidates for heating stellar chromospheres. Ulmschneider (1979) argues that magnetic modes are likely to dominate the transition region and coronae, but that short period acoustic waves are the best candidate for heating the chromospheres of the Sun and stars of spectral type A and later. His argument is based on the following elements: (1) Deubner (1976) measured the short period acoustic flux in the solar photosphere to be of order 10^8 - 10^9 ergs cm^{-2} s^{-1}, which is ample enough to balance the total energy loss of about 6×10^6 ergs cm^{-2} s^{-1} in the outer solar atmosphere even with considerable wave damping in the upper photosphere. Other nonmagnetic modes, for example gravity waves, probably do not carry remotely comparable amounts of energy. (2) The contrast in chromospheric emission lines across the solar surface, presumably due to magnetic heating mechanisms, is not large (Ulmschneider 1974). (3) There is rather good agreement between theoretical and empirical chromospheric heating rates, based on the short period acoustic wave mechanism, for several late-type stars and the Sun.

I will consider the validity of these arguments in the context of a comparison between the predictions of the acoustic wave models and empirical data, but first it is important to state the approximations made in recent theoretical calculations.

Prior to 1977, theoretical models of chromospheres (e.g. Kuperus 1965, 1969; Ulmschneider 1967, 1971; de Loore 1970) assumed weak shock theory and time-independent solutions. In more recent calculations (e.g. Ulmschneider and Kalkofen 1977; Ulmschneider et al. 1978, 1979; Schmitz and Ulmschneider 1979a,b) shocks are treated explicitly with time-dependent hydrodynamic codes. These numerical approaches typically assume mixing-length convection, the Lighthill-Proudman theory for acoustic wave generation, a single period for the acoustic waves, and grey opacity stellar atmospheres. I now consider four comparisons between these calculations and empirical measurements of several kinds.

(1) The most basic test of the wave models is that they correctly predict the T_{eff} and gravity dependences of chromospheric radiative loss rates. This test is difficult because several important emission features (i.e. resonance lines of Ca II, Mg II and H I) must be measured to estimate the radiative loss rate in lines, and it is presently impractical to directly measure the chromospheric radiative loss rate in the H^- continuum. As a first attempt at testing the theoretical models, Linsky and Ayres (1978) estimated that Mg II h and k account for 30 percent of the chromospheric line radiative losses in the Sun and other late-type stars for which the Ca II, Mg II, and H I resonance lines are effectively thick. They then compared normalized radiative loss rates in the Mg II lines, $\mathcal{F}(\text{Mg II})/\sigma T_{eff}^4$, for 32 stars including the Sun and found a systematic trend of decreasing $\mathcal{F}(\text{Mg II})/\sigma T_{eff}^4$ with decreasing effective temperature, but essentially no dependence on stellar surface gravity. The computations by Ulmschneider et al. (1977) of the acoustic flux available to heat chromospheres exhibit the observed T_{eff} dependence, but predict an increase in chromospheric heating of 1-2 orders of magnitude between log g = 4 and log g = 2, that is certainly not seen in the data. Subsequently, Basri and Linsky (1979) determined more accurate values of $\mathcal{F}(\text{Mg II k})/\sigma T_{eff}^4$ from their IUE data and the Copernicus spectra of Weiler and Oegerle (1979). These data are illustrated in Fig. 3. The normalized Mg II fluxes are widely scattered, but they do show little if any dependence of $\mathcal{F}(\text{Mg II k})/\sigma T_{eff}^4$ on stellar luminosity in agreement with the previous data, and perhaps a slow decrease with decreasing T_{eff}.

An important question in this regard is the amount of chromospheric cooling in the H^- continuum and the extent to which the H^- cooling term depends on gravity. Schmitz and Ulmschneider (1979a,b) revised the previous work of Ulmschneider et al. (1977) in a way that has reduced the gravity dependence of the acoustic flux that survives radiative damping in the photosphere, and is therefore available to heat the low chromosphere. They find that the ratio of the computed H^- radiative loss rates to the empirical Mg II radiative loss rates increases with decreasing gravity in a manner consistent with their acoustic flux calculations. For example, their $\mathcal{F}(H^-)/\mathcal{F}(\text{Mg II})$ ratios range from about 2 for the Sun to roughly 20 for the giants Capella and Arcturus. Since Mg II provides roughly a third of the total line losses, $\mathcal{F}(H^-)/\mathcal{F}(\text{lines})$ ranges from order unity to about 7. However, unlike

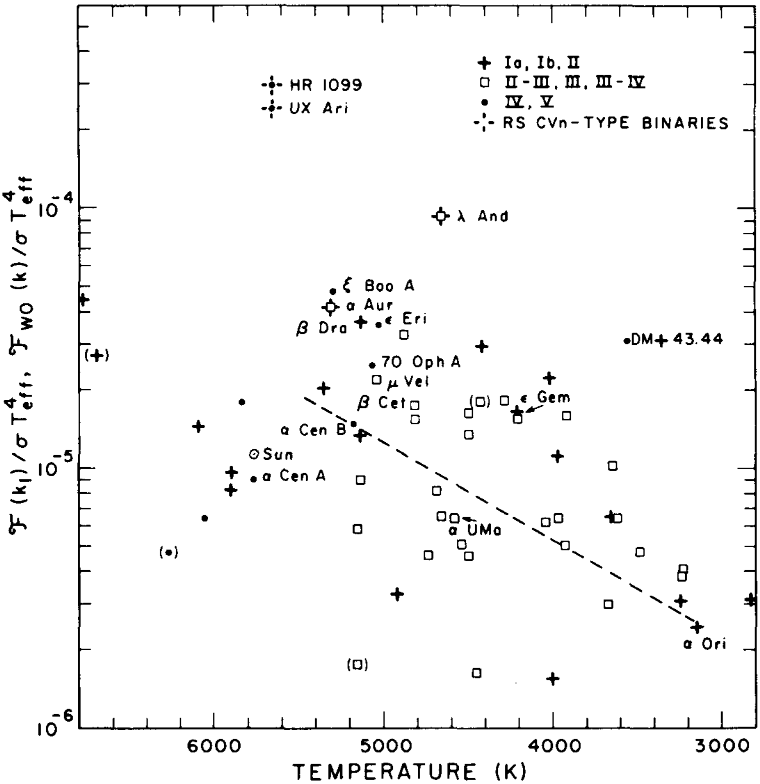

Figure 3. $\mathcal{F}$(Mg II k)/σT^4_{eff} versus T_{eff} (Basri and Linsky 1979).

radiative losses in lines, H^- cooling cannot be measured directly. Schmitz and Ulmschneider instead estimated H^- cooling indirectly using chromospheric models constructed to fit the Ca II and Mg II lines. Not only are the derived H^- radiative loss rates extremely model-dependent, but the use of models constructed to match the Ca II and Mg II lines to calculate the H^- losses is itself questionable. The reason is that the Ca II and Mg II lines average over the intrinsically inhomogeneous stellar atmosphere in a much different way than does in the H^- continuum. Since emission in the near ultraviolet resonance lines is strongly weighted toward the hotter components of an atmosphere, while the mainly visible and near infrared H^- emission is more evenly weighted over the thermal irregularities, the use of models constructed to fit the Ca II and Mg II lines will inevitably overestimate $\mathcal{F}(H^-)$. Finally there remains fundamental disagreement on the proper way to compute H^- radiative losses from a stellar chromosphere (Praderie and Thomas 1972, 1976; Kalkofen and Ulmschneider 1979; Ayres 1979b).

(2) The chromospheric k line radiative loss rates illustrated in Fig. 3 exhibit a wide range of values for stars of similar effective temperature and luminosity.

Excluding the RS CVn-type systems, the range is typically an order of magnitude. The analogous plot of normalized chromospheric radiative losses in the H and K lines (Linsky et al. 1979a) shows a comparable spread. While acoustic wave heating may explain quiet chromospheres, it cannot explain the large diversity of chromospheric radiative loss rates among single stars of similar effective temperature and gravity (same luminosity). In solar plages, chromospheric radiative losses in the Ca II and Mg II resonance lines are commonly 10 times those of the quiet Sun (Kelch and Linsky 1978; Kelch et al. 1979). Since Ca II K line intensities are well correlated with magnetic field strength in the Sun (Skumanich et al. 1975), it is generally presumed that the magnetic field plays an important role in enhancing the chromospheric nonradiative heating rates. In fact, the correlation of Ca II strength with the magnetic field must be viewed as circumstantial evidence for a hydromagnetic origin of chromospheric heating. One likely explanation, then, for the factor of 10 range in $\mathcal{F}(k)/\sigma T_{eff}^4$ at each effective temperature is that stars with low $\mathcal{F}(k)/\sigma T_{eff}^4$ ratios have few solar-type plages, while stars with large ratios are mainly covered with solar-type plages.

(3) A third test is a comparison of the theoretical acoustic wave heating in specific stars with empirically determined radiative loss rates. Ulmschneider et al. (1977) and Schmitz and Ulmschneider (1979a,b) have computed theoretical chromosphere models for the same dwarfs, subgiants, and giants that Ayres et al. (1974), Ayres and Linsky (1975), Kelch (1978), and Kelch et al. (1978, 1979) had previously computed semiempirical models based on the Ca II and Mg II lines. For many of these stars the agreement between computed acoustic fluxes and empirical radiative loss rates (including the estimated H^- contribution) is within a factor of 6, which is not a large factor when one considers the gross uncertainty in the amount of acoustic flux generated in the convective zone (see Gough 1976) and the potential importance of inhomogeneities on determining the "empirical" H^- cooling. The acoustic wave theory has the most difficulty for the cooler dwarfs such as 70 Oph A (K0 V) and EQ Vir (dK5e). For the latter star, in particular, Schmitz and Ulmschneider (1979b) estimate that a factor of 145 times more energy is needed to balance the empirical chromospheric radiative loss rate than is predicted by the acoustic wave theory. Part of the missing flux may be attributed to inadequacies in the theory, for example, the treatment of line blanketing, molecular opacity, and the effects of atmospheric stratification on wave production (Schmitz and Ulmschneider 1979a). However, I feel that the principal reason is the dominance of magnetic heating mechanisms in these active chromosphere stars. The same is almost certainly true for the RS CVn-type systems. For example, the theoretical acoustic heating rates for Capella are considerably less than the apparent chromospheric radiative losses.

(4) A final test is the location in mass column density of the temperature minimum, which is determined by the nonradiative heating rate at the base of the

stellar chromosphere. Cram and Ulmschneider (1978) called attention to inconsistencies between observed and predicted widths of the Ca II K_1 features, which should be formed in the vicinity of T_{min} (but see § VI concerning supergiants). In subsequent computations by Schmitz and Ulmschneider (1979a,b) the agreement between computed and empirical mass column densities at T_{min} has improved except for those stars (70 Oph A, EQ Vir, Capella) that show considerable deficiencies in the computed acoustic flux.

In summary, theoretical models based on the short period acoustic wave theory show promise for explaining the heating of the lower chromospheres of quiet chromosphere stars, but they are clearly inadequate to explain the heating of transition regions and coronae or active chromosphere stars and solar plages. In these "anomalous" cases, magnetic heating mechanisms are presumably dominant. Even for the quiet chromosphere stars the acoustic theory needs to be carefully examined. For example, H^- radiative losses should be calculated for the several classes of thermal inhomogeneities known in the solar case, to establish the reliability of estimating H^- cooling rates from single-component models. In addition, the acoustic wave theory should be extended to more realistic atmospheric models, including nongrey opacity sources and a more complete, nonlinear treatment of the propagation and damping of the sound waves.

IV. WHY DOES THE WILSON-BAPPU RELATION WORK?

Ever since Wilson and Bappu (1957) discovered a simple correlation between the widths of the Ca II H and K line emission cores and stellar absolute luminosity (M_v) extending over 15 magnitudes, many astronomers have expanded the data base and have attempted to explain the origin of this relation. Part of the fascination of this subject must be the inherent simplicity of the correlation and the prospect of obtaining valuable information about stellar chromospheres from simple measurements of line widths. Unfortunately, this is a topic in which one can easily be deluded into feeling that he understands something. In particular, many authors have made back-of-the-envelope calculations and arrived at relations similar in functional form to that originally proposed by Wilson and Bappu (1957), whereas the wide variety of assumptions used are often very different and even contradictory. Unfortunately, there is no substitute for careful analysis of this problem based on realistic radiative transfer calculations. Here I will briefly summarize past observational and theoretical work, and then discuss in detail two recent papers that should revolutionize our approach to the underlying physics of the Wilson-Bappu effect.

Width-luminosity relations have now been found for several lines in addition to Ca II H and K, for example the analogous Mg II h and k resonance lines, $L\alpha$, and $H\alpha$. The width that Wilson and Bappu (1957) measured, W_0 (km s^{-1}), is the separation between the outer edges of the Ca II emission features on 10Å mm^{-1} spectrograms. Lutz (1970) has shown that W_0 is very nearly the full width at half maximum (FWHM) of the emission core. Wilson and Bappu (1957) and Wilson (1959) proposed the following expression for the K line width-luminosity relation

$$M_v = 27.59 - 14.94 \log W_0 (K) \quad . \tag{1}$$

The most extensive compilation of Mg II k line widths is that of Weiler and Oegerle (1979), based on Copernicus observations of 49 late-type stars. Their expression,

$$M_v = 34.93 - 15.15 \log W(k) \quad , \tag{2}$$

has essentially the same slope as that for Ca II, even though the Mg II widths measured at the base of the emission feature. IUE observations will add to this data set and provide widths at different portions of the line profile. Using a small sample of Lα widths (FWHM), McClintock et al. (1975) obtained the relation

$$M_v = (40.2 \pm 4.5) - (14.7 \pm 1.6) \log W(L\alpha) \quad . \tag{3}$$

Finally, Kraft et al. (1964), LoPresto (1971), and Fosbury (1973) have studied the dependence of the Hα line half-width, defined in several different ways, on M_v, but they have not proposed definite functional relationships.

Different characteristic features within the K line also show width-luminosity relations. For example, Ayres et al. (1975) and Engvold and Rygh (1978) find that the separation of the K_1 minimum features is correlated with M_v. Based on high resolution spectra of 26 late-type stars, Engvold and Rygh (1978) derive

$$M_v \simeq \text{const} - 15.2 \log W(K_1) \quad . \tag{4}$$

In addition, Lutz et al. (1973) find that the entire damping wings of the H and K lines broaden with increasing stellar luminosity. Finally, Cram et al. (1979) have found in a sample of 32 stars observed at high dispersion, that both the K_2 peak separation and the K_1 minimum separation exhibit essentially the same width-luminosity slope as the FWHM.

The agreement among the slopes of the four relations above is certainly suggestive of a common, presumably simple, origin. As a first step towards understanding that origin, several authors have expressed the line widths empirically in terms of fundamental stellar parameters. For example, Lutz and Pagel (1979) have proposed the relation

$$\log W_0 = -0.22 \log g + 1.65 \log T_e + 0.10[\text{Fe/H}] - 3.69 \quad , \tag{5}$$

based on data from 55 stars. Lutz and Pagel argue that their relation is more accurate than those derived previously without an abundance term. For the K_1 width, Cram et al. (1979) find

$$\log W(K_1) = -(0.20 \pm 0.02) \log g + (1.1 \pm 0.2) \log T_e - 3.76 \quad , \tag{6}$$

whereas Engvold and Rygh (1978) derive a coefficient of −0.16 for the first term.

Physical interpretations of these width-luminosity relations fall into two distinct classes. The first assumes that the width, generally taken to be W_0 for Ca II K, is formed in the Doppler core of the line profile and therefore responds mainly to turbulent velocities in the chromosphere. For example, Scharmer (1976) followed Goldberg (1957) in assuming that $W_0 \simeq 6\bar{u}$, where $\bar{u}$ is mean the chromospheric turbulent velocity, and arrived at the inevitable result that such velocities are supersonic in giants and highly supersonic in supergiants. Using conservation equations and taking the mechanical energy flux proportional to $\bar{u}^{-3}$, Scharmer (1976) was able to show that $W_0 \simeq 6\bar{u} \sim g^{-1/4}$ in agreement with Eq. (5). However, the derived value of $\bar{u}$ for the Sun is 22 km s^{-1}, far larger than any estimates of turbulent velocities in the solar chromosphere. Fosbury (1973) has studied the Ca II and Hα widths together in order to better determine chromospheric turbulent velocities. He estimated chromospheric wave fluxes from the line widths and concluded that the amplitude of upward propagating acoustic waves increases with luminosity. Most recently, Lutz and Pagel (1979) have derived a relation similar to Eq. (5) assuming slab geometry with a geometrical thickness equal to the K line thermalization length, complete frequency redistribution (CRD), and Doppler control of W_0.

These three papers and previous studies of the same type share a number of difficulties: (1) They assume that W_0 is located in the Doppler core, but give no theoretical or empirical justification for this. (2) They either ignore radiative transfer altogether, despite numerous studies that show that the K and k lines are optically thick and partial redistribution effects are critically important in forming the outer portions of the emission cores, or they treat line transfer in a wholly unrealistic manner. (3) They rarely compute chromospheric densities and ionization self consistently. (4) They do not attempt to explain high resolution solar observations or turbulent velocities measured in the solar chromosphere by various techniques. The ability to arrive at expressions similar to Eq. (5) is often given as sufficient justification that the approaches are accurate enough to explain the underlying physical mechanism.

An alternative physical interpretation for the width-luminosity relations assumes that the width, generally taken to be $W(K_1)$, is formed in the damping wings of the line profile. In this scenario, the width is sensitive primarily to the mass column density above the temperature minimum and is relatively insensitive to chromospheric turbulent velocities. Engvold and Rygh (1978) have argued that $W(K_1) \simeq 7.8\pm1.7$ Doppler half-width units and thus the K_1 minimum features must be formed in the damping wings of the line profile. With this assumption and the approximation that the K_1 feature is formed at the temperature minimum, which models suggest occurs at roughly the same continuum optical depth in late-type stars, Ayres et al. (1975) used the pressure-squared dependence of H^- opacity to derive

$$\log W(K_1) = -0.25 \log g + 0.25 \log A_{met} + \text{const} \quad . \qquad (7)$$

The coefficient of the log g term above is close to that of Eq. (6). Thomas (1973)

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has proposed a somewhat different version of this explanation by showing that the location of the base of the chromosphere, which determines $W(K_1)$, may depend on the upward mass flux, which in turn is related to the chromospheric heating rate.

At this point it should be clear that a synthesis is needed to determine whether these very different explanations for W_0 and $W(K_1)$ are related, and which, if either, remains valid after a realistic study of spectral line formation in the K line. An important paper by Ayres (1979a) goes far in addressing these questions. Ayres proposed simple scaling laws for the thickness and mean electron density of stellar chromospheres as functions of surface gravity and nonradiative heating, based on hydrostatic equilibrium and the assumption that the nonradiative heating is relatively constant with height. He also took into account the influence of ionization on the general structure of a chromosphere and on the plasma cooling functions. He argued that the K_1 features are formed in the damping wings of the line profile on the grounds that PRD calculations now match the limb darkening of the solar Ca II features (Shine et al. 1975; Zirker 1968), which in itself provides strong evidence for near coherent scattering (and thus little Doppler redistribution) beyond the emission peaks. Ayres found that

$$\log W(K_1) = -1/4 \log g + (7/4 \pm 1/2) \log T_{eff} + 1/4 \log \mathcal{F}_{NR} + 1/4 \log A_{met} + \text{const} \quad , \tag{8}$$

where $\mathcal{F}_{NR}$ is the total nonradiative heating rate and A_{met} is the metal abundance. The coefficients are close to the empirical relation [Eq. (6)] and the derived width ratio $W(k_1)/W(K_1) \cong 2.5$ is consistent with the stellar value of 2.5 ± 0.3 estimated by Ayres et al. (1975) and the solar value of $\cong 2.3$.

Ayres (1979a) further assumed that the K_2 emission peaks are formed just outside of the Doppler core and that the line source function is a maximum at one thermalization length below the top of the chromosphere. These approximations lead to

$$\log W(K_2) = -1/4 \log g - (5/4 \pm 1/2) \log T_{eff} - 1/4 \log \mathcal{F}_{NR} - 1/4 \log A_{met} + 1/2 \cdot \log \xi + \text{const} \quad , \tag{9}$$

where ξ is the turbulent broadening velocity. The Mg II-Ca II emission peak separation ratio based on the above relation is $W(k_2)/W(K_2) \cong 0.9$.

Several important conclusions can be drawn from this work:

(1) Both $W(K_2)$ and $W(K_1)$ scale as $g^{-1/4}$ if the total nonradiative heating is independent of gravity -- the former owing to the dependence of chromospheric electron density on gravity and the latter owing to the dependence of chromospheric thickness on gravity. Because both $W(K_2)$ and $W(K_1)$ scale with gravity in the same way, it is reasonable that every width between K_1 and K_2, in particular W_0, should also scale the same way. The theoretical gravity dependence is consistent with the Lutz-Pagel scaling law $W_0 \sim g^{-0.22}$, and explains why the width-luminosity laws for W_0, $W(K_1)$ and $W(K_2)$ have essentially the same slopes (Cram et al. 1979).

(2) Ayres (1979a) found that $W(K_2) \sim \xi^{1/2}$ not $\sim \xi^1$ as generally assumed. This is a result of placing the K_2 feature just outside the Doppler core, in the Lorentzian damping wings. The assumption of Lorentzian control at K_2 is based on the argument that the solar Ca II emission peaks limb darken (Zirker 1968), which suggests significant coherent scattering, and thus little Doppler redistribution, where K_2 is formed. Engvold and Rygh (1978) estimate that on the average $W(K_2)/\Delta\lambda_D = 3.4 \pm 0.2$ for their sample of 26 stars, which suggests that K_2 is formed just outside the Doppler core. Consequently, the $W(K_2)$ and W_0 width-luminosity relations can be explained simply as a gravity effect without having to invoke highly supersonic turbulence in stellar chromospheres.

(3) Ayres predicts that $W(K_2)$ should decrease with $\mathcal{F}_{NR}$, while $W(K_1)$ should increase with $\mathcal{F}_{NR}$. A good test of this prediction is found by comparing solar plage profiles of Ca II (e.g., Smith 1960; Shine and Linsky 1972) with those of the mean quiet Sun. In particular, the nonradiative heating rate is large and easily estimated in plages and the stellar parameters of a plage are the same as those of the quiet Sun. The Ca II plage observations and corresponding data for the k line are consistent with the $\mathcal{F}_{NR}$ dependence of the $W(K_2)$ and $W(K_1)$ scaling laws. In addition, the K line FWHM (approximately equal to W_0) appears to be independent of $\mathcal{F}_{NR}$, which is in accord with Wilson's (1966) result that W_0 appears to be independent of the strength of the emission feature. Furthermore, Linsky et al. (1979a) find rough agreement between measured K_1 widths of a large sample of stars and the gravity and chromospheric heating rate dependences given in Eq. (8).

Finally, I comment on the calculations of Basri (1979), which cast the whole question of the interpretation of width-luminosity relations in a new light. Basri has made a number of prototype PRD calculations of line profiles for chromospheric models of late-type supergiants. His goal was to determine the factors involved in the formation of the emission widths of self-reversed chromospheric resonance lines under conditions of extreme coherency in the line wings. The PRD effects were expected to be particularly severe in supergiants owing to the very small collisional redistriubtion rates in the low density envelopes of such stars.

One set of Basri's calculations assumed a Voigt profile with parameters $a = 5 \times 10^{-4}$, $\varepsilon = 5 \times 10^{-6}$, and $r_0 = 1 \times 10^{-9}$ formed in an isothermal atmosphere. As shown in Fig. 4, he finds that the emergent line profile can have a self-reversed character for small values of the incoherence fraction Λ and r_0, the ratio of continuum to line center opacity, even though the atmosphere is isothermal and therefore has no temperature inversion. The origin of the phantom "K_1" minimum feature is as follows: Outside the Doppler core the photon scattering becomes more coherent with increasing $\Delta x = \Delta\lambda/\Delta\lambda_D$, and the monochromatic source functions rapidly decouple from the line center source function (which itself is close to the local Planck function) such that the emergent intensity decreases with increasing Δx. The intensity then rises in the far wings as the monochromatic source function begins to

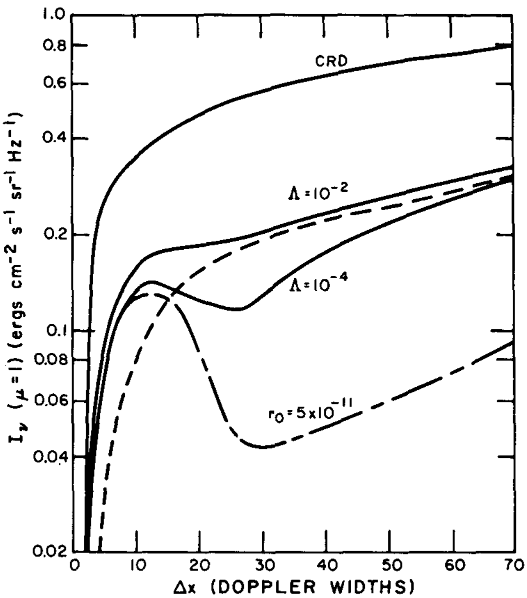

Figure 4. Line profiles for an isothermal atmosphere (Basri 1979, Fig. 4.3).

include a significant contribution from the assumed purely thermal background continuum. The extent to which the phantom K_1 feature occurs depends on the relative importance of the competing terms. Increasing coherence (decreasing Λ) tends to emphasize this Schuster-type process (Mihalas 1970), while increasing collisional redistribution (increasing Λ) or increasing continuum absorption (increasing r_0) deemphasizes it. In addition, Doppler drifting -- the frequency diffusion of photons with each "coherent" scattering owing to residual Doppler motions -- tends to increase the probability of core photons wandering into the line wings. The redistribution of core photons increases the effective noncoherent scattering term, which in turn raises the K_1 minimum over the pure coherent case. In fact, Basri found that microturbulence can influence the location of the K_1 feature even though K_1 is formed far from the Doppler core, by enhancing the Doppler drifting mechanism. Basri's calculations demonstrate the critical importance of properly treating frequency redistribution for very coherent cases and the potential dangers of naively assuming that the K_1 minimum feature is formed at the temperature minimum in extremely low gravity stars.

As a test of what mechanisms affect line profile shapes in realistic supergiant chromospheres, Basri considered the Mg II k line for the not extreme example of β Dra (G2 II), for which $W(k_1) = 2.5$ Å. Figure 5 depicts atmospheric parameters for solar-type temperature distributions (Models A and A') with T_{min} at $\log m_R = -1$ g cm^{-2} and a supergiant-type temperature distribution (Model B) with T_{min} shifted inward in mass by a factor of 100. For Model A, with a maximum turbulent velocity

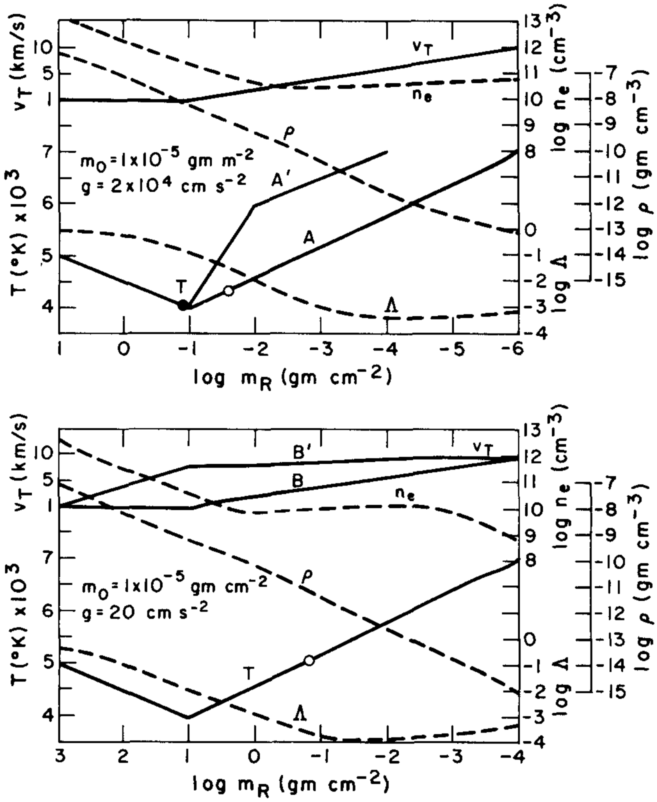

Figure 5. Atmospheric parameters for β Dra models (Basri 1979, Fig. 4.7).

in the chromosphere of 10 km s^{-1} and either the gravity of the Sun or β Dra, $W(k_1)$ occurs near 0.5 Å. By increasing the chromospheric temperature gradient (Model A') to produce a strong emission profile for β Dra, Basri finds that $W(k_1)$ is about 1.5 Å, even when the microturbulence is increased to the highly supersonic value of 30 km s^{-1}. However, the large values of microturbulence tend to wash out the k_2 emission features. Basri concludes that microturbulence by itself cannot be a viable explanation of the $W(k_1) - M_V$ or $W(K_1) - M_V$ relations in supergiants, although highly supersonic microturbulence can broaden W_0.

Alternatively, increasing the mass column density down to the temperature minimum (as is done in Model B) results in $W(k_1)$ = 1.5 Å (see Fig. 6), even when $m_{T_{min}}$ is increased without limit. The apparent lack of sensitivity of $W(k_1)$ to chromospheric column densities occurs because the k_1 minimum feature is strongly decoupled from the temperature structure (as was seen in the isothermal example). The location of k_1 is now determined by the balance of coherent and noncoherent processes. In particular, Doppler drifting is an important incoherence term which can be enhanced by increasing the microturbulence. Basri finds that $W(k_1)$ can be

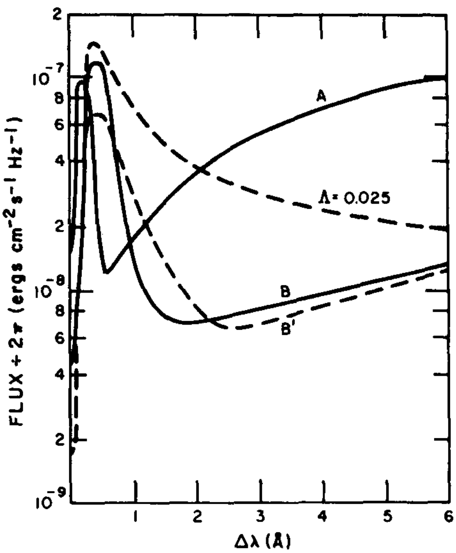

Figure 6. Mg II k lines computed for different β Dra models (Basri 1979, Fig. 4.8b).

broadened to the observed value of 2.5 Å simply by using a barely supersonic microturbulence of 8 km s^{-1} (Model B' in Figs. 5 and 6).

The prototype supergiant calculations leave us with the following unanticipated results: (1) k_1 and K_1 need not be formed at the temperature minimum. (2) Neither the turbulent velocity nor the mass column density explanation for the $W(K_1) - M_V$ relation is viable by itself. (3) Microturbulent velocities can play an important role in determining $W(k_1)$ and $W(K_1)$ via the Doppler drifting mechanism. Even though these conclusions refer to the perhaps extreme case of low density supergiant chromospheres, the most important message is that it is essential to solve the transfer equation properly before one can make meaningful statements concerning the physical basis of width-luminosity relations.

V. ARE THERE SYSTEMATIC FLOW PATTERNS IN STELLAR CHROMOSPHERES?

Until now we have been concerned with the interpretation of chromospheric line intensities and widths. These data provide valuable information on thermal structure and random nonthermal velocities in chromospheres, but they do not contain useful information on systematic flow patterns. Line profile asymmetries may provide such information with proper interpretation, and in fact they are the only means at present of studying chromospheric systematic velocity fields. Because the analysis of line asymmetries is complex, I first consider available theoretical calculations of profiles of optically thick chromospheric lines in the presence of systematic flow patterns, and then consider the extent to which solar and stellar data can be understood in terms of these models.

(1) Athay (1976) has emphasized the caution with which one should approach the question of determining velocity fields from line asymmetries. He provides examples of velocity fields for which even absorption line profiles predict the wrong sign of the flow vector. Needless to say, the analysis of optically thick self-reversed emission cores is more complex and must be undertaken with care.

(2) Using as a test case the Ca II K line formed in the solar chromosphere, Athay (1970) and Cram (1972) have shown that asymmetries provide information on velocity gradients in the line formation region but not on the magnitude or even the direction of the flow in any specific atmospheric layer. For example, Athay (1970) showed that downward motions of 10-20 km s^{-1} in the region of K_3 formation shift K_3 to the red, thereby moving absorbing material (material with a smaller source function than the underlying material producing the K_2 emission peaks) so as to partially obscure the K_{2R} emission peak and uncover the K_{2V} emission peak. The net effect is to produce brighter emission at K_{2V} and weaker emission at K_{2R}, and $\Delta\lambda_{K_3} > 0$. Unfortunately, the exact same asymmetries are produced by assuming upward motions of 3-7 km s^{-1} in the K_2-forming region and no systematic velocities where K_3 is formed. What I refer to as "blue asymmetry," $I(K_{2V}) > I(K_{2R})$ and $\Delta\lambda_{K_3} > 0$, thus only provides information on the systematic vertical velocity gradient, specifically, that $dv/dh < 0$, but no unique information on absolute vertical velocities anywhere. Similarly "red asymmetry," that is $I(K_{2V}) < I(K_{2R})$ and $\Delta\lambda_{K_3} < 0$, implies only that $dv/dh > 0$.

(3) Vertically propagating waves with scales between the microturbulent and macroturbulent limits ("mesoturbulence") and which are nonsinusoidal in character, can also produce line asymmetries. Shine (1975) has synthesized Na D profiles for a solar chromosphere model permeated by shock waves (approximated by vertically propagating sawtooth waves). He finds that the basic asymmetry of the sawtooth function produces time-averaged absorption profiles with line center shifted to the red, and the blue wing brighter than the red wing. Shine's calculations suggest that vertically propagating shock waves can produce blue asymmetries in chromospheric emission cores that might be mistaken for the symptoms of downflows where K_3 is formed.

(4) Heasley (1975) has synthesized the Ca II resonance and infrared triplet lines for models of the solar atmosphere including upward propagating acoustic pulses, perturbations in the local temperature and density induced by the pulses, and resultant changes in the line source functions, all self-consistently. He finds that the passage of a pulse through the chromosphere produces first a blue asymmetry, owing to upward motion where K_2 is formed and no motion where K_3 is formed, and then a red asymmetry, owing to upward motion where K_3 is formed and no motion where K_2 is formed. The effect of including the density and temperature perturbations associated with the pulse is to enhance hydrogen ionization. The increased electron

density in turn drives the collision-dominated line source function closer to the Planck function, thereby enhancing the K_2 emission. In fact, he notes that the dominant influence on the Ca II line source functions is not the velocity field of the pulses, but rather the atmospheric perturbations. Furthermore, the pulses do not change the wavelengths of the K_2 peaks, only their strengths.

The mean quiet Sun K line profile (e.g. White and Suemoto 1968) and the integrated solar disk K line profile (Beckers et al. 1976) both show blue asymmetry, as do the Mg II resonance lines (Lemaire and Skumanich 1973) and Lα (Basri et al. 1979). To interpret this asymmetry, we can take advantage of the high spatial resolution spectra that can be obtained from the Sun. Such spectra in the K line (e.g., Pasachoff 1970; Wilson and Evans 1972) show a variety of single and double peak profiles with red and blue asymmetry, but relatively constant K_2 peak wavelengths, consistent with Heasley's (1975) calculations. The real clue to the cause of the blue asymmetry seen in the whole Sun K line profile is provided by the high spatial resolution time-sequence spectra of Liu (1974). These data show intensity perturbations that travel from the far wings toward line center and produce a strong blue asymmetry when the disturbance reaches the line core. Liu (1974) and Liu and Skumanich (1974) have interpreted this behavior in terms of local heating of the chromosphere by upward propagating waves. The important message for us is that the solar blue asymmetry is very likely produced by something analogous to Heasley's acoustic pulses, that has the largest effect on the K line profile at those phases when the temperature and density perturbations and the upward motions are all positive in the chromospheric layers where K_2 is formed. However, the net blue asymmetry tells us nothing about the direction or magnitude of the solar wind or the nature of possible circulation patterns in the solar chromosphere.

With this background we can consider the stellar data. Profiles of the Ca II and Mg II lines in F-K main sequence stars (cf. Linsky et al. 1979a; Basri and Linsky 1979) typically have blue asymmetry, like the Sun, symptomatic of upward propagating waves in their chromospheres if our solar explanation is correct.

The G and K giants exhibit more complex behavior. Arcturus (K2 III), for example, shows Mg II line profiles with pronounced red asymmetry that did not change during 1973-1976 (McClintock et al. 1978), whereas Chiu et al. (1977) find that the K line asymmetry is variable in their data and in previous work going back to 1961, with blue asymmetry perhaps more common. Chiu et al. (1977) have modeled the red asymmetry Ca II and Mg II line profiles with a mass flux conservative stellar wind; that is, the outflow velocity is inversely proportional to the density and therefore increases rapidly with height. Such a velocity field produces red asymmetries in both the Ca II and Mg II lines, as expected from Athay's (1970) analysis for $dv/dh > 0$. The derived mass loss rate from the best fit models is $8 \times 10^{-9}\ M_\odot\ yr^{-1}$ and the outflow velocity is 13 km s^{-1} at $\tau(K_3) = 1$. The question remains, however, why Arcturus can have simultaneously a blue asymmetry Ca II profile and a strongly red asymmetry Mg II profile. McClintock et al. (1978) argue that the deep absorption feature at -38.3 km s^{-1} that produces or contributes to the red asymmetry of the Mg II profiles is very likely not interstellar absorption and must therefore be intrinsic to the star. Possible explanations for the opposite asymmetries include large systematic velocity gradients in the chromosphere (the Mg II lines should be formed slightly higher in the chromosphere than Ca II) or an expanding circumstellar envelope with large Mg II column density and small Ca II column density, presumably owing to ionization of Ca^+. The latter possibility may be correct, because the slightly cooler giant Aldebaran (K5 III) has Mg II line profiles very similar to Arcturus (van der Hucht et al. 1979), but Ca II lines which contain variable, weak circumstellar absorption features blue shifted by about 30 km s^{-1} (Reimers 1977; Kelch et al. 1978). Reimers (1977) has designated such circumstellar components "K_4."

Stencel (1978) found a statistical trend of K line blue asymmetry for giants hotter than spectral type K3 and red asymmetry for giants cooler than K4. The location of Stencel's Ca II asymmetry dividing line in the H-R diagram is depicted in Fig. 7. If blue asymmetry is symptomatic of upward propagating waves but no large wind in the chromosphere, and red asymmetry indicates the presence of a significant outward mass flux and possibly also a circumstellar shell, then the dividing line indicates the onset of massive winds in stellar chromospheres. Most recently, Stencel and Mullan (1979) (cf. Copernicus data of Weiler and Oegerle 1979) have determined a locus in the H-R diagram (see Fig. 7) where the Mg II resonance lines change their asymmetry in a manner similar to that found by Stencel (1978) for

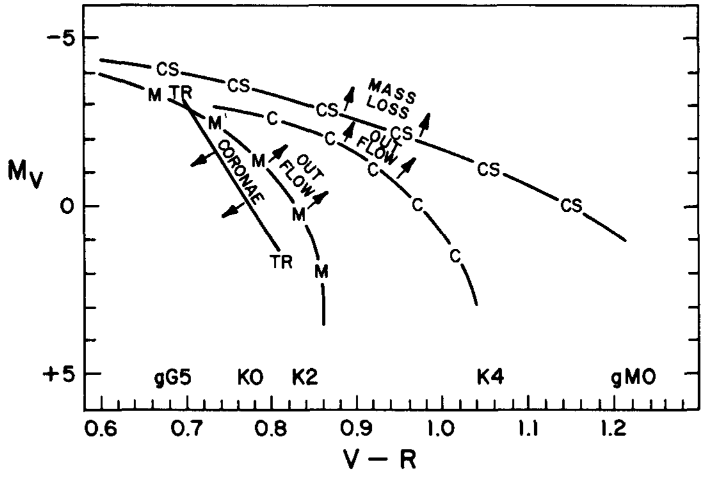

Figure 7. Transition region dividing line (Linsky and Haisch 1979), Mg II (M) asymmetry dividing line (Stencel and Mullan 1979), Ca II (C) asymmetry dividing line (Stencel 1978), and circumstellar (CS) dividing line (Reimers 1977).

H and K. The Ca II and Mg II dividing lines are located slightly to the right of that proposed by Linsky and Haisch (1979) to separate stars exhibiting high excitation emission lines characteristic of a solar-like transition region (material at $20\text{-}250 \times 10^3$ K) from stars showing only chromospheric emission lines (material at less than 10^4 K). Taken together these data suggest that cool stars fall into two distinct classes: those with outer atmospheres consisting of chromospheres, transition regions, and presumably also hot coronae; and those with chromospheres and massive cool winds.

Mullan (1978) has attempted to explain the apparent onset of massive winds in the early K stars. He proposes that the location of the point where the stellar wind becomes supersonic moves deeper into the stellar atmosphere as gravity and effective temperature decrease. Haisch et al. (1979) have shown that Lα radiation pressure may play an important role in initiating the cool stellar winds. The cooling effect of the wind may explain the following:

(a) For giants with color index (V-R) < 0.80 (about spectral type K0 III), the stellar wind is optically thin, but the energy associated with the mass flow is about equal to the nonradiative energy that would otherwise heat a hot corona. Such stars therefore do not have coronae and fall to the right of the Linsky-Haisch dividing line. However, the transonic point of the wind lies above the region where the Mg II lines are formed, consequently the Mg II lines are symmetric or show blue asymmetry. These stars therefore fall to the left of the Mg II asymmetry locus.

(b) For giants with (V-R) > 0.85 (about spectral type K2 III), the wind now affects the upper chromosphere where the Mg II lines are formed. The wind reverses the Mg II asymmetry and the mass loss rate rises because the transonic point has penetrated into the chromosphere where the density is high.

(c) For giants with (V-R) > 1.00 (about spectral type K4 III), the transonic point occurs well into the middle chromosphere where H and K form. The Ca II lines acquire red asymmetry and the wind now carries enough material to produce observable circumstellar features.

In cool supergiants like ϵ Gem (G8 Ib), ϵ Peg (K2 Ib), ξ Cyg (K5 Ib), and α Ori (M2 Iab), the Ca II and Mg II line asymmetries (cf. Linsky et al. 1979a; Basri and Linsky 1979) are dominated by apparent circumstellar absorption and it is difficult to determine the asymmetry of the unmutilated chromospheric line. The problem of the intrinsic asymmetries of chromospheric emission cores in supergiants is further complicated by the following points: (1) ϵ Gem shows apparent circumstellar absorption features at both positive and negative velocities. (2) The Mg II k profile of α Ori and presumably other stars is multilated by overlying circumstellar Fe II and Mn I absorption lines (cf. Bernat and Lambert 1976; de Jager et al. 1979). (3) Basri (1979) has constructed a chromospheric model for α Ori to match the Ca II and Mg II line profiles. He finds that broad, flat-bottomed reversals in the Ca II lines are easily predicted by the chromospheric model without including any circumstellar shell whatsoever. Consequently, our rather casual identification of circumstellar features in chromospheric lines of supergiants must be reconsidered.

Not all cool supergiants show "circumstellar" features. In particular, β Dra (G2 II) exhibits Ca II profiles with very strong blue asymmetry and Mg II profiles with less pronounced blue asymmetry (see Fig. 8). Basri (1979) has modeled these data using a comoving PRD code and a vertical velocity (see Fig. 9) that increases with height. Such a velocity field is consistent with the data, but it is perhaps unphysical and, as noted above, upward propagating waves can produce the same kind of asymmetry.

Variable asymmetry in chromospheric emission lines may turn out to be common in late-type stars as specific stars are monitored for long periods. For example, Hollars and Beebe (1976) have noted changes in the K line of α Aqr (G2 Ib), and Dravins <u>et al</u>. (1977) have found K line asymmetry changes in the δ Scuti star ρ Pup. O'Brien and Lambert (1979) have reported variable He I λ10830 emission from α^1 Her, which may result from a shock front created when high-velocity gas accretes onto the photosphere of α^1 Her. O'Brien (1979) has also reported λ10830 observations of a number of F-M stars. Many show variable absorption or emission, and α Aqr shows evidence of enormous outflow velocites of nearly 200 km s^{-1}.

The interpretation of asymmetries in chromospheric lines (Balmer series, Ca II, Na I) of T Tauri stars is a matter of dispute. Blue shifted absorption components in these lines have generally been interpreted as symptoms of a strong stellar wind (e.g. Herbig 1962). Nevertheless, Ulrich (1976) has demonstrated that nonspherically symmetric accretion can produce apparent blueshifted absorption components from an infalling postshock gas. Ulrich and Knapp (1979) find that absorption components in Hα are not reliable indicators of gas flow direction, contrary to the common presumption, but instead the Na D line absorption features are more reliable flow-vector diagnostics. They conclude that accretion occurs in the major fraction of T Tauri stars and that discrete clouds of ejected material, perhaps due to flares, continually pass through the generally infalling gas.

I wish to thank Drs. T. R. Ayres and G. S. Basri for their comments on the text, and many collegues for sending me preprints and unpublished data for inclusion in this paper. This work was supported in part by NASA through grants NAS5-23274 and NGL-06-003-057 to the University of Colorado.

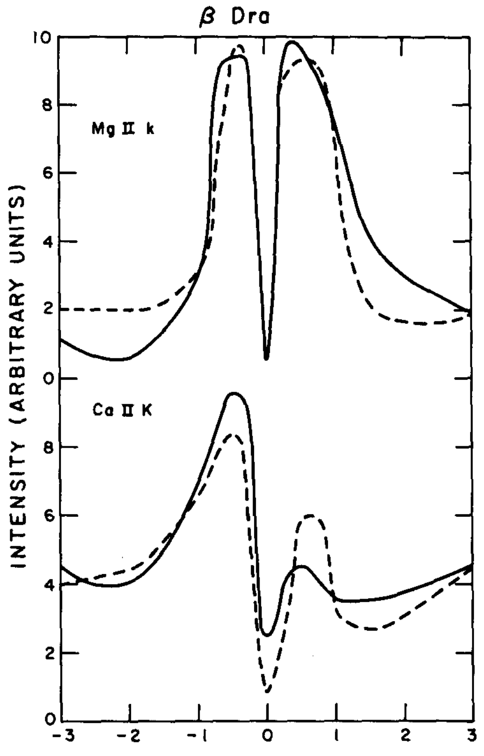

Figure 8. Computed β Dra Ca II and Mg II profiles (Basri 1979, Fig. 5.3).

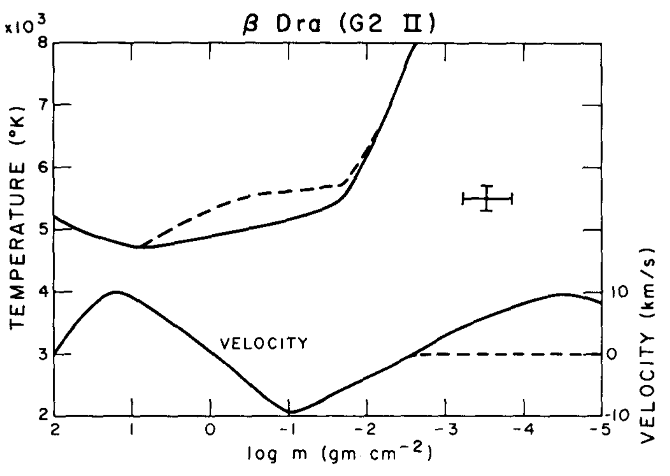

Figure 9. β Dra model and systematic velocities (Basri 1979, Fig. 5.2).

References

Anderson, C. M. 1974, Ap. J., 190, 585.
Athay, R. G. 1970, Solar Phys., 11, 347.
Athay, R. G. 1976, The Solar Chromosphere and Corona: Quiet Sun, D. Reidel, Dordrecht.
Avrett, E. H. 1979, private communication.
Ayres, T. R. 1979a, Ap. J., 228, 509.
Ayres, T. R. 1979b, private communication.
Ayres, T. R. and Linsky, J. L. 1975, Ap. J., 200, 660.
Ayres, T. R. and Linsky, J. L. 1976, Ap. J., 201, 212.
Ayres, T. R. and Linsky, J. L. 1979, in preparation.
Ayres, T. R., Linsky, J. L., Rodgers, A. W., and Kurucz, R. L., 1976, Ap. J., 210, 199.
Ayres, T. R., Linsky, J. L., and Shine, R. A. 1974, Ap. J., 192, 93 (1974).
Ayres, T. R., Linsky, J. L., and Shine, R. A. 1975, Ap. J. (Letters), 195, L121.
Baliunas, S. L., Avrett, E. H., Hartmann, L., and Dupree, A. K. 1979, Ap. J. (Letters), in press.
Baliunas, S. L. and Dupree, A. K. 1979, Ap. J., 227, 870.
Barnes, T. G. and Evans, D. S. 1976, M.N.R.A.S., 174, 489.
Basri, G. S. 1979, unpublished Ph.D. thesis, University of Colorado.
Basri, G. S. and Linsky, J. L. 1979, Ap. J., in press.
Basri, G. S., Linsky, J. L., Bartoe, J.-D. F., Brueckner, G., and Van Hoosier, M. E. 1979, Ap. J., 230, 924.
Beckers, J. M., Bridges, C. A., and Gilliam, L. B. 1976, A High Resolution Spectral Atlas of the Solar Irradiance from 380 to 700 Nanometers, Vol. 1 [AFGL-TR-76-0126(I)].
Bernat, A. P. and Lambert, D. L. 1976, Ap. J., 204, 803.
Blanco, C., Catalano, S., and Marilli, E., 1976, Astr. Ap., 48, 19.
Blanco, C., Catalano, S., and Marilli, E. 1978, Proceedings of the 4th International Colloquium on Astrophysics.
Blanco, C., Catalano, S., Marilli, E., and Rodono, M. 1974, Astr. Ap., 33, 257.
Bohm-Vitense, E. and Dettmann, T. 1979, Ap. J., in press.
Brown, A., Jordan, C., and Wilson, R. 1979, in Proceedings of the Symposium "The First Year of IUE," to appear.
Carpenter, K. G. and Wing, R. F. 1979, B.A.A.S., 11, 419.
Chapman, G. A. 1977, Ap. J. Suppl., 33, 35.
Chiu, H. Y., Adams, P. J., Linsky, J. L., Basri, G. S., Maran, S. P., and Hobbs, R. W. 1977, Ap. J., 211, 453.
Cook, J. W. and Nicolas, K. R. 1979, Ap. J., 229, 1163.
Cram, L. E. 1972, Solar Phys. 22, 375.
Cram, L. E., Krikorian, R., and Jefferies, J. T. 1979, Astr. Ap., 71, 14.
Cram, L. E. and Mullan D. J. 1979, Ap. J., to appear.
Cram, L. E. and Ulmschneider, P. 1978, Astr. Ap., 62, 239.
de Jager, C., Kondo, Y., Hockstra, R., van der Hucht, K. A., Kamperman, T., Lamers, H. J. G. L. M., Modisette, J. L., and Morgan, T. 1979, Ap. J., 230, 534.
de Loore, C. 1970, Astr. Space Sci. 6, 60.
Deubner, F.-L. 1976, Astr. Ap., 51, 189.
Doherty, L. R. 1973, in Stellar Chromospheres, ed. S. D. Jordan and E. H. Avrett, NASA SP-317, p. 99.
Doschek, G. A., Feldman, U., Mariska, J. T., and Linsky, J. L. 1978, Ap. J. (Letters), 226, L35.
Dravins, D., Lind, J., and Sarg, K. 1977, Astr. Ap., 54, 381.
Dupree, A. K., Black, J. H., Davis, R., Hartmann, L., and Raymond, J. C. 1979a, in Proceedings of the Symposium "The First Year of IUE," (in press).
Dupree, A. K., Moore, R. T., and Shapiro, P. R. 1979b, Ap. J. (Letters), 229, L101.
Evans, R. G., Jordan, C., and Wilson, R. 1975, M.N.R.A.S., 172, 585.
Engvold, O. and Rygh, B. O. 1978, Astr. Ap., 70, 399.
Fosbury, R. A. E. 1973, Astr. Ap., 27, 129.
Fosbury, R. A. E. 1974, M.N.R.A.S., 169, 147.
Giampapa, M. S. 1979, private communication.
Goldberg, L. 1957, Ap. J., 126, 318.

Gough, D. O. 1976, Proc. IAU Colloq. No. 36, ed. R. M. Bonnet and P. Delache (Clermont-Fenand: Paris), p. 3.
Haisch, B. M. and Linsky, J. L. 1976, Ap. J. (Letters), 205, L39.
Haisch, B. M., Linsky, J. L. and Basri, G. S. 1979, Ap. J., in press.
Hartmann, L., Davis, R., Dupree, A. K., Raymond, J., Schmidtke, P. C., and Wing, R. F. 1979, Ap. J. (Letters), in press.
Heasley, J. N. 1975, Solar Phys., 44, 275.
Heasley, J. N., Ridgway, S. T. Carbon, D. F., Milkey, R. W., and Hall, D. N. B. 1978, Ap. J. 219, 970.
Herbig, G. H. 1962, Adv. Astr. Ap., 1, 47.
Hollars, D. R. and Beebe, H. A. 1976, Pub. A.S.P., 88, 934.
Jordan, S. D. and Avrett, E. H. 1973, Stellar Chromospheres, NASA SP-317.
Kalkofen, W. and Ulmschneider, P. 1979, Ap. J., 227, 655.
Kelch, W. L. 1978, Ap. J., 222, 931.
Kelch, W. L. and Linsky, J. L. 1978, Solar Phys., 58, 37.
Kelch, W. L., Linsky, J. L., Basri, G. S., Chiu, H. Y., Chang, S. H., Maran, S. P. and Furenlid, I. 1978, Ap. J., 220, 962.
Kelch, W. L., Linsky, J. L., and Worden, S. P. 1979, Ap. J., 229, 700.
Kippenhahn, R. 1973, Stellar Chromospheres, ed. S. D. Jordan and E. H. Avrett, NASA SP-317, p. 265.
Kondo, Y., de Jager, C., Hoekstra, R., van der Hucht, K. A., Kamperman, T. M., Lamers, H.J.G.L.M., Modisette, J. L., and Morgan, T. H. 1979, Ap. J., 230, 533.
Kraft, R. P., Preston, G. W., and Wolf, S. C. 1964, Ap. J., 140, 237.
Kuperus, M. 1965, Recherches Astr. Obs. Utrecht, 17, 1.
Kuperus, M. 1969, Space Sci. Rev., 9, 713.
Lemaire, P. and Skumanich, A. 1973, Astr. Ap., 22, 61.
Linsky, J. L. 1977, in The Solar Output and Its Variation, ed. O. R. White (Boulder: Colorado Associated University Press), p. 477.
Linsky, J. L. 1979, in Report of Commission 36 in Transactions of the IAU, 17, in press.
Linsky, J. L. 1980, in Annual Rev. Astr. Ap., 18, in preparation.
Linsky, J. L., and Ayres, T. R. 1978, Ap. J., 220, 619.
Linsky, J. L. and Haisch, B. M. 1979, Ap. J. (Letters), 229, L27.
Linsky, J. L., Hunten, D. M., Sowell, R., Glackin, D. L., and Kelch, W. L. 1979b, Ap. J. Suppl., in press.
Linsky, J. L., Worden, S. P., McClintock, W., and Robertson, R. M. 1979a, Ap. J. Suppl., in press.
Linsky, J. L. et al. 1978, Nature, 275, 389.
Lites, B. W., Shine, R. A., and Chipman, E. G. 1978, Ap. J., 222, 333.
Liu, S. Y. 1974, Ap. J., 189, 359.
Liu, S. Y. and Skumanich, A. 1974, Solar Phys., 38, 109.
LoPresto, J. C. 1971, Pub. A.S.P., 83, 674.
Lutz, T. E. 1970, Ap. J., 75, 1007.
Lutz, T. E., Furenlid, I., and Lutz, J. H. 1973, Ap. J., 184, 787.
Lutz, T. E. and Pagel, B. E. J. 1979, M.N.R.A.S., submitted.
Machado, M. E., Emslie, A. G., and Brown, J. C. 1978, Solar Phys., 58, 363.
Machado, M. E. and Linsky, J. L., 1975, Solar Phys., 42, 395.
McClintock, W., Henry, R. C., Moos, H. W., and Linsky, J. L. 1975, Ap. J., 202, 733.
McClintock, W., Moos, H. W., Henry, R. C., Linsky, J. L., and Barker, E. S. 1978, Ap. J. Suppl., 37, 223.
Mihalas, D. 1970, Stellar Atmospheres (Freeman: San Francisco), p. 330.
Morrison, N. D. and Linsky, J. L. 1978, Ap. J., 222, 723.
Mullan, D. J. 1978, Ap. J., 226, 151.
O'Brien, G. 1979, private communication.
O'Brien, G. and Lambert, D. L. 1979, Ap. J. (Letters), 229, L33.
Pagel, B. E. J. and Wilkins, D. R. 1979, M.N.R.A.S., submitted.
Pasachoff, J. M. 1970, Solar Phys., 12, 202.
Praderie, F. 1973, Stellar Chromospheres, ed. S. D. Jordan and E. H. Avrett, NASA SP-317, p. 79.
Praderie, F. 1977, Mem. S. A. It., 553.
Praderie, F. and Thomas, R. N. 1972, Ap. J., 172, 485.

https://doi.org/10.1017/S0252921100075436 Published online by Cambridge University Press

Praderie, F. and Thomas, R. N. 1976, Solar Phys., 50, 333.
Raymond, J. C. and Dupree, A. K. 1978, Ap. J., 222, 379.
Reimers, D. 1977, Astr. Ap., 57, 395.
Schmitz, F. and Ulmschneider, P. 1979a, Astr. Ap., in press.
Schmitz, F. and Ulmschneider, P. 1979b, Astr. Ap., in press.
Scharmer, G. B. 1976, Astr. Ap., 53, 341.
Shine, R. A. 1975, Ap. J., 202, 543.
Shine, R. A. and Linsky, J. L. 1972, Solar Phys., 25, 357.
Shine, R. A. and Linsky, J. L. 1974, Solar Phys., 39, 49.
Shine, R. A., Milkey, R. W., and Mihalas, D. 1975, Ap. J., 199, 724.
Skumanich, A., Smythe, C., and Frazier, E. N. 1975, Ap. J., 200, 747.
Simon, T., Kelch, W. L., and Linsky, J. L. 1979, Ap. J., submitted.
Simon, T. and Linsky, J. L. 1979, in preparation.
Smith, E., van P. 1960, Ap. J., 132, 202.
Snow, T. P. and Linsky, J. L. 1979, in Proc. Conf. on Astr. Ap. from Spacelab, ed. P. L. Bernacca and R. Ruffini (Dordrecht: Reidel), in press.
Stein, R. F. and Leibacher, J. 1974, Ann Rev. Astr. Ap., 12, 407
Stencel, R. E. 1978, Ap. J. (Letters), 223, L37.
Stencel, R. E. and Mullan, D. J. 1979, Ap. J., submitted.
Thomas, R. N. 1973, Astr. Ap., 29, 297.
Tripp, D. A., Athay, R. G., and Peterson, V. L. 1978, Ap. J., 220, 314.
Ulmschneider, P. 1967, Z. Ap., 67, 193.
Ulmschneider, P. 1971, Astr. Ap., 12, 297.
Ulmschneider, P. 1974, Solar Phys., 39, 327.
Ulmschneider, P. 1979, Space Sci. Rev., in press.
Ulmschneider, P. and Kalkofen, W. 1977, Astr. Ap., 57, 199.
Ulmschneider, P., Schmitz, F., and Hammer, R. 1979, Astr. Ap., in press.
Ulmschneider, P., Schmitz, F., Kalkofen, W., and Bohm, H. U. 1978, Astr. Ap., 70, 487.
Ulmschneider, P., Schmitz, F., Renzini, A., Cacciari, C., Kalkofen, W. and Kurucz, R. L. 1977, Astr. Ap., 61, 515.
Ulrich, R. K. 1976, Ap. J., 210, 377.
Ulrich, R. K. and Knapp, G. R. 1979, Ap. J. (Letters), 230, L99.
van der Hucht, K. A., Stencel, R. E., Haisch, B. M., and Kondo, Y. 1979, Astr. Ap., in press.
Vernazza, J. E., Avrett, E. H., and Loeser, R. 1973, Ap. J., 184, 605.
Vernazza, J. E., Avrett, E. H., and Loeser, R. 1976, Ap. J. Suppl., 30, 1.
Weiler, E. J. and Oegerle, W. R. 1979, Ap. J. Suppl., 39, 537.
White, O. R. and Suemoto, Z. 1968, Solar Phys., 3, 523.
Willstrop, R. V. 1972, private communication.
Wilson, O. C. 1959, Ap. J., 130, 499.
Wilson, O. C. 1966, Science, 151, 1487.
Wilson, O. C. 1978, Ap. J., 226, 379.
Wilson, O. C. and Bappu, M. K. V. 1957, Ap. J., 125, 661.
Wilson, P. R. and Evans, C. D. 1972, Solar Phys., 18, 29.
Withbroe, G. L. and Noyes, R. W. 1977, Ann. Rev. Astr. Ap., 15, 363.
Worden, S. P., Schneeberger, T. J., and Giampapa, M. S. 1979, Ap. J., in press.
Young, A. T. 1979, private communication.
Zirin, H. 1976, Ap. J.,
Zirker, J. B. 1968, Solar Phys., 3, 164.