THE QUIESCENT CHROMOSPHERES AND TRANSITION REGIONS OF ACTIVE DWARF STARS: WHAT ARE WE LEARNING FROM RECENT OBSERVATIONS AND MODELS?

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ABSTRACT

I will review the rapid progress in our understanding of active dwarf stars, which has been stimulated by recent IUE, Einstein, and ground-based observations, by asking a series of questions. The most fundamental question is the extent to which magnetic fields control nonflare phenomena in these stars. There are a number of aspects to this question:

(1) What is the evidence for large scale magnetic structures similar to solar plages in these stars and how does a plage system differ from a quiescent spectrum?

(2) Can the enhanced heating in these stars be explained by solar-like magnetic flux tubes?

(3) What roles do systematic flows play in active dwarf atmospheres?

(4) What is the relation between heating rates in different layers of these stars?

(5) By what mechanisms are active dwarf chromospheres and transition regions heated?

(6) What are semiempirical models telling us about active dwarf stars?

Recent observations are permitting us to begin to answer these questions.

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I. DO MAGNETIC FIELDS CONTROL THE NONFLARE PHENOMENA IN ACTIVE DWARF STARS?

I suspect that there is nearly complete agreement among astronomers studying late-type dwarf stars that the active phenomena observed in these stars are somehow a direct consequence of strong, variable magnetic fields. I have chosen to review the topic of quiescent, that is nonflaring, chromospheres and transition regions (TRs) of active dwarf stars by pointing out the range of phenomena in these stars that are probably magnetic in character and by suggesting how the magnetic fields likely control these phenomena.

This topic is difficult because there exist only a few measurements of magnetic fields in active dwarf stars and none yet for the M dwarfs. Even so, the existing magnetic field measurements (reviewed by Vogt 1982; Marcy 1982) are averages over the stellar surface, whereas the true fields are likely inhomogeneous and filamentary. Furthermore, theoretical calculations of heating processes and the energy balance in magnetic flux tubes, taking into account magnetic forces and realistic flux tube geometries, are extremely difficult. In view of these difficulties, I cannot be rigorous but must instead by speculative, and will follow solar analogies in trying to explain the interesting results coming from IUE and Einstein. There is a danger, however, in this approach as solar analogy may be a poor guide for explaining phenomena on stars with parameters very different from the Sun.

It is important to ask what the properties of stellar chromospheres and TRs would be for stars without magnetic fields. According to the Vogt-Russell theorem (cf. Lang 1980), the mass, age, and initial chemical composition of a star determine its effective temperature, radius, and gravity, and hence its location in the H-R diagram. Thus, for nonmagnetic stars there are unique values for the luminosity and convective zone parameters at each position in the H-R diagram. Furthermore, the atmospheric structure should be relatively uniform across the surface of these stars, except for small variations due to gravity darkening at the poles, meridional circulation, and the spatial variations due to the cellular nature of convection. The nonradiative heating by acoustic waves or other nonmagnetic waves generated by convective motions should still produce chromospheres, TRs, and coronae in late-type stars, but the heating rates should be relatively small. We therefore expect only quiescent outer atmospheric layers that are weak, steady emitters in the ultraviolet and X-rays, are spatially homogeneous, and show few differences between stars of similar effective temperature and gravity.

By contrast with this rather boring picture of idealized, nonmagnetic stellar atmospheres, we know that magnetic flux tubes in the solar atmosphere are the basic structure responsible for atmospheric inhomogeneity, are regions of enhanced nonradiative heating, are the locations of time-variable phenomena on time scales of seconds to months, are regions of important systematic flows, and are characterized by very different energy balance and atmospheric properties than regions of weak fields. The main theme of this review then is to describe and compare the phenomena that are similar in active and quiescent dwarf stars, and to summarize the various roles that magnetic fields likely play in modifying the chromospheres and TRs of the active stars. Some recent reviews relevant to this topic include Dupree (1981;1982), and Linsky (1980;1981a,b,c,d;1982).

II. WHAT IS THE BASIC STRUCTURE OF ACTIVE DWARF ATMOSPHERES?

a) Spatial Inhomogeneity

The best evidence we have for the existence of large scale bright structures in the chromospheres and TRs of stars comes from measurements of periodic variations in the intensity of specific spectral features at their presumed rotational periods. Vaughan et al. (1981), for example, monitored the chromospheric Ca II H and K lines to derive rotational periods of 19 stars, mainly dwarfs of spectral type F6-M0. These data argue conclusively for the inhomogeneous distribution of brightness across the chromospheres of these stars, and solar analogy argues that the structures primarily responsible for this patchiness are bright plage regions that are non-uniformly distributed in longitude and that are long-lived compared to a rotational period. If a star were completely covered with plages or the plages were uniformly distributed in longitude, then there would be no modulated intensity signal to indicate a rotational period. Hallam and Wolff (1981) followed a similar technique using IUE to determine rotational periods of three dwarf stars — 111 Tau (F8 V), ε Eri (K2 V), and 61 Cyg A (K5 V). They observed rotational modulation of intensity in lines of Lyα, Si II 1812 Å, and Mg II 2796 Å. Several such monitoring programs are under way, in some cases with coordinated magnetic field observations to confirm the hypothesis that the plage regions have strong magnetic fields.

Close binary systems with cool components, which are tidally forced to be rapid rotators, typically show bright, ultraviolet emission lines and photometric variability indicative of rotational modulation of dark star spots (e.g. Kunkel 1975; Hall 1981; Vogt 1983). One therefore expects that the ultraviolet emission line flux should vary with rotational phase such that emission line maximum (maximum coverage by plages) corresponds to photometric minimum (maximum coverage by dark star spots). Baliunas and Dupree (1982) tested this correlation for the long-period RS CVn system, λ And (G8 III-IV + ?) and confirmed that the emission lines are strong at photometric minimum and weak at photometric maximum. Marstad et al. (1982) and Byrne et al. (1982) monitored three subgiant RS CVn systems (HR 1099, II Peg, and AR Lac) and the two dwarf binaries BY Dra and AU Mic. They found clear evidence for periodic variability in HR 1099 and II Peg. For HR 1099, the data cover three rotational periods and are consistent, indicating that the plages are long-lived. The II Peg data reveal important clues concerning stellar plages:

(1) The strength of all the II Peg emission lines increases rapidly at orbital phase 0.45, is roughly constant for one-half the period, and then decreases just as rapidly at phase 0.95 (see Fig. 1). This is strong evidence for the rotational modulation of a relatively compact plage group centered at phase 0.70. The compactness of this plage group and the absence of large intensity changes for half a period are important new information.

(2) The increase in emission line strength corresponds to the decrease in photometric brightness (see Fig. 1) measured simultaneously by the FES on IUE, indicating that the plage group overlies dark star spots and thus the plages are regions of strong magnetic fields.

(3) The spectrum of II Peg at plage maximum differs considerably from that at plage minimum (see Fig. 2) in the sense that the high temperature TR lines (C IV 1550 Å, Si IV 1400 Å, and C II 1335 Å) are enhanced by much larger factors than the chromospheric lines (Si II 1812 Å, C I 1657 Å, and Mg II 2800 Å). This phenomenon is seen in solar plages and throughout the IUE data, as we shall see; therefore, it is an important consequence of magnetic fields in stellar atmospheres that requires an explanation.

b) Time Variability

According to our corollary to the Vogt-Russell theorem, nonmagnetic stars emit nearly constant flux, and flux variability, therefore, should be a direct consequence of a quantity not included in the classical theory, namely a magnetic field. Variability on many time scales has already been detected in the chromospheric and TR emission lines in late-type stars. For example, Wilson (1978) discovered periodic variations in the Ca II flux from G-K dwarf stars with periods ~10 years,

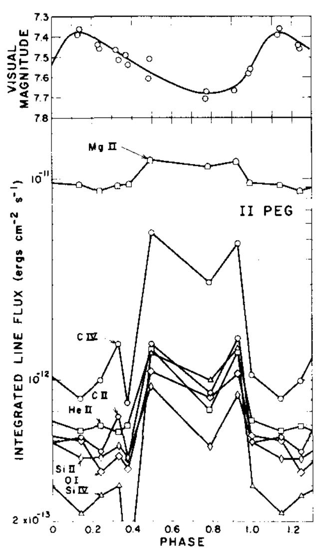

Fig. 1. Observed flux (from Marstad et al. 1982) in the Mg II λ2800, C IV λ1550, He II λ1640, C II λ1335, Si II λ1812, O I λ1304, and Si IV λ1400 features for II Peg as a function of phase. Also given at the top are FES visual magnitudes obtained simultaneously with the IUE spectra.

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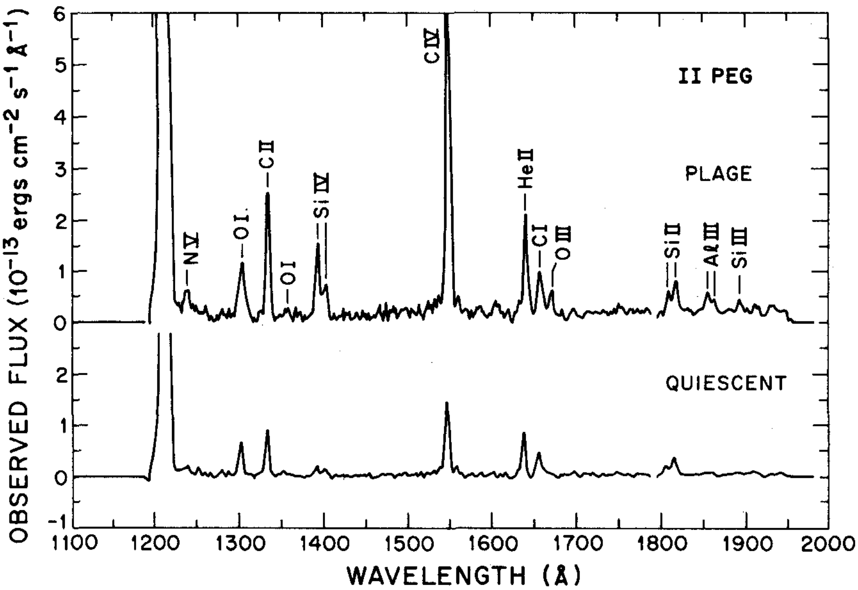

Fig. 2. Composite IUE spectra from Marstad et al. (1982) of the RS CVn-type system II Peg when the plage is on the disk (sum of three spectra) and when the plage is not present (sum of five spectra).

which he ascribed to magnetic cycles. White and Livingston (1981) found similar changes in the solar Ca II line flux between minimum and maximum in the solar cycle, and they argued that these changes are due to differences in the fractional area coverage by plages and not to any changes in the chromospheric network. We believe that the stellar data can be interpreted in a similar way.

Flares, a major topic of this Colloquium, have been detected in IUE spectra of the RS CVn systems UX Ari (Simon, Linsky and Schiffer 1980a) and HR 1099 (Marstad et al. 1982), as well as the dMe flare stars GL 867A (Butler et al. 1981) and Proxima Centauri (Haisch et al. 1982). Such flares probably also are magnetic in character, with the dMe star flares similar to solar flares and the RS CVn flares perhaps involving reconnection between flux tubes of the two stars. In addition to the expected enhancement of the emission lines, Butler et al. (1981) found continuous ultraviolet emission during a flare on GL 867A. One property seen in both the dMe and RS CVn flares is the relative enhancement of the TR lines compared to the chromospheric emission lines. This is illustrated by comparing the IUE spectra of HR 1099 during a flare and at quiescent times immediately before and after the flare (see Fig. 3). This important property will be discussed in §VI below. Also, Byrne et al. (1982) detected emission line variability in BY Dra and AU Mic, on time scales of minutes to hours, and Baliunas et al. (1981) detected similar variability in ε Eri.

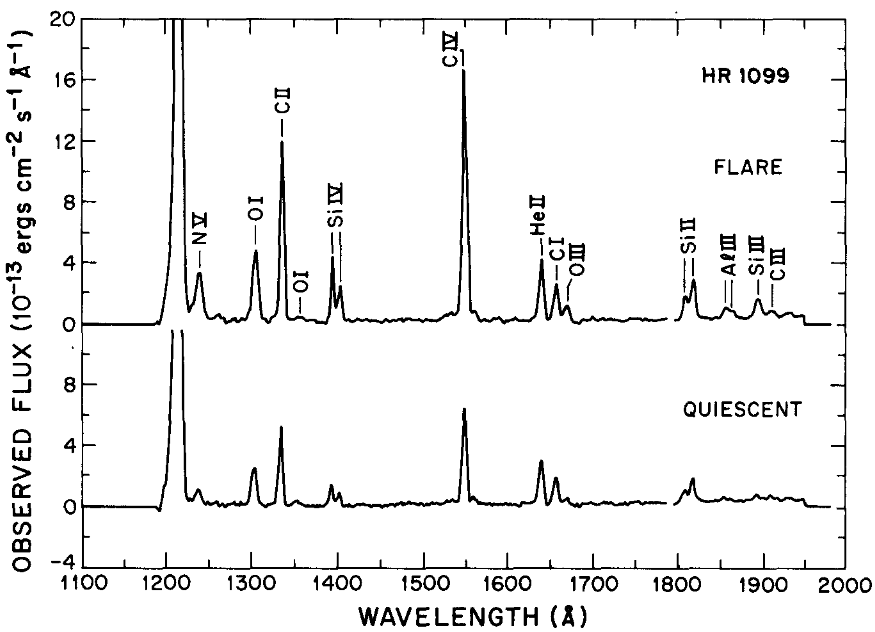

Fig. 3. IUE spectra of the RS CVn-type system HR 1099 obtained during a flare and when the system was quiescent.

III. CAN THE ENHANCED HEATING IN ACTIVE DWARF STARS BE EXPLAINED BY SOLAR-LIKE FLUX TUBES?

A vital role played by the magnetic field is to enhance the local nonradiative heating rate in the chromosphere and higher layers above that which occurs in regions of weak or no fields. This conclusion is based on the tight spatial correlation of bright chromospheric emission with photospheric magnetic field strength (e.g. Skumanich, Smythe and Frazier 1975). Stein (1981) has summarized the arguments why slow mode MHD waves are the most likely heating mechanism for those regions in stellar chromospheres that have strong magnetic fields.

It is important to go beyond this general conclusion to a quantitative evaluation of the nonradiative heating rates at different atmospheric layers in different types of stars. One way of comparing the nonradiative heating rates is by plotting emission line surface fluxes, the flux per unit area of the star, as a function of mean temperature of formation of each line in different stars. Linsky et al. (1982) compared line surface fluxes for nine active chromosphere dwarf stars and six quiet chromosphere dwarf stars of spectral types G2-M5.6e using IUE observations. The surface fluxes of these stars divided by the mean quiet Sun values are shown in Figure 4. Several conclusions can be drawn from these data:

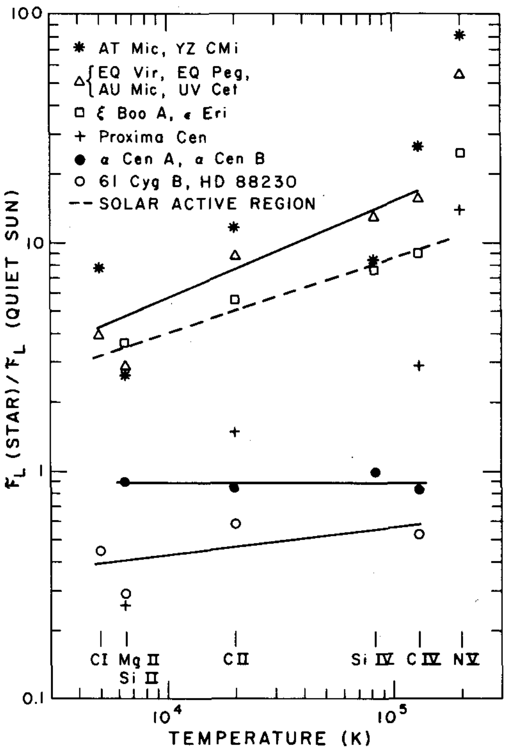

Fig. 4. Ratios of emission-line surface fluxes from Linsky et al. (1982) for six groups of stars and a bright solar active region relative to the quiet Sun. The stars are grouped according to their C IV ratios into three groups of dMe stars (AT Mic and YZ CMi; EQ Vir, EQ Peg, AU Mic, and UV Cet; Proxima Centauri), the dM stars (61 Cyg B and HD 88230), the active G-K dwarfs (ξ Boo A and ε Eri), and the quiet G-K dwarfs (α Cen A and α Cen B). Straight lines are drawn to indicate rough trends in the data for several groups of stars. The data for ξ Boo A and ε Eri are similar to those for a solar active region.

(1) The surface fluxes of the M dwarf stars with the weakest emission lines are about a factor of three below the mean quiet Sun. These stars likely have very weak magnetic fields with few plage regions, and since 61 Cyg B (K7 V) shows rotationally modulated Ca II emission (Vaughan et al. 1981), the plage regions on these stars are intrinsically fainter (implying lower heating rates) than the mean quiet Sun.

(2) The two stars most like the Sun [α Cen A (G2 V) and α Cen B (K1 V)] have surface flux ratios close to unity independent of temperature, suggesting magnetic fields similar to those on the Sun.

(3) The active chromosphere stars, including the dMe stars, have surface flux ratios that increase from 3-8 in the chromosphere to 10-100 at 2×10^5 K in the TR. Similar trends in the surface flux ratios are detected in other active stars including: (a) G giants and supergiants (e.g. Hartmann, Dupree and Raymond 1982; Stencel et al. 1982a,b) for which the ratios increase from 1 in the chromosphere to about 10 in the TR, and (b) RS CVn systems (e.g. Simon and Linsky 1980) for which the ratios increase from 10-20 in the chromosphere to as large as 600 in the TR. T Tauri stars (e.g. Imhoff and Giampapa 1982) also show very large ratios.

To what extent can we explain these large surface flux ratios by assuming that the active stars are mostly covered by solar-like plage

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regions? Included in Figure 4 is a dashed line indicating the surface flux ratios for a bright solar plage (Vernazza and Reeves 1978). Since the active M dwarf stars, RS CVn binaries, and T Tauri stars lie above this line, even complete coverage by solar-like plages cannot explain the large surface flux ratios. Furthermore, there is evidence described in the previous section (see Fig. 1) that these active stars also have a patchy distribution of emitting regions.

There is another important point, however, that must be considered. Solar plages are not homogeneous regions, but instead consist of many individual magnetic flux tubes that are not resolved in the existing data as their widths are much smaller than 1 arcsec (Frazier and Stenflo 1973; Stenflo 1973). By comparison, the solar plage data in Figure 4 were obtained by the EUV spectrometer-spectroheliometer on *Skylab*, which had a spatial resolution of 5×5 arcsec^2 (Vernazza and Reeves 1978). The High Resolution Telescope Spectrograph (HRTS) experiment (cf. Brueckner, Bartoe and Van Hoosier 1977; Basri et al. 1979) obtained ultraviolet solar spectra with a resolution of 1×1 arcsec^2. These data show a range of intensities between the brightest portions of plages and the darkest quiet regions that is a factor of 100 in the C IV 1548 Å line (Brueckner, private communication). Schindler et al. (1982) used HRTS data to show that the He II 1640 Å line in the brightest plage regions is a factor of 50 brighter than the mean quiet Sun value. Even in these data, the magnetic flux tubes are not resolved, and therefore we cannot yet say whether the observed flux ratios for chromospheric and TR lines in the active dwarf stars, RS CVn systems, and T Tauri stars can be explained by solar-like flux tubes covering portions of their surfaces. It is interesting, however, that the TR line widths observed by Ayres et al. (1982a) are no different in three active dwarf stars (χ^1 Ori, ξ Boo A, ε Eri) compared with two quiet dwarf stars (α Cen A, α Cen B), implying that there may be no great difference between magnetic flux tubes in the two types of stars except for the fractional surface coverage.

IV. WHAT ROLES DO SYSTEMATIC FLOWS PLAY IN ACTIVE DWARF STAR ATMOSPHERES?

Perhaps the most exciting and unexpected discovery by *IUE* concerning cool stars is the very recent evidence concerning flows of the 10^5 K plasma. Stencel et al. (1982a,b) measured line centroid velocities for 18 lines in the SWP high dispersion spectrum of the supergiant β Dra (G2 Ib) by fitting least-squares Gaussians to the observed profiles. They estimated the velocity at the base of the chromosphere using eight subordinate or intersystem lines of C I, O I, S I, and Cℓ I. A measurement of the mean velocity of ten high excitation lines of He II, C III, C IV, N V, O III, Si III, and Si IV gave a relative motion of the high and low excitation lines of 20 ± 4 km s^{-1}. The TR plasma is thus flowing down into the star, and we are observing a stellar "antiwind."

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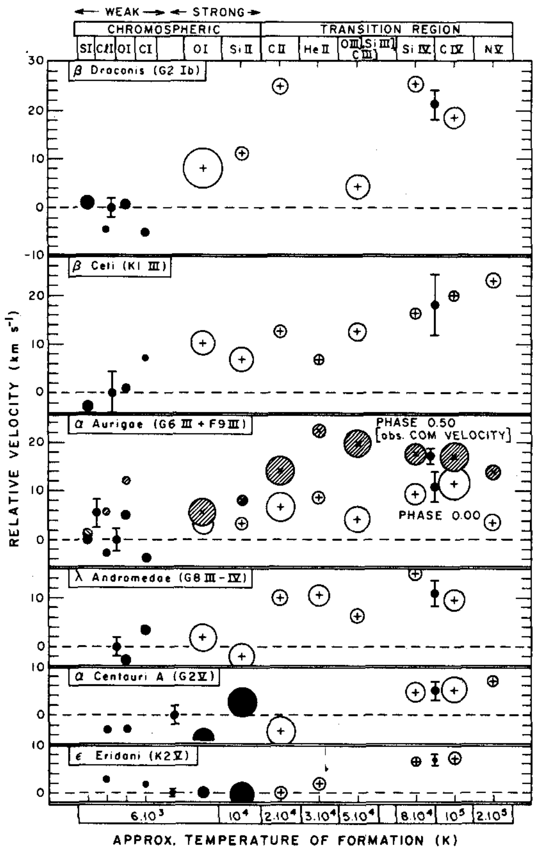

Fig. 5. A comparison of the line-of-sight velocities of high and low excitation lines obtained by Ayres et al. (1982b). The size of the bubbles indicates the total relative flux of the lines of a given ion. The filled circles are narrow chromospheric lines used in obtaining the flux-weighted mean zero velocity, and the standard error of the mean is indicated by the error bars to the left. The open circles indicate the mean velocities of higher excitation lines, and the error bars to the right, indicate the flux-weighted mean velocity of the four C IV and Si IV lines and the error of this mean (including the error of the zero velocity determination). The partially filled bubbles for Capella indicate velocities obtained from a small aperture observation at phase 0.50. These velocities were placed on an absolute center of mass velocity scale by comparison with a platinum lamp exposure obtained after the Capella exposure. Note that the velocity difference between high and low excitation lines is the same for both Capella data sets, but the small aperture data indicate that the chromospheric lines also appear to exhibit a small red shift.

This was an unexpected discovery, because we are accustomed to studying outflows (winds) in luminous late-type stars with mass loss rates that generally increase towards the upper right-hand corner of the H-R diagram. To confirm this result, Ayres et al. (1982b) then re-examined high dispersion IUE observations of active chromosphere stars, and found that β Ceti (K1 III), α Aur Ab (F9 III), λ And (G8 III-IV+?), and ε Eri (K2 V) also show net redshifts of TR emission lines relative to chromospheric lines (see Fig. 5). Even the quiescent dwarf star α Cen A (G2 V) shows a redshift at the 2.5σ level. They also reobserved α Aur Ab during conjunction (when both components of the α Aur A system have the same radial velocity) through the IUE small aperture to obtain an absolute velocity scale, with the result (see Fig. 5) that the chromospheric lines have an absolute redshift of about 5 km s^{-1} and the TR lines have an absolute redshift of 17 km s^{-1}.

At first sight, the idea of downflows ("antiwinds") in stars of a wide range of luminosities seems preposterous, but solar downflows of 10-20 km s^{-1} are typically seen in such lines as C IV and Si IV in the OSO-8 (Roussel-Dupré and Shine 1982), Skylab (Doschek, Feldman and Bohlin 1976; Feldman, Cohen and Doschek 1982), and HRTS (Brueckner 1981; Dere 1982) data. These downflows are best seen in observations of the chromospheric network and plages, where magnetic flux tubes are located, but the downflows are detected even in integrated light because the downflowing regions are bright in ultraviolet emission lines and thus make large contributions to the integrated light line profiles. An interesting result seen in the high spatial resolution HRTS data is that the downflow velocities increase with temperature from 10^4 to 10^5 K (Dere 1982), but Doschek and Feldman (1977) measured small downflow velocities (≈5 km s^{-1}) even for the chromospheric Mg II lines in the solar supergranulation network. Ayres et al. (1982b) detected the same increase in absolute downflow velocities between the chromosphere and TR of α Cen Ab.

Several explanations have been proposed. The flows may be produced by coronal material that is cooling, condensing, and falling back down to the chromospheric footpoints of magnetic loops after an interruption of the internal heating source (Rosner, Tucker and Vaiana 1978). The downflows may be part of a circulation pattern within large flux tubes for which the upleg portion of the circulation is too cool (spicules, for example) to be visible in C IV (Pneuman and Kopp 1977). It is even possible that material is flowing upward at C IV temperatures more rapidly than it is flowing downward, such that the decrease in density required by mass conservative flow will greatly reduce the emission measure of the upward moving gas (since $F_L \sim n_e^2$), resulting in a net redshift (Doschek, Feldman and Bohlin 1976). In any case, the appearance of redshifts is clear evidence for the existence of strong, closed magnetic field structures in stellar atmospheres.

There are important consequences of redshifts, which we henceforth interpret as true downflows of material in magnetic flux tubes:

(1) The existence of downflowing gas implies an enthalpy flux of heat from the corona that must be included in any study of the energy balance of a stellar TR. Pneuman and Kopp (1977), for example, demonstrated that the enthalpy flux in a typical solar downflow exceeds the thermal conductive flux.

(2) Since many stars should have both downflows and upflows and since the downflowing regions probably emit brighter emission lines, one should be especially careful in estimating stellar mass loss rates from integrated disk Doppler shifts. The Sun does have a wind!

V. WHAT IS THE RELATION BETWEEN HEATING RATES IN DIFFERENT LAYERS OF ACTIVE DWARF STARS?

Using SWP low dispersion observations of 28 cool stars, Ayres, Marstad and Linsky (1981) showed that the emission line fluxes of chromospheric and TR lines are not linearly correlated (see Fig. 6). Instead, as one goes to stars with brighter chromospheric emission (i.e. greater $f_{\mathrm{Mg\ II}}/\ell_{\mathrm{bol}}$), the TR lines brighten even faster such that $(f_{\mathrm{C\ IV}}/\ell_{\mathrm{bol}}) \sim (f_{\mathrm{Mg\ II}}/\ell_{\mathrm{bol}})^{1.5}$ and the coronal X-ray flux brightens faster yet. Walter, Basri and Laurent (1982) and Oranje, Zwaan and Middlekoop (1982) found similar results. This phenomenon was previously noted in the comparison of the II Peg plage to quiescent spectra (Fig. 2), and the flare to quiescent spectra for HR 1099 (Fig. 3) and the dMe star Proxima Centauri (Haisch et al. 1982). It is also seen by comparing solar plage to quiescent spectra and thus must be a general property of stellar atmospheres.

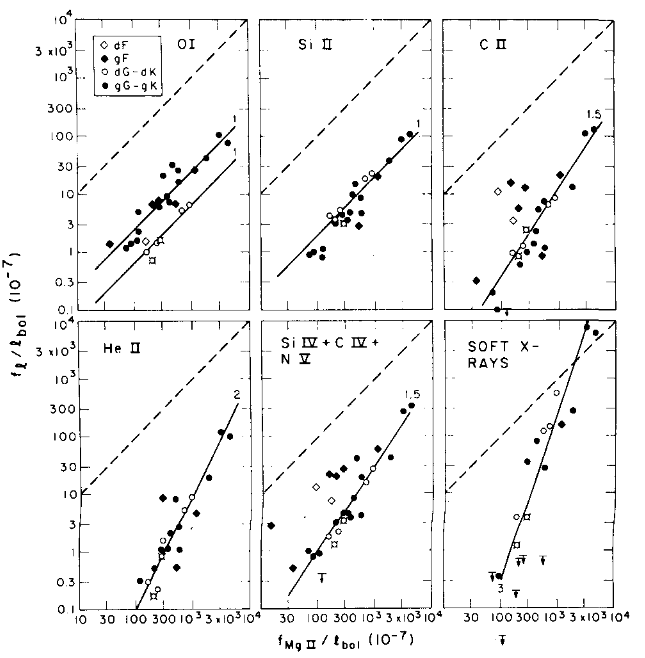

Fig. 6. Correlation plots of chromospheric, TR, and coronal fluxes compared to the Mg II line relative flux (Ayres, Marstad and Linsky 1981).

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Hammer, Linsky and Endler (1982) proposed an explanation for this phenomenon. They pointed out that the radiative loss rate in TR emission lines for realistic magnetic flux tube models (e.g. Rosner, Tucker and Vaiana 1978) depends on pressure to a higher power than the corresponding radiative loss rate in chromospheric emission lines (e.g. models in Vernazza et al. 1981). Thus, with increasing mechanical energy flux, the location of the base of the TR (the intersection point of the curves in Fig. 7) moves to larger pressures and the TR lines brighten by a larger factor than the chromospheric lines.

For their sample of ten active dwarf stars (including solar plages), Linsky et al. (1982) showed that the fraction of the stellar flux emitted by the chromosphere increases a factor of 5 as T_{eff} decreases from 5770 to 3200 K, but the fraction emitted by the TR increases a factor of 100. Thus the relative heating rates in different atmospheric layers may depend on T_{eff} as well as the magnetic field.

VI. BY WHAT MECHANISMS ARE ACTIVE DWARF STAR CHROMOSPHERES AND TRANSITION REGIONS HEATED?

Linsky and Ayres (1978) showed, on the basis of Mg II fluxes, that the chromospheric radiative loss rate per unit surface area of a star shows no dependence on stellar gravity. This implies that the heating rate is also independent of gravity, contrary to computations for the dissipation of shocks produced by nonmagnetic acoustic waves, which imply a g^{-1} dependence and a T_{eff} dependence different than the observed. This result was modified slightly by Stencel et al. (1980),

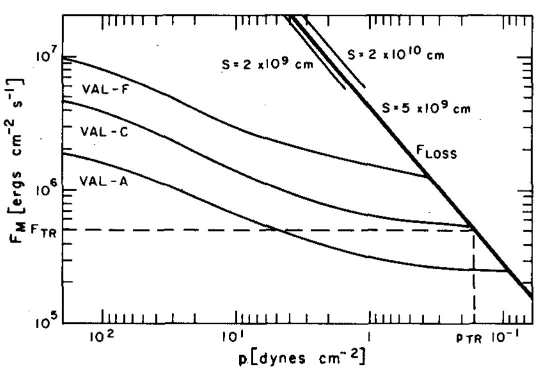

Fig. 7. Total mechanical energy flux F_M as a function of the pressure p for the chromospheric models A, C, and F of Vernazza, Avrett and Loeser (1981). The transition region lies at the intersection point with a curve (drawn heavy) that gives the total energy losses F_{Loss} of the transition region and corona as a function of the base pressure and the semilength S of the coronal loops (cf. Rosner, Tucker and Vaiana 1978). From Hammer, Linsky and Endler (1982).

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who showed that _IUE_ observations of cool supergiants are consistent with a small increase ($\sim g^{-1/4}$) in the heating rate as the gravity decreases. These data and the observed large range in heating rates for stars of similar T_{eff} and g, provide important clues on the chromospheric heating mechanism.

Stein (1981) and Ulmschneider and Stein (1982) derived approximate scaling laws for how the emitted flux from a chromosphere (F_{chromo}) depends on T_{eff}, g, and B for four wave heating modes (acoustic, Alfvén, acoustic slow, and magnetic fast). Only the acoustic slow mode for weak or equipartition magnetic fields predicts a relation

$$\frac{F_{chromo}}{\sigma T_{eff}^4} \approx g^{-0.192}\, T_{eff}^{2.13} \quad ,$$

consistent with the above data. In addition, the chromospheric heating rate will depend on the fractional surface coverage by the magnetic flux tubes, which can explain the range of radiative loss rates in stars of similar T_{eff} and g. Thus stellar observations have played a major role in guiding theoretical calculations by pointing out the important role played by magnetic fields.

In addition to acoustic slow mode heating, the previously discussed enthalpy flux carried by downflows may be an important heating source in the TRs of flux tubes (e.g. Wallenhorst 1980,1981). Also, Cram (1982) has pointed out that the absorption of coronal X-rays in the quiescent chromospheres of dMe stars may be an important chromospheric heating source. In Table 1 we compare surface fluxes in soft X-rays, C IV λ1550 (the largest TR emitter), the Mg II resonance lines (the largest emitters in solar-like chromospheres), and the Balmer

Table 1. Comparison of Surface Fluxes for Active and Quiescent Dwarf Stars

Star	Spectral Type	Surface Fluxes (ergs cm^{-2} s^{-1}) F_X	$F_{C\ IV}$	$F_{Mg\ II}$	$F_{Balmer\ Lines}$
α Cen A	G2 V	6.6(3)	5.9(3)	1.1(6)	--
ξ Boo A	G8 V	3.1(6)	8.8(4)	4.5(6)	--
α Cen B	K1 V	2.6(4)	4.6(3)	9.5(5)	--
ε Eri	K2 V	4.9(5)	3.3(4)	2.4(6)	--
EQ Vir	K5e V	7.8(6)	1.4(5)	2.0(6)	--
AU Mic	M1.6e V	1.6(7)	1.3(5)	8.9(5)	4.5(6)
EQ Peg	M3.7e V	3.8(6)	7.5(4)	--	--
Proxima Cen	M5.5e V	1.2(6)	1.9(4)	1.0(5)	--
UV Cet	M5.6e V	1.1(6)	5.9(4)	1.4(5)	2.4(6)

Note: In columns 3-7, the figure in parentheses is the power of ten.

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lines (the largest emitters in dMe star chromospheres) from data presented by Linsky et al. (1982), Vaiana et al. (1981), and Helfand and Caillault (1982). Assuming that as much X-ray flux is absorbed in the chromosphere as leaves the star, these data suggest that Cram (1982) may be correct. Since solar coronal X-ray emission is almost entirely confined to magnetic loops, even the nonmagnetic regions of dMe star chromospheres may be heated indirectly by magnetically controlled plasma.

VII. WHAT ARE SEMIEMPIRICAL MODELS OF ACTIVE DWARF STARS TELLING US?

Until now, we have summarized the different qualitative roles played by magnetic fields. In addition, several investigators have built detailed models of solar and stellar atmospheres for regions in which fields are important. Chapman (1981), Ulmschneider and Stein (1982), and Linsky (1980) have reviewed this work. No models are wholly satisfactory as yet due to gross simplifications in the assumed geometry, treatment of the radiative transfer equation, and the strong dependence of the magnetic flux tube parameters on the assumed filling factor, but I will mention those trends in the models that are likely to be valid:

a) One-Component Atmospheric Models

The simplest approach is to construct a one-component model atmosphere to match line profiles and fluxes for the brightest regions of a solar plage or the integrated flux of a star with very bright emission lines. Since the data are spatial averages including magnetic flux tubes (the active component) and nonmagnetic plasma (the quiet component) plasma, the derived differences between the active model and the reference quiet Sun or star model are lower limits to the true differences between the properties of magnetic flux tubes and the nonmagnetic regions. Thus we need to extrapolate these trends to the case of complete filling of the aperture by flux tubes.

One-component models of solar plages include the work of Shine and Linsky (1974) using the Ca II lines, Morrison and Linsky (1978) and Kelch and Linsky (1978) using the Mg II lines, Basri et al. (1979) using Lα, and Vernazza et al. (1981) using a number of continuum and emission line features. These models have a number of elements in common that are illustrated in Figure 8:

(1) The minimum temperature (T_{min}) reached between the photosphere and chromosphere is enhanced by several hundred degrees (270 K in the Vernazza et al. Model F and about 200 K in the Morrison-Linsky models) compared to the quiet Sun. There is also considerable enhancement of temperature, and thus nonradiative heating, in the upper layers of the photosphere.

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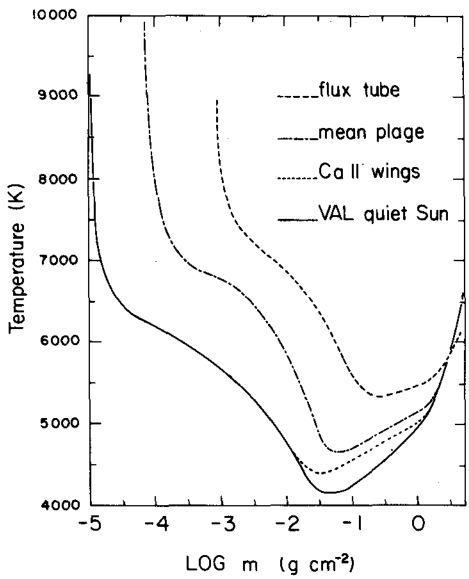

Fig. 8. Plage, flux tube, and quiet Sun models. The solid line is the VAL quiet Sun model. The short dashed lines (Ca II wings) represent a modification of the VAL designed to reproduce the Ca II H and K damping wings. The dash-dot curve is a plage model based on H I $L\alpha$, Ca II K, and Mg II k data obtained by the French (LPSP) experiment on OSO-8. The long dashed (higher) curve represents a flux tube model with a chromospheric portion matching the OSO-8 plage profiles with a 20% filling factor. The photospheric portion ($m > 0.3$ g cm^{-2}) is similar to the class of flux tube models advocated by Chapman (1977). From Chapman (1981), courtesy of Colorado Associated University Press.

(2) The location of T_{min} is displaced inward to larger values of column mass density (m); for example, T_{min} is deeper by 40 km and $m(T_{min})$ increases from 0.05 to 0.08 g cm^{-2} between the quiet Sun (Model C) and Model F in the Vernazza et al. grid.

(3) Similarly, the location of the steep rise in temperature beginning at 8000 K and extending through the TR is also displaced inwards to larger values of mass column density. For example, the grid point corresponding to 10,000 K is located 40 km deeper and $m(T = 10^4$ K) increases from 6×10^{-6} to 1.2×10^{-5} g cm^{-2} between the mean quiet Sun and Model F in the Vernazza et al. grid. In the Shine and Linsky (1974) grid the range in $m(T = 10^4$ K) is nearly a factor of 40. Since the temperature rises steeply in all TR models, the TR pressure ($P_{TR} \approx m(T = 10^4$ K)g) is nearly constant for each model. Thus a sequence of models with increasing P_{TR} typically produces a sequence of emission lines with increasing flux.

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(4) Different authors have assumed different functional forms of the temperature structure, T(m), between the T_{min} and the top of the chromosphere ($T \approx 10^4$ K), but a general result is that T(m) and the local electron density at each column mass density are larger for models with greater m($T = 10^4$ K) values. Thus, typical chromospheric lines like Ca II H and K, Mg II h and k, Lα, and Si II $\lambda\lambda$1808, 1816 brighten as m($T = 10^4$ K) increases.

(5) Avrett (1981) computed radiative loss rates for the five Vernazza et al. models, the Basri et al. (1979) plage model, a flare model from Machado et al. (1980), and two stars (α Boo and λ And). For the Vernazza et al. models and the plage model, Ca II and Mg II are the dominant emitters, although hydrogen becomes important at the base of the TR. Thus, the observed Ca II and Mg II surface fluxes in the Sun and solar-like stars should be accurate diagnostics of the chromospheric heating rate as had been assumed previously, but, for the dMe stars, the Balmer lines are more important chromospheric emitters (Linsky et al. 1982).

To what extent do models of active chromosphere stars show properties similar to the models of solar plages? Linsky (1980) and Ulmschneider and Stein (1982) have reviewed this question. There are three groups of models that can be used to answer it: models of F-K dwarf stars (Kelch, Linsky and Worden 1979; Simon, Kelch and Linsky 1980b), models of dM and dMe stars (Giampapa, Worden and Linsky 1982), and models of RS CVn-type active subgiants (Simon and Linsky 1980; Baliunas et al. 1979). Evidence for enhanced heating in the upper photosphere and temperature minimum region is clearly shown in the dMe models and perhaps also in the active F-K dwarfs. In addition, the dMe stars and the active G-K dwarfs (see also Ayres et al. 1982a) show broader base widths of the Ca II and Mg II resonance lines, indicating that the column mass density at the temperature minimum is systematically larger in stars with enhanced heating. Finally, all of these active star models have m($T = 10^4$ K) similar to solar plages, so that TR pressures are enhanced over quiet stars with similar T_{eff} and gravity. Thus, the differences between solar plages and quiet models are repeated in the active and quiet late-type stars.

Fosbury (1974) and Cram and Mullan (1979) showed that the Balmer lines are useful diagnostics of chromospheric structure in M dwarfs; in particular, as the amount of chromospheric material in an M dwarf model increases, the Hα line first becomes a deeper absorption feature and then goes into emission. Models of dM and dMe stars computed by Kelch et al. (1979) and Giampapa et al. (1982) to match the Ca II lines show this behavior. In the solar context, Basri et al. (1979) found that the peculiar property of the Hα line in being relatively bright at line center and dark at ±0.5 Å in plages compared to the quiet Sun can be simply explained as a consequence of their different atmospheric structure.

b) Two-Component Atmospheric Models

Chapman (1981) conclusively argued that no one-component model can accurately represent the properties of unresolved flux tubes, but instead the true models for flux tubes must be more extreme versions of the one-component plage models. Three approaches have been followed in estimating flux tube properties:

(1) To estimate the factor by which flux tubes fill the aperture and then to solve for the flux tube parameters assuming that the remaining portion of the aperture is represented by a quiet atmosphere model. Chapman (1981) derived such a flux tube model from OSO-8 plage spectra of the Lyα, Ca II, and Mg II lines assuming a 20% filling factor (see Fig. 8). His solar flux tube model has T_{min} enhanced by 1200 K, $m(T_{min})$ displaced inwards from 0.04 to 0.3 g cm^{-2}, chromospheric temperatures enhanced by nearly 2500 K, and $m(T = 10^4$ K) displaced inwards from 1×10^{-5} to 1×10^{-3} g cm^{-2}.

(2) To assume a diverging flux tube in horizontal pressure equilibrium (gas and magnetic forces) with the surrounding nonmagnetic atmosphere. Chapman (1977,1979) matched spatially averaged spectra by assuming a quiet model and solving for the parameters of the flux tubes assuming a value for the base magnetic flux.

(3) To assume a geometry with isolated flux tubes embedded in a nonmagnetic medium and then to solve the transfer equation in two dimensions including the horizontal flow of radiation. Two examples are the work of Stenholm and Stenflo (1977) and Owocki and Auer (1980). This approach increases the computational complexity, but it is probably a necessary complication in the chromosphere where most lines are effectively thin and thus photoexcitation from adjacent structures may be important.

VIII. SOME SUGGESTIONS FOR FUTURE WORK

I began this talk by mentioning some of the inherent difficulties in this topic, and I suspect that you now appreciate what I meant. While we have made real progress recently in identifying the roles played by magnetic fields in stellar chromospheres and TRs, we now recognize how little we know. Let me conclude by stating how we will probably make real progress in this area:

(1) We must resolve individual flux tubes on the Sun in order to derive their physical properties in a definitive way. I anticipate that this will be the most important accomplishment of the Solar Optical Telescope (SOT) when it flies at the end of this decade.

(2) I suspect that future high spectral resolution stellar observations with IUE and Space Telescope will reveal new phenomena and trends with stellar parameters that will point towards the important physical processes which future theoretical studies must include.

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(3) We must elucidate the basic physical processes responsible for downflows in flux tubes.

(4) Even though heating processes will probably remain poorly understood for some time, it is nevertheless important to model magnetic flux tubes properly, taking into account the energy balance, dynamics, and radiative transfer for parameterized heating rates. It is important to study the stability of such models and to look for unique signatures of the location and mechanism of the heating.

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REFERENCES

Avrett, E.H.: 1981, in "Solar Phenomena in Stars and Stellar Systems," eds. R. M. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 173.
Ayres, T.R., Linsky, J.L., Simon, T., Jordan, C., and Brown, A.: 1982a, in preparation.
Ayres, T.R., Marstad, N.C., and Linsky, J.L.: 1981, Ap. J. 247, p. 545.
Ayres, T.R., Stencel, R.E., Linsky, J.L., Simon, T., Jordan, C., Brown, A., and Engvold, O.: 1982b, in preparation.
Baliunas, S.L., Avrett, E.H., Hartmann, L., and Dupree, A.K.: 1979, Ap. J. (Letters) 233, p. L129.
Baliunas, S.L., and Dupree, A.K.: 1982, Ap. J. 252, p. 668.
Baliunas, S.L., Hartmann, L., Vaughan, A.H., Liller, W., and Dupree, A.K.: 1981, Ap. J. 246, p. 473.
Basri, G.S., Linsky, J.L., Bartoe, J.-D.F., Brueckner, G.E., and Van Hoosier, M.E.: 1979, Ap. J. 230, p. 924.
Brueckner, G.E.: 1981, in "Solar Active Regions," ed. F. Q. Orrall (Boulder: Colorado Assoc. Univ. Press), p. 113.
Brueckner, G.E., Bartoe, J.-D.F., and Van Hoosier, M.E.: 1977, in "Proceedings of the OSO-8 Workshop," eds. E. Hansen and S. Schaffner (Boulder, LASP), p. 380.
Butler, C.J., Byrne, P.B., Andrews, A.D., and Doyle, J.G.: 1981, Monthly Notices Roy. Astron. Soc. 197, p. 815.
Byrne, P.B., Butler, C.J., Andrews, A.D., Linsky, J.L., Simon, T., Marstad, N., Rodono, M., Blanco, C., Catalano, S., and Marilli, E.: 1982, in "Proceedings of the Third European IUE Conference," in press.
Chapman, G.A.: 1977, Ap. J. Suppl. Ser. 33, p. 35.
Chapman, G.A.: 1979, Ap. J. 232, p. 923.
Chapman, G.A.: 1981, in "Solar Active Regions," ed. F. Q. Orrall (Boulder: Colorado Assoc. Univ. Press), p. 43.
Cram, L.E.: 1982, Ap. J. 253, p. 768.
Cram, L.E. and Mullan, D.J.: 1979, Ap. J. 234, p. 579.

Dere, K.: 1982, Solar Phys. 77, p. 77.
Doschek, G.A. and Feldman, U.: 1977, Ap. J. Suppl. 35, p. 471.
Doschek, G.A., Feldman, U., and Bohlin, J.D.: 1976, Ap. J. (Letters) 205, p. L177.
Dupree, A.K.: 1981, in "Solar Phenomena in Stars and Stellar Systems," eds. R. M. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 407.
Dupree, A.K.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research" (in press).
Feldman, U., Cohen, L., and Doschek, G.A.: 1982, Ap. J. 255, p. 325.
Fosbury, R.A.E.: 1974, Monthly Notices Roy. Astron. Soc. 169, p. 147.
Frazier, E.N. and Stenflo, J.O.: 1973, Solar Phys. 27, p. 330.
Giampapa, M.S., Worden, S.P., and Linsky, J.L.: 1982, Ap. J. (in press).
Haisch, B.M., Linsky, J.L., Bornmann, P.L., Stencel, R.E., Golub, L., and Antiochos, S.K.: 1982, Ap. J. (submitted).
Hall, D.S.: 1981, in "Solar Phenomena in Stars and Stellar Systems," eds. R. M. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 431.
Hallam, K.L. and Wolff, C.L.: 1981, Ap. J. (Letters) 248, p. L73.
Hammer, R., Linsky, J.L., and Endler, F.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research" (in press).
Hartmann, L., Dupree, A.K., and Raymond, J.C.: 1982, Ap. J. 252, p. 214.
Helfand, D.J. and Caillault, J.P.: 1982, Ap. J. 253, p. 760.
Imhoff, C.L. and Giampapa, M.S.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research" (in press).
Kelch, W.L. and Linsky, J.L.: 1978, Solar Phys. 58, p. 37.
Kelch, W.L., Linsky, J.L., and Worden, S.P.: 1979, Ap. J. 229, p. 700.
Kunkel, W.W.: 1975, in "Variable Stars and Stellar Evolution," eds. V. E. Sherwood and L. Plaut (Dordrecht: Reidel), p. 15.
Lang, K.R.: 1980, "Astrophysical Formulae," 2nd ed. (Berlin: Springer-Verlag), p. 510.
Linsky, J.L.: 1980, Ann. Rev. Astr. Ap. 18, p. 439.
Linsky, J.L.: 1981a, in "Solar Phenomena in Stars and Stellar Systems," eds. R. M. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 99.
Linsky, J.L.: 1981b, in "Effects of Mass Loss on Stellar Evolution," eds. C. Chiosi and R. Stalio (Dordrecht: Reidel), p. 187.
Linsky, J.L.: 1981c, in "Physical Processes in Red Giants," eds. I. Iben, Jr. and A. Renzini (Dordrecht: Reidel), p. 247.
Linsky, J.L.: 1981d, in "X-ray Astronomy in the 1980's," NASA Technical Memorandum 83848, p. 13.
Linsky, J.L.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research" (in press).
Linsky, J.L. and Ayres, T.R.: 1978, Ap. J. 220, p. 619.
Linsky, J.L., Bornmann, P.L., Carpenter, K.G., Wing, R.F., Giampapa, M.S., and Worden, S.P.: 1982, Ap. J. (in press).
Machado, M.E., Avrett, E.H., Vernazza, J.E., and Noyes, R.W.: 1980, Ap. J. 242, p. 336.
Marcy, G.W.: 1983, in "Solar and Stellar Magnetic Fields: Origins and Coronal Effects (Proceedings of IAU Symp. 102, J. Stenflo(ed.)).
Marstad, N. et al.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research" (in press).
Morrison, N.D. and Linsky, J.L.: 1978, Ap. J. 222, p. 723.
Oranje, B.J., Zwaan, C., and Middelkoop, F.: 1982, Astr. Ap. (in press).

Owocki, S.P. and Auer, L.H.: 1980, Ap. J. 241, p. 448.
Pneuman, G.W. and Kopp, R.A.: 1977, Astr. Ap. 55, p. 305.
Rosner, R., Tucker, W.H., and Vaiana, G.S.: 1978, Ap. J. 220, p. 643.
Roussel-Dupre, D. and Shine, R.A.: 1982, Solar Phys. 77, p. 329.
Schindler, M., Kjeldseth-Moe, O., Bartoe, J.-D.F., Brueckner, G.E., and Van Hoosier, M.E.: 1982, Ap. J. (submitted).
Shine, R.A. and Linsky, J.L.: 1974, Solar Phys. 39, p. 49.
Simon, T., Kelch, W.L., and Linsky, J.L.: 1980b, Ap. J. 237, p. 72.
Simon, T. and Linsky, J.L.: 1980, Ap. J. 241, p. 759.
Simon, T., Linsky, J.L., and Schiffer F.H. III: 1980a, Ap. J. 239, p. 911.
Skumanich, A., Smythe, C., and Frazier, E.N.: 1975, Ap. J. 200, p. 747.
Stencel, R.E., Linsky, J.L., and Ayres, T.R.: 1982a, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research" (in press).
Stencel, R.E., Linsky, J.L., Ayres, T.R., Jordan, C., and Brown, A.: 1982b, Ap. J. (submitted).
Stencel, R.E., Mullan, D.J., Linsky, J.L., Basri, G.S., and Worden, S.P.: 1980, Ap. J. Suppl. 44, p. 383.
Stenflo, J.O.: 1973, Solar Phys. 32, p. 41.
Stenholm, L.G. and Stenflo, J.O.: 1977, Astr. Ap. 58, p. 273.
Stein, R.F.: 1981, Ap. J. 246, p. 966.
Ulmschneider, P. and Stein, R.F.: 1982, Astr. Ap. 106, p. 9.
Vaiana, G.S. et al.: 1981, Ap. J. 245, p. 163.
Vaughan, A.H., Baliunas, S.L., Middelkoop, F., Hartmann, L.W., Mihalas, D., Noyes, R.W., and Preston, G.W.: 1981, Ap. J. 250, p. 276.
Vernazza, J.E., Avrett, E.H., and Loeser, R.: 1981, Ap. J. Suppl. 45, p. 635.
Vernazza, J.E. and Reeves, E.M.: 1978, Ap. J. Suppl. Series 37, p. 485.
Vogt, S.S.: 1983, this volume.
Wallenhorst, S.G.: 1980, Ap. J. 241, p. 229.
Wallenhorst, S.G.: 1981, Ap. J. 249, p. 176.
Walter, F.M., Basri, G.S., and Laurent, R.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research" (in press).
White, O.R. and Livingston, W.C.: 1981, Ap. J. 249, p. 798.
Wilson, O.C.: 1978, Ap. J. 226, p. 379.

DISCUSSION

Jordan: I'm surprised that you didn't mention that the HeII widths are different in these stars. Other lines have normal widths but HeII is clearly anomalous.

Linsky: Which stars are you specifically referring to?

Jordan: α Cen A, α Cen B, ξ BooA and ε Eri.

Linsky: Remind me, which way do they go.

Jordan: α Cen A or one of them is distinctly narrower. The formation of HeII is rather more complicated than the other lines. It may be formed partly through recombination from the corona and partly through transient excitation. My explanation would be that one mechanism or the other may be dominant as one goes from one star to another with different temperature gradients. I don't find it very surprising.

Linsky: A plot of HeII (λ1640) flux normalized to L_{bol} against X-ray flux normalized in the same way shows that all of the active dwarfs lie approximately in a straight line. This suggests, but does not prove, that the mechanisms of formation are the same in these stars.

de la Reza: Is there a correlation between the Balmer emission-line strength and photometrically determined rotation period? If there is a correlation then we may expect that the absorption features will not be visible when rotation is high.

Linsky: The Balmer-line observations I referred to were made with a resolution of 120mA. At this the lines were not fully resolved but were obviously broadened. I would interpret this as an optical effect. Is your argument that the lines are rotationally broadened?

de la Reza: If the rotation is high perhaps the predicted flat tops to the emission-line profiles will disappear. I am suggesting that this might be a way to resolve some of the difficulties that exist with photometrically determined rotation periods.

Worden: Perhaps I can answer that. In our data on rapidly rotating stars, like YY Gem and other close binaries, the central reversals are smeared out. Simulations which we have done with L. Cram, M. Giampapa and others also confirm this. Its a very key point that one must take the effect of rotation out.

______ (Some recording lost)

Giampapa: Just to expand on Pete (Worden's) comment, a high pressure transition region will also smear out the central reversal. So as he suggests one would have to make systematic observations of the Hα line to determine any rotational effects on the line profile.

Bromage: Was I correct in seeing a value of 29 ± 3 km/s for the FWHM of high-resolution lines on AU Mic?

Linsky: That's correct.

Bromage: The instrumental profile is equivalent to 20 km s^{-1} and is not well known. How can you then get an error of ± 3 km s^{-1}

Linsky: The numbers I have shown refer to the widths after taking out the instrumental profile. We assumed an instrumental correction corresponding to 12000 and took that out by taking the sum of the squares.

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Bromage: But the profile is not Gaussian and indeed is not very well known.

Linsky: That's correct and there is considerable uncertainty but I think that there is no doubt that the width of the line is less than it is in stars like α Cen A and ξ Boo A.

Dupree: You suggested that there might be short timescale variations in the UV flux from the dMe stars. I am a little puzzled because some of the variations seem to be of the order of 10-15% while the reproductibility of IUE is generally thought to be 20-25%. Can you comment on the size of the error bars?

Linsky: Those of us have worked with IUE for a long time recognize that there are problems with photometry of the integrated line profiles in low dispersion. These photometric errors get much larger as you go to the weaker lines. However in AT Mic for instance, the C IV line which is one of the strongest shows variations of 70% which appears to be real. On the other hand where we have variations of about 10-20% we would be concerned about its reality.