IV. THE ROLE OF MAGNETIC FIELDS IN THE STRUCTURE AND ENERGY BALANCE OF STELLAR ATMOSPHERES

THE ROLE OF MAGNETIC FIELDS IN STELLAR CHROMOSPHERES AND TRANSITION REGIONS

Jeffrey L. Linsky[1]
Joint Institute for Laboratory Astrophysics National Bureau of Standards and University of Colorado, Boulder, Colorado 80309 USA

ABSTRACT

In this review based largely on observations with the IUE and Einstein satellites, I will summarize the different roles that magnetic fields play in controlling the structure and energy balance in the chromospheres and transition regions of late-type stars. Solar observations clearly show that magnetic flux tubes are the dominant structural element in the solar atmosphere, but the rotational modulation of plages (structures that are bright in ultraviolet emission lines) that overlie dark starspots provide strong evidence that magnetic flux tubes are the dominant structural elements in late-type stellar atmospheres as well. The wide range of radiative loss rates (and thus heating rates) observed in chromospheric and transition region emission lines also provides evidence for the importance of magnetic fields, but it is not yet clear whether the most active stars can be understood in terms of a large fractional coverage by solar-like magnetic flux tubes or whether brighter flux tubes are needed. I propose that the existence of a boundary between solar-like stars and those with little or no hot plasma, as well as the different types of G-K giants and supergiants, can be understood in terms of the fractional surface coverage by closed magnetic structures. Transition region downflows, the chromospheric heating mechanism, and the relative heating rates at different layers can be simply explained by the control of the energy balance by magnetic fields. Finally, I will intercompare models computed for active and quiet regions on the Sun with similar models computed for active and quiet stars, that is stars with intrinsically bright or weak emission lines.

---

[1] Staff Member, Quantum Physics Division, National Bureau of Standards.

J. O. Stenflo (ed.), Solar and Magnetic Fields: Origins and Coronal Effects, 313–338.

I. INTRODUCTION

The organizers of this IAU Symposium have asked me to review a very difficult topic. While I will do my best to rise to this challenge, I feel that I should describe the inherent difficulties of the topic before we proceed further.

From the point of view of an observer, one can say very little about the role magnetic fields play in stellar atmospheres, because we have very few measurements of magnetic fields in cool stars and even these measurements are spatially averaged whereas the stellar fields are likely inhomogeneous and filamentary. Other speakers have reviewed what we know about the role magnetic fields play in the solar atmosphere, and it seems reasonable to assume that magnetic fields play similar roles in solar-like stars, but we do not know a priori which stars are solar-like and which are very different. Furthermore, we have not yet resolved individual magnetic flux tubes in the solar atmosphere, and as a result we have no definitive information yet on the role played by magnetic fields even in this case.

From the point of view of a theoretician, the situation may be worse. The introduction of magnetic forces and magnetic flux tube geometries into the hydrodynamic equations makes it almost impossible to solve the equations for nonradiative heating rates and the steady state response of the flux-tube embedded atmosphere to this heating. One must either ignore the magnetic force terms, simplify the geometry, or make some other drastic approximations in order to make any progress. I suspect that the past emphasis on acoustic wave heating, ignoring the magnetic fields that are located at the sites of the greatest heating in the solar atmosphere, was due to difficulties in solving the MHD equations for realistic geometries.

In view of these difficulties I cannot be rigorous but must instead be speculative, and will follow solar analogies in trying to explain the interesting results coming from IUE and Einstein. There is a danger in this approach as a solar analogy may be a poor guide for explaining phenomena on stars with parameters very different from the Sun. Nevertheless, let us pursue solar analogies in a self-consistent manner, because they should be reliable when we understand the basic physical processes underlying the solar phenomena.

It is important to ask what the properties of stellar chromospheres and transition regions (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 thus its location in the H-R diagram. Thus for nonmagnetic stars, there are unique values for the luminosity and convective zone properties at each point 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 is to describe similar phenomena in late-type stars and to summarize the various roles that magnetic fields likely play in modifying the chromospheres and TRs of these stars. I will conclude by comparing atmospheric models for stars believed to have large and small areas covered by strong magnetic fields, and by suggesting some unsolved problems for future work. Some recent reviews relevant to this topic include Dupree (1981a,b;1982), and Linsky (1980;1981a,b,c, d;1982).

II. INHOMOGENEITY AND VARIABILITY IN STELLAR CHROMOSPHERES AND TRANSITION REGIONS

a) Spatial Inhomogeneity

Earlier in this symposium Marcy and Spruit reviewed the observations and theory of photospheric magnetic fields in late-type stars, and Zwaan and Vaiana reviewed the evidence for stellar magnetic structure using chromospheric and coronal indicators. I do not wish to convince you again that magnetic fields are responsible for atmospheric structure, but rather to point out how this may be true.

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 the presumed rotational period of the star. 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 inhomogeneously 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 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 typically show bright ultraviolet emission lines and photometric variability indicative of rotational modulation of dark star spots (e.g. Kunkel 1975; Hall 1981). 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) did this experiment on the long-period RS CVn system, λ And (G8 III-IV + ?), confirming that the emission lines are strong at photometric minimum and weak at photometric maximum. Marstad et al. (1982) monitored three RS CVn systems (HR 1099, II Peg, AR Lac) and the prototype BY Dra system, and found clear evidence for periodic variability in HR 1099 and II Peg. For HR 1099, the data cover three rotational periods (P = 2.8 days) and are consistent, indicating that the plages are long-lived. For II Peg, the 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

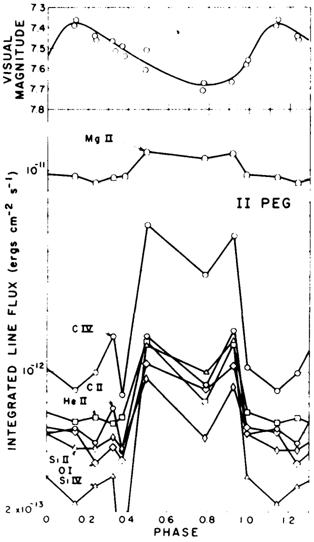

Fig. 1. Observed flux (from Marstad et al. 1982) in the Mg II λ2800, C IV λ1550, He II λ1640, C II λ1335, Si II λ1812, O I λ1304, and Si IV λ1400 features for II Peg as a function of phase. Also given at the top are FES visual magnitudes obtained simultaneously with the IUE spectra.

plage group and the absence of large intensity changes during the 3.3 day half 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, indicates 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 as can be seen in Figure 2, in the sense that the high temperature TR lines (C IV 1549 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 magnetic fields. Variability

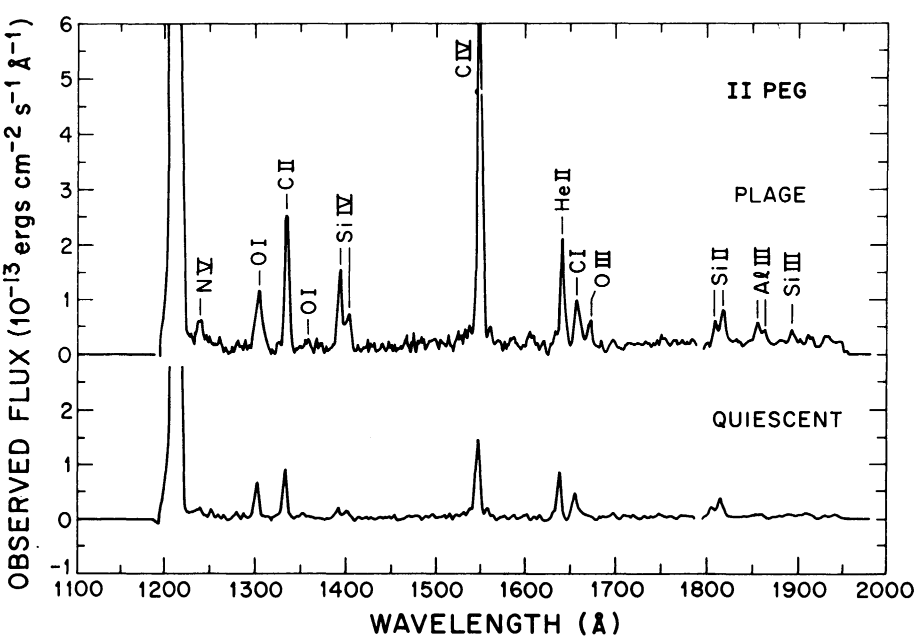

Fig. 2. Composite IUE spectra from Marstad et al. (1982) of the RS CVn-type system II Peg when the plage is on the disk (sum of three spectra) and when the plage is not present (sum of five spectra).

on many time scales has already been detected from the chromospheres and TRs 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, 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 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). Also, Baliunas et al. (1981) detected short time scale variations in the Ca II lines in α Tau (K5 III), λ And (G8 III-IV + ?), and ε Eri (K2 V). Such flares are probably also 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.

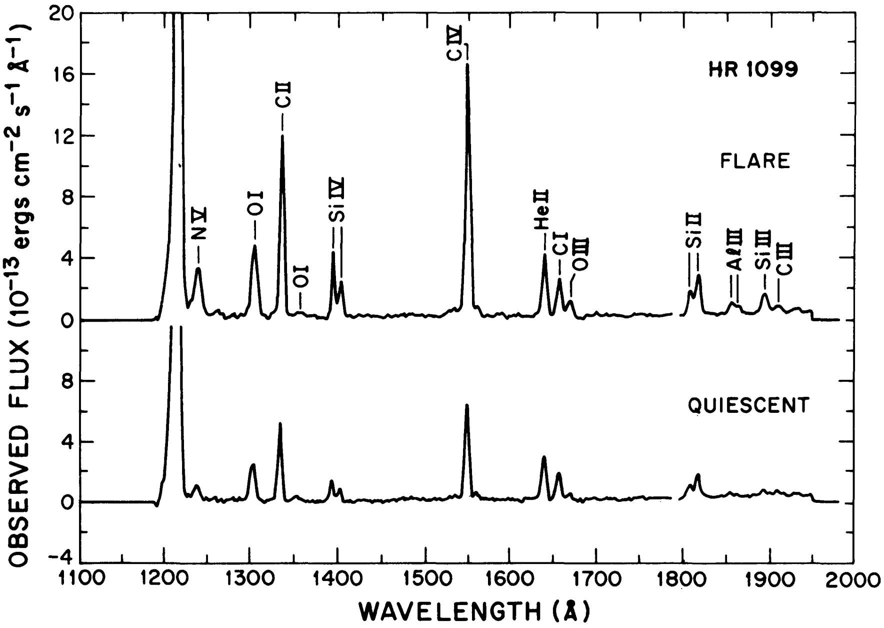

Fig. 3. IUE spectra of the RS CVn-type system HR 1099 obtained during a flare and when the system was quiescent.

III. ENHANCED HEATING

A vital role played by the magnetic field is to enhance the local nonradiative heating rate in the chromosphere and higher layers over 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 these rates in different stars 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. 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:

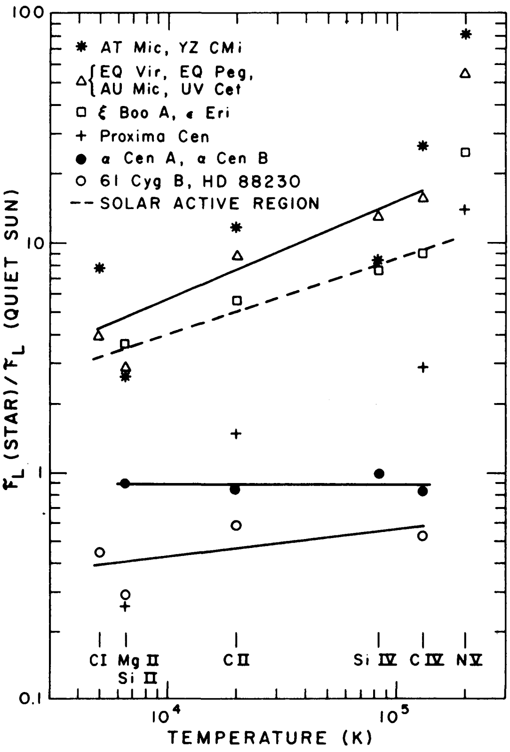

Fig. 4. Ratios of emission-line surface fluxes from Linsky et al. (1982) for six groups of stars and a bright solar active region relative to the quiet Sun. The stars are grouped according to their C IV ratios into three groups of dMe stars (AT Mic and YZ CMi; EQ Vir, EQ Peg, AU Mic, and UV Cet; Proxima 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 values. These stars likely have very weak magnetic fields with few plage regions. 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, and hence the heating rates lower, than for the 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, indicating 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 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 1972; 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.

IV. THE EXISTENCE, LOCATION, AND WIDTH OF THE TRANSITION REGION BOUNDARY IN THE H-R DIAGRAM

Prior to IUE and Einstein, one could only speculate concerning which portions of the H-R diagram contain stars with outer atmospheric layers and winds similar to the Sun and which portions contain stars with very different outer atmospheres and winds. The rich data from these two spacecraft have partially answered this question and also, I believe, told us that the question was improperly posed. Since magnetic fields control the energy balance in the outer layers of a star, there must be a range of outer atmospheric properties for stars in each location in the H-R diagram. Thus, the answer to the question is not straightforward, since magnetic fields play a crucial role.

Near the beginning of IUE operations, Linsky and Haisch (1979) noted a trend in the ultraviolet spectra of cool giants and supergiants in which the warmer stars with $V-R < 0.80$ (the yellow giants) show emission lines formed at all temperatures up to 10^5 K, whereas the cooler stars with $V-R > 0.80$ (the red giants) show only chromospheric emission lines. On this basis they proposed a nearly vertical dividing line in the H-R diagram near $V-R = 0.80$ (see Fig. 5) separating the yellow giants that typically have TRs from the red giants that do not. Subsequently, Ayres et al. (1981a) showed that the Einstein soft X-ray observations are consistent with the typical presence of hot coronae in stars to the left of a similar boundary and the absence of coronae in single stars to the right (see Fig. 5). Also Stencel (1978), and Stencel and Mullan (1980a,b) presented evidence for the onset of massive cool winds (observed by asymmetries in the Mg II lines) in stars lying to the right of a similar boundary.

The idea of a boundary as proposed by Linsky and Haisch has been criticized on the basis of the few stars in the original data sample, the absence of detected TR emission lines in some yellow giants (Hartmann, Dupree and Raymond 1982), and the existence of some red giants, the so-called hybrid stars, that show evidence for cool winds and C IV emission lines (Hartmann, Dupree and Raymond 1980,1981; Reimers 1982). The hybrid stars were proposed to have winds that are cool far from the star, on the basis of blue-shifted absorption features in the Mg II lines, and 10^5 K outflowing plasma closer to the star, on the basis of the observed broad C IV emission lines. These valid criticisms led to a reexamination of the existence of a boundary by Simon, Linsky and Stencel (1982) on the basis of a much larger sample of 39 single stars. They found (see Fig. 5 and subsequent data in Simon and Linsky 1982, and Hartmann et al. 1982) that the yellow giants show a wide range of C IV normalized fluxes (i.e. $f_{\mathrm{C\,IV}}/\ell_{\mathrm{bol}}$), including stars with small upper limits, that they ascribed to a mixed evolutionary status of these stars. Some stars have just recently

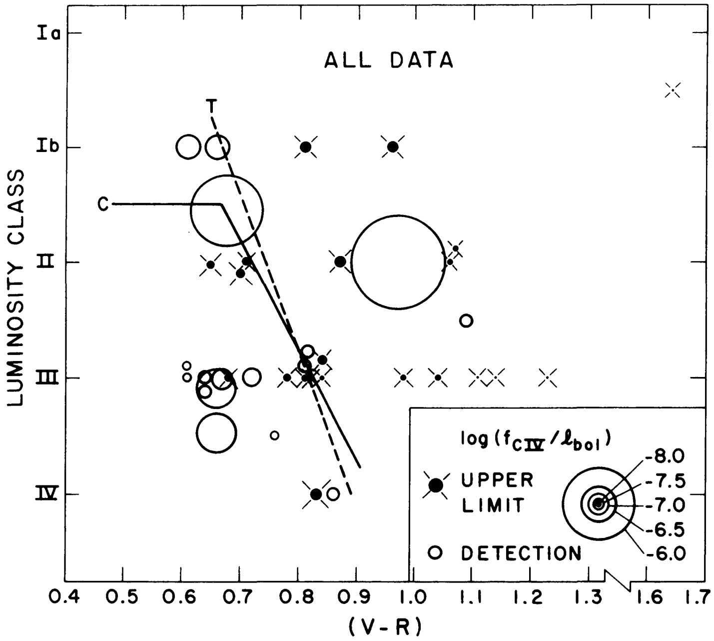

Fig. 5. H-R diagram showing measured ratios of the C IV λ1550 flux to the apparent stellar bolometric luminosity from Simon, Linsky and Stencel (1982). Open circles are detections and filled circles are upper limits. The line marked T is that originally proposed by Linsky and Haisch (1979) to separate stars with (to the left) and without (to the right) 10^5 K plasma. The line marked C was proposed by Ayres et al. (1981a) to separate stars that generally show soft X-ray emission (to the left) from stars that generally do not (to the right). Two of the three detections to the right of the line marked T are previously unknown binary systems.

evolved from the upper main sequence and could be relatively rapid rotators with strong dynamo-amplified magnetic fields and bright emission lines, whereas some may be post-helium flash stars that are slow rotators or stars that were slow rotators on the main sequence. Among the 18 red giants in their sample, only three stars have detectable C IV emission, but two of these three show ultraviolet continuum emission indicative of previously unknown companions (56 Peg and α UMa) and the third is the hybrid star α TrA (Hartmann et al. 1981). In a separate IUE study of 15 red giants, Strickland and Sanner (1981) also found no evidence for C IV emission. Simon et al. (1982) therefore concluded that the boundary originally proposed by Linsky and Haisch is real in that single stars to the right, with the exception of one hybrid star, contain significantly less 10^5 K plasma than typical single stars to the left of the boundary.

The question of a boundary remains open, however, for the following reasons. First, for the red giants, fluorescence in the fourth positive system of CO can produce emission features near the C IV 1550 Å and C II 1335 Å lines (Ayres, Moos and Linsky 1981b). Thus, high dispersion spectra are needed to estimate reliably upper limits for these emission line strengths. Second, the C IV lines detected in such hybrid stars as ι Aur (K3 II) and θ Her (K2 II) (cf. Reimers 1982) are at the level of some noise features. T. Simon recently re-observed θ Her with a 175 min SWP low-dispersion exposure, and saw no evidence for C IV emission. Thus, C IV emission in some of the hybrids is variable or not definitively detected. Third, the existence of a boundary demands a physical explanation.

A clear picture is now emerging from the observations of the G and K giants and supergiants on both sides of the boundary. I believe that three types of stars are present in this group as a consequence of different magnetic field strength and geometry:

(1) There are active stars, of which β Dra (G2 Ib) is a prototype, which show bright TR emission lines emitted by a geometrically thin region, bright X-ray emission, no evidence for any outflow of material, and redshifted emission lines (see next section). These are stars for which closed magnetic flux tubes dominate their outer atmospheres, and are responsible for enhanced heating and the suppression of outflowing gas. These stars probably have large magnetic fields either because they have just recently evolved from the upper main sequence (β Dra may be an example) or because they are members of close binary systems that are forced to rotate synchronously (the cool components of RS CVn systems and the W UMa stars are examples).

(2) There are quiet stars, of which α Boo (K2 III) is a prototype, which show no evidence of TRs or hot coronae to very small upper limits (Ayres, Simon and Linsky 1982a), have cool winds with significant mass loss, and geometrically extended chromospheres as determined from *IUE* studies of the C II 2325 Å intersystem lines (Stencel et al. 1981). These stars probably have no, or very few, closed magnetic flux tubes but rather have outer atmospheres with magnetically open topologies like coronal holes, and little or no hot plasma. These stars are probably slow rotators. Precisely how the decay of magnetic fields can lead to a star changing from active to quiet remains to be worked out in detail.

(3) I believe that the hybrid stars, of which α TrA (K4 II) and α Aqr (G2 Ib) are prototypes, are hybrid but in a different sense than originally proposed. These stars show weak and likely variable TR emission lines, no detected X-ray emission, and evidence for a cool wind. I believe that there is no real evidence for 10^5 K winds in these stars, since broad C IV emission lines occur in β Dra which shows no other evidence for a wind, but Doppler shift measurements are needed to answer this point. I would describe these stars as hybrid

in the sense that their outer atmospheres contain mostly open field lines along which the cool wind flows, but they do contain a few closed magnetic flux tubes from which the 10^5 K lines are emitted. Rotational modulation of these few flux tubes could explain the variability. These tubes may also contain 10^6 K plasma emitting soft X-rays, but the X-rays are absorbed by the surrounding cool plasma.

We need to ask why there are apparently no active single stars to the right of the boundary near (V-R) ≈ 0.80. I suspect that the explanation may be very simple. Gray (1981) measured the rotational velocities of five G5 III stars; four are slow rotators (v sin i ≈ 4 km s^{-1}) and one, ε UMi, is a quickly rotating (v sin i = 24 km s^{-1}) RS CVn system. These data led him to propose that as stars evolve to this location in the H-R diagram from the upper main sequence, the coupling of dynamo-generated magnetic fields and mass loss rapidly decreases the stellar rotation. The absence of active stars among the single red giants is likely due to the weak magnetic fields resulting from their slow rotation.

V. SYSTEMATIC DOWNFLOWS OF TRANSITION REGION PLASMA

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 then 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."

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. 6). 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. 6) 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}.

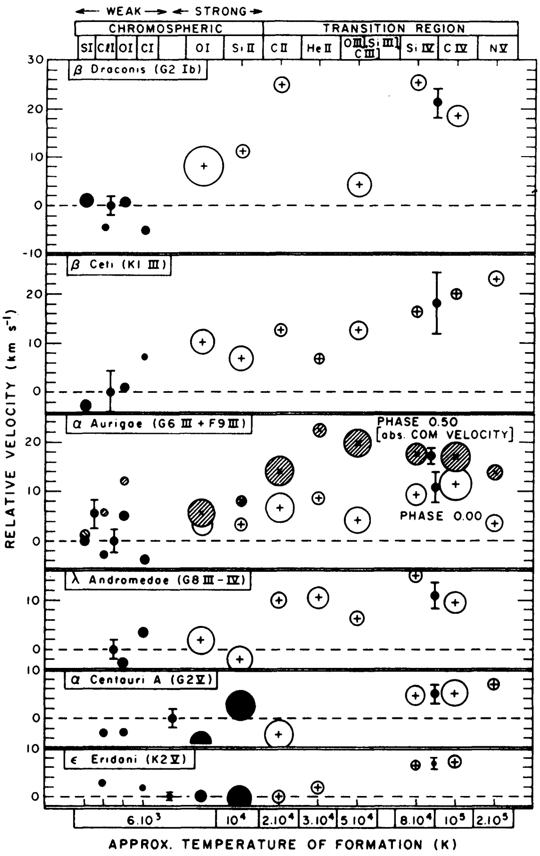

Fig. 6. A comparison of the line-of-sight velocities of high and low excitation lines obtained by Ayres et al. (1982b). The size of the bubbles indicates the total relative flux of the lines of a given ion. The filled circles are narrow chromospheric lines used in obtaining the flux-weighted mean zero 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.

At first sight, the idea of downflows ("antiwinds") in luminous stars, seems preposterous, however, 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 even detected in integrated light because they 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 ($\approx$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 following the 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 visibility 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 a stellar atmosphere.

There are several important consequences of redshifts, which we 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) An important result from the stellar redshift measurements that cannot be obtained from the solar data alone is the trend of redshift velocity (from the C IV and Si IV doublets) with stellar gravity. Ayres et al. (1982b) found an inverse relation of the form,

$$v_* \approx 8\ (g_*/g_\odot)^{-0.15}\ \mathrm{km\ s^{-1}} \quad .$$

This relation allows one to estimate a crude lower limit on the typical flux tube height using energy conservation,

$$h_{min} \geq \frac{v_*^2}{2g_*} \approx 10^2 \ (g_*/g_\odot)^{-1.3} \ \text{km} \quad ,$$

which predicts a rapid increase with decreasing stellar gravity.

(3) 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!

VI. ENERGY BALANCE IN STELLAR CHROMOSPHERES AND TRANSITION REGIONS

a) The Heating Mechanism for Late-Type Stellar Chromospheres

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 observed. This result was modified slightly by Stencel et al. (1980), 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 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

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

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 for 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.

b) Relation Bewteen Heating Rates in Stellar Chromospheres, Transition Regions, and Coronae

Using SWP low dispersion observations of 28 cool stars, Ayres, Marstad and Linsky (1981c) showed that the emission line fluxes of chromospheric and TR lines are not linearly correlated (see Fig. 7). Instead, as one goes to stars with brighter chromospheric emission (i.e. $f_{Mg\ II}/\ell_{bol}$), the TR lines brighten even faster such that $(f_{C\ IV}/\ell_{bol}) \sim (f_{Mg\ II}/\ell_{bol})^{1.5}$ 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.

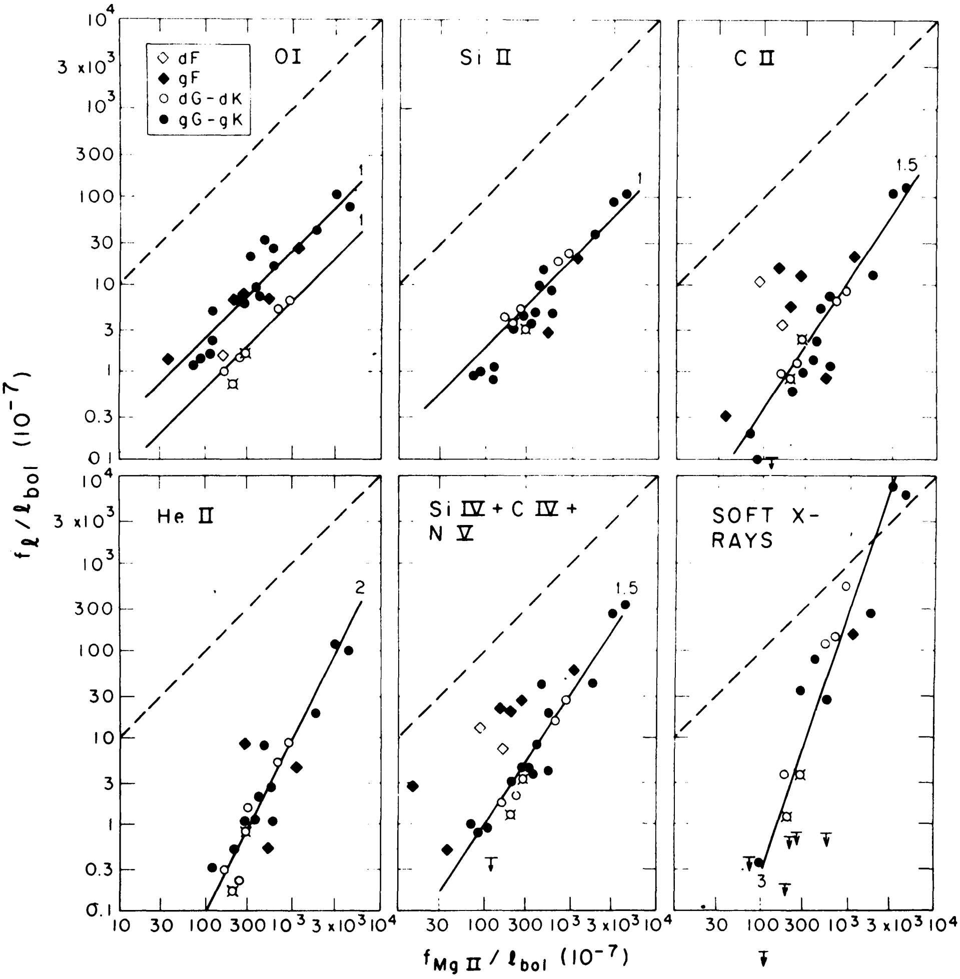

Fig. 7. Correlation plots of chromospheric, TR, and coronal fluxes compared to the Mg II line relative flux (Ayres, Marstad and Linsky 1981c).

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 (intersection point of the curves in Fig. 8) moves to larger pressures and the TR lines brighten by a larger factor than the chromospheric lines.

There are additional factors that must be included in realistic future energy balance studies of stellar chromospheres and TRs:

(1) 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.

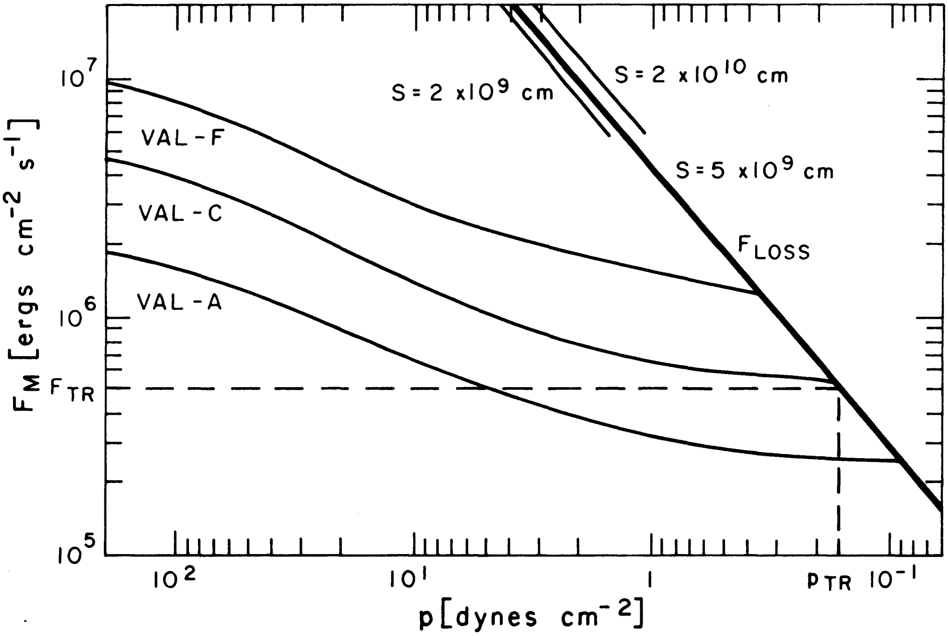

Fig. 8. Total mechanical energy flux F_M as a function of the pressure p for the chromospheric models A, C, and F of Vernazza, Avrett and Loeser (1981). The transition region lies at the intersection point with a curve (heavy line) that gives the total energy losses F_{Loss} of the TR and corona as a 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).

(2) The enthalpy flux can be an important heating source for stellar TRs. Thus models should include dynamic phenomena — downflows and also upflows (e.g. spicules).

(3) Cram (1982) called attention to the importance of heating of dMe star chromospheres by coronal X-rays. 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. MODELS FOR ATMOSPHERIC LAYERS WITH AND WITHOUT MAGNETIC FIELDS

Until now we have summarized the different qualitative roles played by magnetic fields, but 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 despite these simplifications.

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 (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 9:

(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.

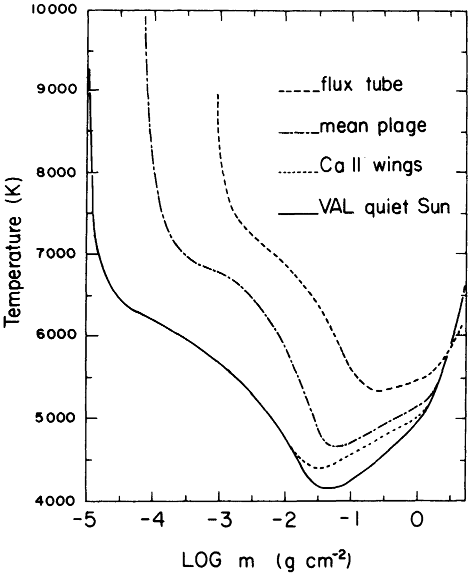

Fig. 9. Plage, flux tube, and quiet Sun models. The solid line is the VAL quiet Sun model. The short dashed lines (Ca II wings) represent a modification of the VAL designed to reproduce the Ca II H and K damping wings. The dash-dot curve is a plage model based on H I Lα, Ca II K, and Mg II k data obtained 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 displaced inward about 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.

(4) Different authors have assumed different functional forms of the temperature structure, T(m), between the temperature minimum 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 increasing m($T = 10^4$ K). Thus typical chromospheric lines like Ca II H and K, Mg II h and k, Lα, and Si II λλ1808, 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. 1982c) 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 stars 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 plage and quiet models are repeated in the active and quiet late-type stars.

b) Two-Component Atmospheric Models

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

(1) One approach is 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 filled by a quiet atmosphere model. Chapman (1981) derived such a flux tube model from OSO-8 plage spectra of the Lα, Ca II, and Mg II lines assuming a 20%

filling factor (see Fig. 9). 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) A second type of model, typified by the work of Chapman (1977,1979), assumes a diverging flux tube in horizontal pressure equilibrium (gas and magnetic forces) with the surrounding nonmagnetic atmosphere. Again one tries to match 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) A third approach is to assume a geometry with isolated flux tubes embedded in a nonmagnetic medium and then solving 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 that future theoretical studies must include.

(3) The basic physical processes responsible for downflows in flux tubes and the existence of the TR and coronal boundaries in the H-R diagram remain unknown.

(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.

This work was supported in part by NASA grants NAG5-82, NGL-06-003-057, and NAG5-199 through the University of Colorado. I would like to thank my colleagues T. R. Ayres, P. L. Bornmann, S. Drake, R. Hammer, N. C. Marstad, M. Schindler, T. Simon, R. E. Stencel, and F. M. Walter for stimulating discussions and for permission to describe unpublished work at this time.

REFERENCES

Avrett, E.H.: 1981, in R. M. Bonnet and A. K. Dupree (eds.), "Solar Phenomena in Stars and Stellar Systems," Reidel, Dordrecht, p. 173.
Ayres, T.R., Linsky, J.L., Simon, T., Jordan, C., and Brown, A.: 1982c, in preparation.
Ayres, T.R., Linsky, J.L., Vaiana, G.S., Golub, L., and Rosner, R.: 1981a, Astrophys. J. 250, p. 293.
Ayres, T.R., Marstad, N.C., and Linsky, J.L.: 1981c, Astrophys. J. 247, p. 545.
Ayres, T.R., Moos, H.W., and Linsky, J.L.: 1981b, Astrophys. J. (Letters) 248, p. L137.
Ayres, T.R., Simon, T., and Linsky, J.L.: 1982a, Astrophys. J. (submitted).
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, Astrophys. J. (Letters) 233, p. L129.
Baliunas, S.L., and Dupree, A.K.: 1982, Astrophys. J. 252, p. 668.
Baliunas, S.L., Hartmann, L., Vaughan, A.H., Liller, W., and Dupree, A.K.: 1981, Astrophys. J. 246, p. 473.
Basri, G.S., Linsky, J.L., Bartoe, J.-D.F., Brueckner, G.E., and Van Hoosier, M.E.: 1979, Astrophys. J. 230, p. 924.
Brueckner, G.E.: 1981, in F. Q. Orrall (ed.), "Solar Active Regions," Colorado Assoc. Univ. Press, Boulder, p. 113.
Brueckner, G.E., Bartoe, J.-D.F., and Van Hoosier, M.E.: 1977, in E. Hansen and S. Schaffner (eds)., "Proceedings of the OSO-8 Workshop," LASP, Boulder, p. 380.
Butler, C.J., Byrne, P.B., Andrews, A.D., and Doyle, J.G.: 1981, Monthly Notices Roy. Astron. Soc. 197, p. 815.
Chapman, G.A.: 1977, Astrophys. J. Suppl. Ser. 33, p. 35.
Chapman, G.A.: 1979, Astrophys. J. 232, p. 923.
Chapman, G.A.: 1981, in F. Q. Orrall (ed.), "Solar Active Regions," Colorado Assoc. Univ. Press, Boulder, p. 43.
Cram, L.E.: 1982, Astrophys. J. 253, p. 768.
Dere, K.: 1982, Solar Phys. 77, p. 77.
Doschek, G.A. and Feldman, U.: 1977, Astrophys. J. Suppl. 35, p. 471.
Doschek, G.A., Feldman, U., and Bohlin, J.D.: 1976, Astrophys. J. (Letters) 205, p. L177.
Dupree, A.K.: 1981a, in R. M. Bonnet and A. K. Dupree (eds.), "Solar Phenomena in Stars and Stellar Systems," Reidel, Dordrecht, p. 407.
Dupree, A.K.: 1981b, in C. Chiosi and R. Stalio (eds.), "Effects of Mass Loss on Stellar Evolution," Reidel, Dordrecht, p. 87.

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, Astrophys. J. 255, p. 325.
Frazier, E.N. and Stenflo, J.O.: 1972, Solar Phys. 27, p. 330.
Giampapa, M.S., Worden, S.P., and Linsky, J.L.: 1982, Astrophys. J. (in press).
Gray, D.F.: 1981, Astrophys. J. 251, p. 155.
Haisch, B.M., Linsky, J.L., Bornmann, P.L., Stencel, R.E., Golub, L., and Antiochos, S.K.: 1982, Astrophys. J. (submitted).
Hall, D.S.: 1981, in R. M. Bonnet and A. K. Dupree (eds.), "Solar Phenomena in Stars and Stellar Systems," Reidel, Dordrecht, p. 431.
Hallam, K.L. and Wolff, C.L.: 1981, Astrophys. 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.: 1980, Astrophys. J. (Letters) 236, p. L143.
Hartmann, L., Dupree, A.K., and Raymond, J.C.: 1981, Astrophys. J. 246, p. 193.
Hartmann, L., Dupree, A.K., and Raymond, J.C.: 1982, Astrophys. J. 252, p. 214.
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, Astrophys. J. 229, p. 700.
Kunkel, W.W.: 1975, in V. E. Sherwood and L. Plaut (eds.), "Variable Stars and Stellar Evolution," Reidel, Dordrecht, p. 15.
Lang, K.R.: 1980, "Astrophysical Formulae," 2nd ed., Springer-Verlag, Berlin, p. 510.
Linsky, J.L.: 1980, Ann. Rev. Astron. Astrophys. 18, p. 439.
Linsky, J.L.: 1981a, in R. M. Bonnet and A. K. Dupree (eds.), "Solar Phenomena in Stars and Stellar Systems," Reidel, Dordrecht, p. 99.
Linsky, J.L.: 1981b, in C. Chiosi and R. Stalio (eds.), "Effects of Mass Loss on Stellar Evolution," Reidel, Dordrecht, p. 187.
Linsky, J.L.: 1981c, in I. Iben, Jr. and A. Renzini (eds.), "Physical Processes in Red Giants," Reidel, Dordrecht, 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, Astrophys. J. 220, p. 619.
Linsky, J.L., Bornmann, P.L., Carpenter, K.G., Wing, R.F., Giampapa, M.S., and Worden, S.P.: 1982, Astrophys. J. (in press).
Linsky, J.L. and Haisch, B.M.: 1979, Astrophys. J. (Letters) 229, p. L27.
Machado, M.E., Avrett, E.H., Vernazza, J.E., and Noyes, R.W.: 1980, Astrophys. J. 242, p. 336.
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, Astrophys. J. 222, p. 723.

Oranje, B.J., Zwaan, C., and Middelkoop, F.: 1982, Astron. Astrophys. (in press).

Owocki, S.P. and Auer, L.H.: 1980, Astrophys. J. 241, p. 448.

Pneuman, G.W. and Kopp, R.A.: 1977, Astron. Astrophys. 55, p. 305.

Reimers, D.: 1982, Astron. Astrophys. 107, p. 292.

Rosner, R., Tucker, W.H., and Vaiana, G.S.: 1978, Astrophys. 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, Astrophys. 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, Astrophys. J. 237, p. 72.

Simon, T. and Linsky, J.L.: 1980, Astrophys. J. 241, p. 759.

Simon, T. and Linsky, J.L.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research" (in press).

Simon, T., Linsky, J.L., and Schiffer F.H. III: 1980a, Astrophys. J. 239, p. 911.

Simon, T., Linsky, J.L., and Stencel, R.E.: 1982, Astrophys. J. 257, p. 225.

Skumanich, A., Smythe, C., and Frazier, E.N.: 1975, Astrophys. J. 200, p. 747.

Stencel, R.E.: 1978, Astrophys. J. (Letters) 223, p. L37.

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, Astrophys. J. (submitted).

Stencel, R.E., Linsky, J.L., Brown, A., Jordan, C., Carpenter, K.G., Wing, R.F., and Czyzak, S.: 1981, Monthly Notices Roy. Astron. Soc. 196, p. 47P.

Stencel, R.E. and Mullan, D.J.: 1980a, Astrophys. J. 238, p. 221.

Stencel, R.E. and Mullan, D.J.: 1980b, Astrophys. J. 240, p. 718.

Stencel, R.E., Mullan, D.J., Linsky, J.L., Basri, G.S., and Worden, S.P.: 1980, Astrophys. J. Suppl. 44, p. 383.

Stenflo, J.O.: 1973, Solar Phys. 32, p. 41.

Stenholm, L.G. and Stenflo, J.O.: 1977, Astron. Astrophys. 58, p. 273.

Stein, R.F.: 1981, Astrophys. J. 246, p. 966.

Stickland, D.J. and Sanner, F.: 1981, Monthly Notices Roy. Astron. Soc. 197, p. 791.

Ulmschneider, P. and Stein, R.F.: 1982, Astron. Astrophys. 106, p. 9.

Vaughan, A.H., Baliunas, S.L., Middelkoop, F., Hartmann, L.W., Mihalas, D., Noyes, R.W., and Preston, G.W.: 1981, Astrophys. J. 250, p. 276.

Vernazza, J.E., Avrett, E.H., and Loeser, R.: 1981, Astrophys. J. Suppl. 45, p. 635.

Vernazza, J.E. and Reeves, E.M.: 1978, Astrophys. J. Suppl. Series 37, p. 485.

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, Astrophys. J. 249, p. 798.

Wilson, O.C.: 1978, Astrophys. J. 226, p. 379.

DISCUSSION

KOUTCHMY: In your analysis of the global solar activity compared with the stellar activity, why did you not incorporate more *transient* events like events connected with *flares* or, even, the so-called super-energetic events as they are almost permanently occuring over the surface of the Sun, at least at the time of the maximum of the solar activity cycle? They produce a lot uf UV and X-ray radiation probably connected with some kind of dissipation or change of the magnetic field. So, should they not play a significant role for G-K stars as well?

LINSKY: At present we have no way of distinguishing between continuous heating processes and heating by a large number of microflares in stars.

LAGO: In your graph showing the dividing line in the H-R diagram, where would you place T Tauri stars that have massive winds and yet strong line emission from transition regions. For instance in RU Lupi, C IV is very strong, and yet the IUE data we obtained suggest a P Cygni-type profile for the C IV line.

LINSKY: The proposed dividing line was based entirely on observations of evolved stars, for which the processes of angular momentum loss and dynamo magnetic field regeneration have greatly modified the initial properties of a stellar atmosphere. Thus I would not expect the T Tauri stars to fit at all into the concept of a dividing line.

UCHIDA: In relation to the evolutionary aspects you mentioned in your talk, I would like to mention that Dr. Bappu and myself have recently proposed a mechanism for the revival of the magnetic activity in giants after they have lost their magnetic activity in the long life on the main sequence. This is, in our proposal, due to the contraction, in the evolution to the giant stage, of the core and its spin-up. The convection develops to deeper layers as the envelope expands and is cooled, and as the convection reaches deep down, a dynamo layer reappears in the bottom region of the envelope and leads to the revival of the dynamo. This suggests that not only the surface rotation, but the rotation in the invisible interior could be essential.

HARTMANN: (1) In your discussion of downdrafts in transition-region lines, you neglected to mention that even the optically thin lines exhibit very large widths, much larger than the redshifts, and much larger than in the sun. This seems to me to be a very important fact. (2) If you have a general, roughly spherically symmetric downflow in an optically thick line, you will tend to get an inverse P-Cygni profile, with blueshifted emission. (3) Open magnetic-field regions in the sun are sources of hot wind. If we are to use the solar analogy, we would expect this to be true of stars as well. I don't understand why the opening up of magnetic field lines will necessarily result in a cool wind.

LINSKY: (1) Most of the stars with redshifted lines detected to date are giants and supergiants with transition region line widths greater than for the Sun. I suspect that these stars have upflows and downflows of greater magnitude than seen in the Sun. One indication of this is that the inferred net downflows are larger. (2) It is correct that *optically thick* emission lines formed in an expanding extended atmosphere can exhibit a net redshift due to the absorption or scattering of radiation in the blue side of the line profile by expanding gas in front of the star. However, we can test this possible explanation for the observed transition region redshifts by looking to see if the redshift decreases or disappears as one goes to lines of decreasing optical depth in the sequence C IV λ1551, λ1548, Si IV λ1393, λ1402, N V λ1238, λ1242, and finally the O III, Si III, and C III intersystem lines, which must be optically thin. We do not find such a trend in our data, except perhaps for β Dra. On the other hand, the intersystem lines for the small aperture Capella data show a larger redshift than the C IV lines. Thus the opacity explanation does not appear to be valid. (3) If it is valid to think in terms of Parker-type critical points for late-type giant winds, then the critical temperature should decrease with decreasing stellar gravity. For the Sun we know that the coronal gas in closed magnetic regions is hotter than for open regions, presumably because of increased heating and the absence of wind expansion and conduction to space as cooling mechanisms. On the basis of solar analogy I would argue that the open field regions of late-type giants would be cooler than the closed field regions and much cooler than solar coronal holes.

ZWAAN: (1) One comment in passing: You seemed to suggest that plages overlie sunspots. However, in the solar case plages border sunspots, and that may be important in modelling solar-type stars. (2) As to your category of quiet giants: also the *chromospheric* emission of these stars is quite low. During my talk last Monday I have discussed indications that the chromospheric flux attains a lower-limit value for these stars. There is one category of single K-type giants showing an enhanced Ca II H and K emission: many of the intrinsically brighter ($M_V < +1$) K-type giants do. These may correspond to your hybrid stars. (3) You have shown inferred heating rates as a function of surface gravity. However, how do you disentangle heating rates and filling factors?

LINSKY: (1) The II Peg data I showed imply a general spatial correlation of starspots with plages, but the data are insufficient to argue whether or not these two types of structures are cospatial in detail. (2) Your point is well taken. Based on the limited data available, the Mg II surface fluxes for the hybrids are similar to the quiet Sun, whereas for the prototype quiet giant α Boo, the Mg II surface flux is 0.15 times that of the quiet Sun. Thus the chromospheric surface fluxes for the single K giants may be correlated with the hybrid stellar characteristics. (3) The inferred heating rates are based on the measured radiative loss rates independent of filling factors.

NOYES: Two comments: (1) (relevant to Linsky's response to Zwaan). The star HD 1835 (G2V) shows perhaps 30 × as great photometric modulation (i.e. spots with 30 × as much area), but only a few times greater chromospheric (Ca II) emission. This reduction in plage/spot ratio may be less in younger stars. (2) Note that the *minimum* chromospheric flux of "active chromosphere" stars (e.g. HD 1835, but also many others) is much larger than the maximum integrated chromospheric flux from the sun. This suggests that dynamo generation of quiet chromosphere (magnetic-field related) emission also evolves downward with time. The study of spectra from "quiet" stars (i.e., of minimum activity) can thus lead to additional and independent information on the origins of magnetic activity.

GAIZAUSKAS: With regard to the spatial relation between plages and sunspots, I wish to point out that plages overlie a spot *only* when the spot is just emerging. When seen near the limb, the bright Hα emission overlying newly emerging spots has a lot of local vertical structure, extending to heights of say 10^4 km. Once the spot has fully emerged, in about 2 days, it is free of overlying plage. At that stage the plage covers the typical collection of trailing pores and is much dimmer. At the limb, a mature region shows much less vertical structure in its plage. Now if your stellar observations demand that the plage and sunspot emissions be cospatial, an analogy with the sun would suggest that a great deal of flux is continually emerging near your starspots.

LINSKY: The II Peg data permit us to say only that the plage and spots are cospatial to within ±20° in longitude or so, which is too coarse for detailed solar comparison. It is likely, however, that there is continuously emerging flux near the spots in RS CVn-type stars.