Session IV

"OUTER ATMOSPHERIC STRUCTURE"

STELLAR PLAGES

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Abstract. The solar surface contains of bright regions (plages) and dark regions (sunspots) superposed on the photosphere. If the solar analogy is valid, then active late-type stars should also exhibit bright, spatially distinct plages. These plages can be detected by rotational modulation of chromospheric flux, or by Doppler imaging in chromospheric/transition region lines. I review the evidence for the existence of plages, with particular emphasis on two very active systems: AR Lacertae, for which we have sequences of Doppler imaging observations since 1984, and AB Doradus, which we observed extensively in 1994. I conclude that we need to be cautious when relying on the solar analogy to interpret observations of the most active late-type stars.

> *"...one man's chromosphere is another man's extended atmosphere"*
> O. C. Wilson

1. Introduction – the solar plages

The chromosphere is that part of the stellar atmosphere above the temperature minimum, where non-radiative heating controls the energy balance, and the temperature rises to ~30,000K (Linsky 1980). This temperature rise is slow, spread over many pressure scale heights, because of the wealth of strong sources of radiational cooling at these temperatures. The lines of H Lyman α and Balmer α, Ca II K & H, and Mg II k & h are among the dominant sources of chromospheric radiation, and strong emission in these lines in a late-type star is generally considered diagnostic of the presence of a chromosphere. Chromospheres appear to be ubiquitous in the cool half of the H-R diagram, from the late-A stars (Walter, Matthews, & Linsky 1995) to the coolest stars known (Linsky et al. 1995).

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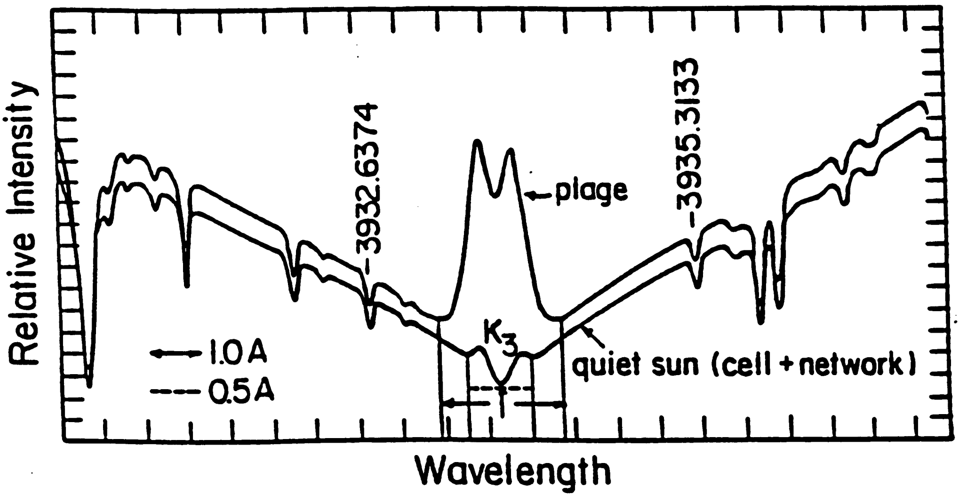

Figure 1. The solar Ca II K line in plage (upper trace) and in the quiet Sun (lower trace), from White & Livingston (1981).

The solar chromosphere is a highly structured, complex, and time variable set of structures. It can be approximated by a three component model: plage, network, and supergranule cells (Skumanich et al. 1984). Plage is visible as a bright region in white light associated with sunspots, but stands out with much higher contrast in the light of the chromospheric emission lines of Ca II K & H or Hα.

Plages are regions of strong ($< B > \sim$ 340 G), primarily vertical magnetic field. A feature of the high photosphere and lower chromosphere, plage exhibits higher contrast near and on the limb. Plage fields seem to be replenished by field sloughed off from sunspots. As solar plages decay, plage field drifts poleward and merges with the network. Plage is co-spatial with strong active regions. Details of plages and the structure of the solar atmosphere are discussed in many places (e.g., Zirin 1988; Gurman 1992; Title et al. 1992; Schrijver, this volume).

Solar plage is detectable spectroscopically via enhancements in chromospheric line fluxes (Figure 1). Skumanich, Smythe, & Frazier (1975) showed that the strength of the solar Ca II K emission core increased linearly with magnetic field strength. The Ca II K surface flux is about 2-3 times that of the cells, while the network exhibits a surface flux 20-30% brighter than the cells (Skumanich et al. 1984). The solar chromospheric emission strength modulates on the 11 year sunspot cycle, with about a 15% peak-to-peak variation (J. Lean, private communication). Skumanich et al. (1984) argued that the bulk of the flux variation is due to increase in the plage, as the filling factor of the network (40%) does not vary significantly throughout the solar cycle. The very active Sun has a plage filling factor of about 5% (Oranje 1983).

The topic of this review is not solar plage, but stellar plage. Surface structures, including chromospheric plage, are difficult to observe on other stars, as is made clear throughout these proceedings. With few exceptions, stars are observed as unresolved point sources, yet we wish to deduce the presence of discrete stuctures on other stars, and estimate their physical properties. There are techniques, among them Doppler imaging (Vogt & Penrod 1983; Vogt, Penrod, & Hatzes 1987) and eclipse mapping, which can be used to observe and map regions of contrasting surface brightness, but these techniques are generally applicable only to rapid rotators and members of eclipsing binary systems. For solar-like stars, we are generally forced to interpret spatially unresolved data.

Interpretation of stellar data is necessarily guided by the solar analogy. The solar analogy is the assumption that the Sun is a typical star, and that the atmospheric phenomena seen in solar-like stars (i.e., late-type dwarfs and subgiants) can be interpreted in terms of known solar structures. I shall do so, but I caution the reader that preconceptions often misdirect interpretations.

2. Plages on other solar-like stars

For reasons that will become clear, I consider solar-like stars to be G-K dwarfs with rotation periods P_{rot} longer than about 3 days (V_{eq} ~15 km s^{-1}). Few of these are amenable to eclipse mapping, and none rotate sufficiently rapidly for Doppler imaging analyses. Spectroscopic or spectrophotometric observations of chromospheric lines provide the best observational evidence of plage emission in solar-like stars. The solar-like stars exhibit a considerable spread in their Ca II K emission surface flux F_{CaII} (e.g., Vaughan & Preston 1980, Rutten 1986), with the Sun near but above the empirical lower bound of the distribution. The lower bound in F_{CaII}, the basal flux, is the sum of the network+cell emission plus the photospheric flux within the spectrophotometric bandpass (Rutten 1986; Schrijver 1995). The flux excess, $\Delta F_{Ca\ II} = F_{CaII}$ less the basal flux, represents primarily plage emission. A star with $\Delta F_{Ca\ II}=0$ is expected to have no plage emission. This $\Delta F_{Ca\ II}$ shows about a two order of magnitude spread, with the Sun near the logarithmic mean. Orange (1983) showed that this range can be explained solely by varying the plage filling factor, with the most active G dwarfs having plage filling factors of 65%, or less if the plage contrast was higher than in the solar case. Schrijver (1988) discussed how one constructs active stars out of solar components.

Solar plage is not uniformly distributed around the star, so as the Sun rotates the Ca II flux modulates. The rotationally-averaged flux also modulates on the 11 year sunspot cycle. Stellar plage can be expected to behave similarly. In 1965 O.C. Wilson began a program to monitor the Ca II emission cores of a large number of solar-like stars on a monthly basis, to search for stellar cycles. These cycles have been found in many stars now (Wilson 1978; Baliunas & Vaughan 1985; Baliunas et al. 1995; Donahue, this volume). Furthermore, nightly monitoring of these stars (Vaughan et al. 1981, Baliunas et al. 1983) shows periodic modulation of the Ca II K emission flux, which is most likely due to rotational modulation of plage emission, in about $\frac{3}{4}$ of the G-K dwarfs. No modulation is seen in stars earlier than spectral type F7, and most of the G-K dwarfs without discernable periods are *less* active than the Sun, with smaller $\Delta F_{Ca\ II}$. These stars may not now have plages. The range of variation due to the rotational modulation, about 10–20%, is similar in the Sun and the stars.

This rotational modulation of the Ca II emission flux is the strongest and most direct evidence for the existence of solar-like plages on other stars. The chromospheric indicators of solar-like stars, G-K dwarfs with P_{rot} longer than about 3 days, do indeed appear quantitatively similar to the Sun.

3. Evidence for plages on active cool stars

Those stars with the most prominent chromospheric emission have ΔF_{CaII} up to two orders of magnitude higher than that of the Sun (Figure 2). This emission can be readily interpreted as solar-like plage, although the surface flux enhancement implies surface filling factors uncomfortably close to, or greater than, unity[1] .

Rotational modulation of the chromospheric lines is not always detectable in the most active stars. It is seen in many of the more slowly rotating RS CVn systems, including λ And (Baliunas et al. 1983), IM Peg (Huenemoerder, Ramsey, & Buzasi 1990), and ζ And (Shcherbakov et al. 1995). However, if it is present in the more active, more rapidly rotating systems, it may be masked by their sporadic variability.

I report here on two projects designed to detect stellar plage in very active stars using rotational modulation and Doppler imaging techniques in the Mg II k&h chromospheric emission lines. The Doppler imaging techniques used are described elsewhere (Walter et al. 1987; Neff et al. 1989; Neff, this volume), and will not be restated here. What we can detect are regions of contrasting surface brightness. In the chromospheric lines of Mg II

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[1] This is not the case in the corona, where the flux excesses cannot be accounted for by simply increasing the filling factors of solar-like atmospheric structures (Schrijver 1988).

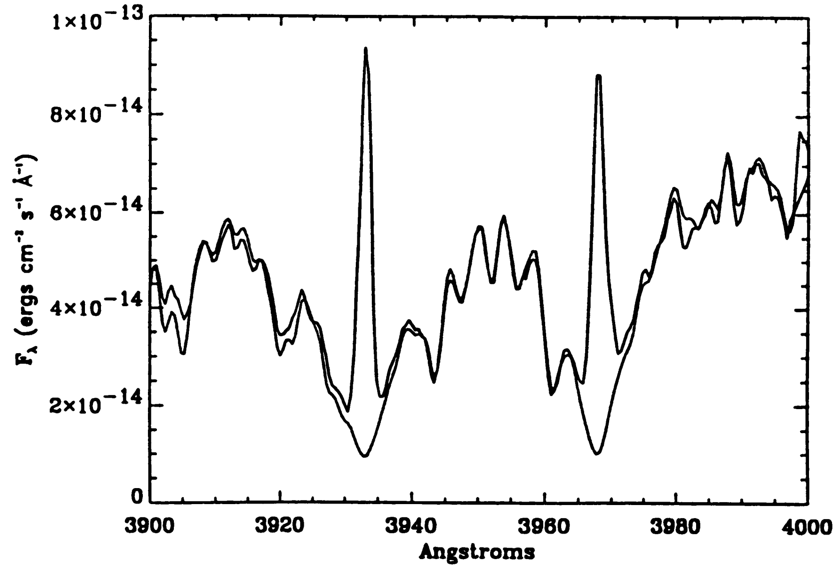

Figure 2. A comparison of the Ca II K fluxes of two K0 stars: 54 Psc and II Peg. 54 Psc (HD 3651) is a K0 V with a 13.8 day period and $< S >=0.171$ (Baliunas et al. 1995). This is an inactive star which may be entering a Maunder minimum (Donahue et al. 1995). II Peg, K0 IV, is an SB1 RS CVn system with $P_{rot}=6.7$ days. The spectra were obtained using the KPNO 2.1m GOLDCAM spectrograph; the ~1Å resolution is insufficient to resolve the emission core in 54 Psc.

k&h, we expect plages to appear as bright regions. Although we will refer to these bright regions of contrasting surface flux as plages, bear in mind that they are not necessarily the same physical structures as solar plages.

3.1. THE CASE OF AR LACERTAE

The eclipsing binary system AR Lacertae (HD 210344) is not the closest or brightest, or the most active, of the RS CVn systems, but is nearly ideal for long term study of chromospheric activity levels. The system geometry is simple: primary eclipse is total, which permits the fluxes of the two stars to be completely separated. The physical parameters of the stars are well known. AR Lac flares infrequently, and the flares tend to be short, in stark contrast to the behavior of systems such as HR 1099 (e.g., Neff 1991). This permits accurate separation of long term variability from short term flaring, even in short data sets. The stars rotate at rates that makes Doppler imaging possible, and in a short enough period to make monitoring over two rotation periods (needed to distinguish between rotational modulation and secular variations) practical.

We have undertaken Mg II k line Doppler imaging observations of

AR Lac with the IUE approximately biennially since 1983. These observations revealed the presence of distinct bright regions (plages) on the K star. At each epoch the system was distinct different.

October 1983: We observed AR Lac eight times within one orbit, with spectra obtained primarily near eclipse phases. Using Doppler imaging techniques to decompose the Mg II k and h emission line profiles, we determined that the emission arose from uniform emission from the two stars plus two discrete bright regions on the surface of the K star (Walter et al. 1987). Because of the non-uniform phase coverage, and coverage over only 0.7 of a single orbital cycle, we could not demonstrate conclusively whether these features were actually stable *spatial* regions (i.e., plages) or merely *temporal* variations (slow flares).

September 1985: We obtained a more complete set of observations with continuous coverage, but over only 0.8 of a cycle (Neff et al. 1989). Three plages were visible on the K star; one at high latitude and two others probably near the equator and extended significantly above the photosphere. The plage fluxes varied on an orbital timescale, and were suggestive of limb brightening. The *relative positions* of the plages suggested that they were the same features seen in the 1983 data, but migrated in longitude. A large portion of the leading hemisphere of the G star was not visible in Mg II (see §3.1.4).

September 1987: We observed for 2 full orbital cycles (Pagano et al. 1992a). There were pronounced hemispheric differences in Mg II flux and line width from both stars. There still were three plages on the K star, and they appeared to be in the same *relative* positions as the plages observed in 1985 and 1983, but at slightly different longitudes. The velocity curves of two of the plages, however, place them well above the surface of the K star. The repeated phase coverage permitted us for the first time to show that some of the profile variations from both the G and K star were indeed cyclic, and some were sporadic.

September 1989: We obtained 23 spectra over 80% of a single orbit. Two plages were evident.

December 1991: We obtained 102 hours of uninterrupted coverage using the IUE, supplemented by 8 snapshots with the Hubble Space Telescope (HST)/GHRS at Mg II k&h and C IV, and by eight ROSAT PSPC pointings simultaneous with the HST observations. We also had 48 hours of overlapping VLA observations and continuous ground-based optical photometry and spectroscopy. Initial results of this campaign are summarized in Walter et al. (1993). The Mg II flux from the G star was nearly constant outside of eclipse, while the Mg II flux from the K star was more variable, and possibly modulated. The C IV flux of the G star showed a ~30% modulation, while the C IV flux of the

K star did not vary significantly. A single plage was visible on the K star.

October 1994: In just over two complete stellar rotation periods, we obtained 55 well exposed spectra appropriate for Doppler imaging. Based on the C IV light curve there were no large flares, and only two small flares, to complicate the search for periodic variations. No surface maps are yet available.

At each epoch we detected evidence of discrete, small, regions which were brighter than the surrounding line. We call these *plages* for convenience. At all epochs the bulk of the flux arises in a symmetric component centered on the rest velocity of the star. We refer to this as the *network*. This is not meant to connote more than a phenomenological similarity between these and solar structures. On occasion the network component has displayed possible rotational modulation. We have only seen plages on the K star; never on the G star. The mean Mg II k surface fluxes of the G and K star are comparable.

3.1.1. *Activity cycles*

There is no clear evidence for any activity cycle, as measured by the Mg II flux (Pagano et al. 1994, 1995), during the 12 years we have been monitoring AR Lac. No appreciable trend is seen in the G star flux. The K star flux has decreased monotonically by about 30% since 1985, after a rapid increase in mean flux after 1983. The trend echoes the variation in spotted area on the star (Lanza et al. 1995), but with about a 5 year lag. The number of detectable plages and the observed range of variability both peaked when the mean flux was largest in 1985–1987.

3.1.2. *Plage parameters*

We can estimate the filling factor of these bright regions (see Walter et al. 1987; Neff et al. 1989) and determine lower limits to the surface flux densities of the plage and network components. The filling factor of the plage varies between 0.02 and 0.2, and the inferred surface flux is about 10^7 erg cm^{-2} s^{-1}. If the network fills the rest of the star, its surface flux is about $2{\times}10^6$ erg cm^{-2} s^{-1}. Note that this network surface flux is comparable to solar plage surface flux (e.g., Rutten 1986).

3.1.3. *Plage migration*

The plages we see at the different epochs often seem to lie at the same relative position (i.e., the angular separations between them do not vary with time), so it is natural to interpret the plages observed years apart as the same plages, or at least plages arising in long-lived regions of flux emergence. Such active longitudes are seen on the Sun, and are required to give coherence to rotational modulation of plage emission over many stellar rotations, since individual plages (at least on the Sun) are ephemeral. Pagano et al. (1992b) showed that, between 1983 and 1990, the plage regions migrated to lower stellar longitude, shifting about half way around the star, where the reference longitude is tied to the binary orbit. The starspots show a similar migration, but lead the plages by about 180°, a result similar to that reported by Catalano (this volume). This extreme phase shift between the bright and dark regions is not seen in the Sun, and may suggest that our interpretation of the structures in terms of solar features may be incorrect.

3.1.4. *Evidence for extended chromospheric structures*

A feature in rigid rotating with the star will exhibit a velocity amplitude, relative to the centroid of the star, of $v = (1+h)\ V \sin i \cos(l)$, where l is the latitude of the feature on the star and h is the height above the photosphere in units of stellar radii. The amplitudes of the plage velocity curves often exceed $V \sin i$ of the K star, suggesting that the emitting regions are above the photosphere, at heights of about $0.5R_K$ if equatorial, and more if at high latitude.

A pronounced dark spot is seen on the surface of the G star in the 1987 Doppler images (Neff et al. 1989). This dark spot results from the failure of the Mg II emission from the G star to reappear as the G star emerged from eclipse, and the fact that the model was limited to surface emission features. Although the possibility of a very quiet (black) hemisphere cannot be excluded, it now seems plausible that we may have seen an absorption event, with the G star projected behind a large extended cool structure. More direct evidence for the existence of cool structures extended above the K star comes from X-ray eclipse light curves. When sufficient time coverage exists, the primary eclipse (K star in front) is asymmetric, with either ingress or egress much slower than expected by a simple occultation model. The 1984 EXOSAT light curve shows a slow egress (White et al. 1990), with the mean flux level not reached until nearly orbital phase $\phi=0.2$. The 1993 ASCA light curve (White et al. 1994) shows a slow ingress. The egress light curve is consistent with geometric occultation of the background star. Four months later I observed AR Lac with the EUVE. In the DS/S light curve, ingress was consistent with geometrical obscuration, but egress was slow, with the flux not returning to the mean out-of-eclipse level until $\phi=0.2$, or nearly at quadrature (Figure 3).

The simplest explanation for the asymmetries is the existence of an obscuring cloud above the surface of the K star. The optical depths as a function of phase in the three observations appear similar, despite the very different wavelength ranges. If the three events are physically similar, one can exclude enhanced photoelectric absorption on the line of sight as the

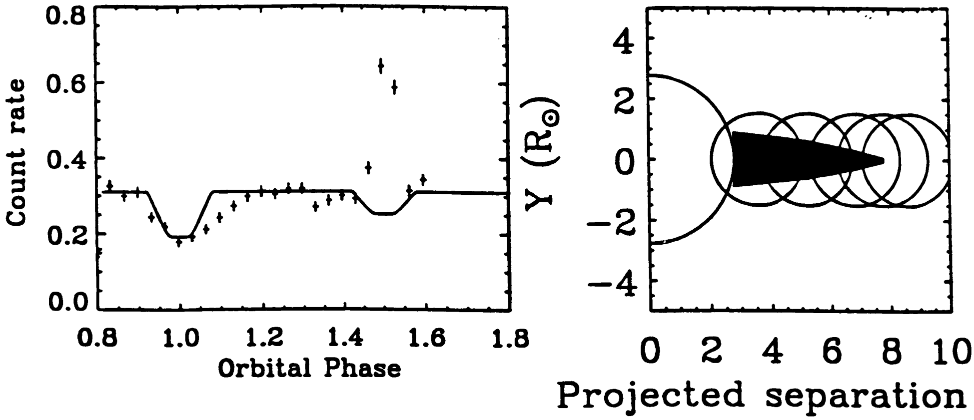

Figure 3. (Left) The EUVE DS light curve (Walter 1995). The solid line is the expected light curve for purely geometrical eclipses, scaled to the mean out-of-eclipse level. Primary eclipse has a depth of 42%, and is clearly asymmetric on egress. A flare coincides with secondary minimum. (Right) Simple geometrical model of the obscuration needed to account for the attenuation seen on egress from primary eclipse. The G star is plotted at the five phases observed following primary minimum. The shaded area is optically thick.

explanation. Based on the coronal emission measure, one can also exclude enhanced electron scattering as the explanation. Reduced emission on the hemisphere of the G star facing the K star alone cannot explain the light curve. The only self-consistent explanation is for obscuration by optically thick material, which blocks a smaller fraction of the G star as it rises above the limb of the K star. These possibilities are enumerated in Walter (1995). A resulting simple model is shown in Figure 3. The obscuring material must extend out to about 2 R_K (6 $R_\odot$). At the column necessary to be opaque at ASCA wavelengths ($n_H > 10^{22}$cm^{-2}), the inferred n_e of 10^{11} to 10^{12} cm^{-3} is at the upper end of the range observed in solar prominences. Existence of a similar structure in 1987 – essentially a *disparition brusque* – could explain the lack of Mg II emission seen from the G star upon egress from eclipse.

3.2. THE CASE OF AB DORADUS

AB Doradus (HD 36705) is one of the most active single early K dwarfs known (e.g., Collier-Cameron 1982). It is a very rapid rotator with a period of 0.514 days and V sin i = 80 km s^{-1}. It has a strong Li I absorption

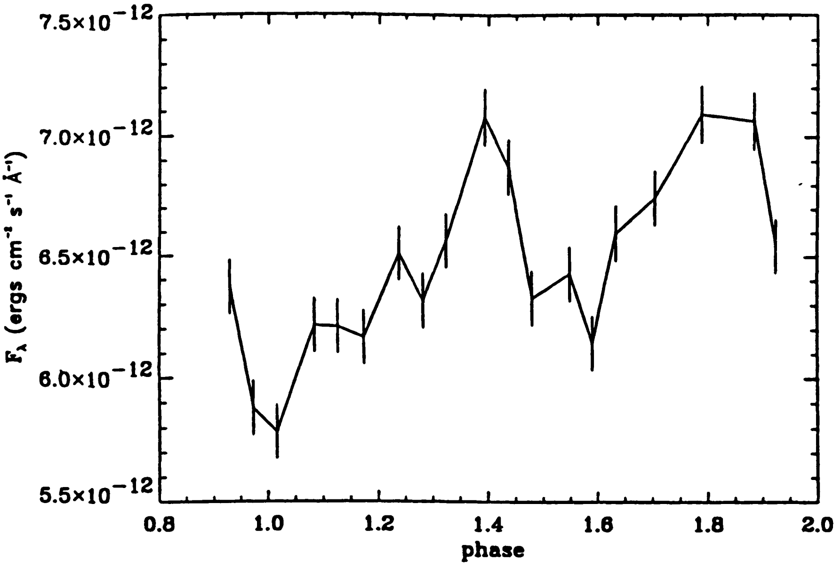

Figure 4. The integrated Mg II k flux of AB Dor on 14 November 1994.

line (Rucinski 1983) and Pleiades space motions (Innis et al. 1986), and is thought to be approximately Pleiades-age. At a distance of 15 pc (Guirado 1995), it is on the zero-age main sequence. The phenomena exhibited by this star include flares (Pakull 1981; Robinson & Collier-Cameron 1986), large dark spots (Collier-Cameron & Unruh 1994), strong X-ray (Pakull 1981) and UV emission line fluxes (Vilhu et al. 1991), bright nonthermal radio emission (Slee et al. 1986; Lim et al. 1992), and extended co-rotating cool prominences located at two stellar radii (Collier-Cameron & Robinson 1989). There is clear evidence for spatially-extended material about this star, in the form of cool prominences or Hα clouds (Collier-Cameron et al. 1990).

AB Dor was the focus of a multiwavelength coordinated campaign in November 1994. As part of this campaign, I obtained HST/GHRS observations of Mg II, Si IV, and C IV over a single orbital cycle, with the aim of seeking plages – compact regions of contrasting surface brightness identifiable in the line profiles. That exercise proved futile: no plages were evident. There was no convincing evidence for rotational modulation either; the dips in the total k line flux (Figure 4) are attributable to the absorption events, previously seen at Hα, which cross the stellar surface in about an hour. The dynamic spectrum (Figure 5 upper) shows the absorption events crossing the line profile in about one hour. Applying the solar analogy, if the absorption events are due to passage of cool prominences across the face of the star, one might expect them to be associated with the spotted

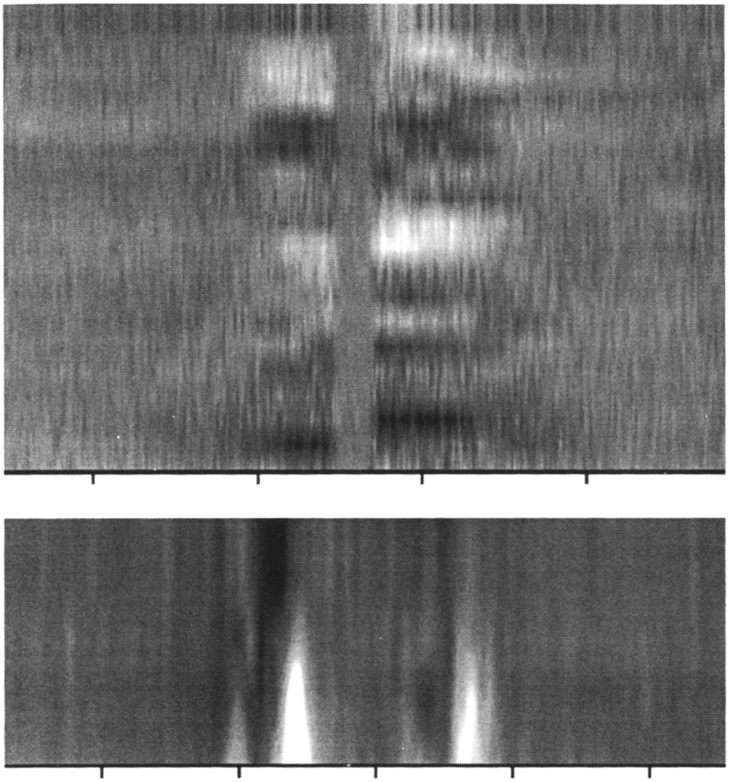

Figure 5. Upper panel: the dynamic Mg II k spectrum from 19 individual spectra taken approximately every 30 minutes covering one rotation (see Figure 4). The wavelength runs from 2793.5 through 2797.8Å (ticks every Angstrom). Lower panel: the dynamic C IV spectrum (four 5 minute integrations) at ϕ=1.0, during the deepest Mg II absorption event. The wavelength scale runs from 1543.7 through 1554.2Å (ticks every two Angstroms). In both figures time (orbital phase) runs from the bottom up. The mean spectra have been subtracted, and data have been smoothed along the time axis. Absorption features are dark. The bright features are not excess emission, but represent a lack of absorption.

hemisphere. Optical minimum corresponds to ϕ=0.5 (Rucinski, Garrison, & Duffey 1995), which is out of phase with most prominent absorption events (ϕ=0.0).

During the deepest absorption event (centered at phase 1.0) we detected an absorption dip at C IV. The C IV observation consisted of four 5 minute integrations at ϕ=0.0, centered between the second and third of the Mg II exposures. The line profile changed smoothly over the 20 minutes due to the passage of the absorption dip across the line profile (Figure 5). The cool prominences clearly contain hot plasma, with temperatures of order 10^5 K, magnetically-confined at about one stellar radius above the photosphere.

4. Are the most active stars truly solar-like, or how far can we stretch the solar analogy?

The data discussed above suggested that the chromospheres of very active stars have some distinctly un-solar-like characteristics. The solar-like stars can be restricted to those main sequence stars with P_{rot} longer than about 3 days (equatorial rotation rate V_{eq} ~15 km s^{-1}). The un-solar-like stars include rapidly rotating dwarfs, rapid rotators in close binary systems, including the secondaries of RS CVn and Algol systems, FK Comae stars, and the naked T Tauri stars. There are gross differences between the chacteristics of the two groups:

Starspot Latitude: Few sunspots are seen above 30^o absolute latitude. It is reasonable to assume that slowly-rotating solar-like dwarfs also have near-equatorial spots.

Active, rapidly rotating stars seem to have their spots near or at the poles. Types of stars with high latitude spots include RS CVn systems (Vogt, this volume), naked T Tauri stars (Joncour et al. 1994; Strassmeier et al. 1994), rapidly rotating dwarfs (Unruh, this volume; Stout-Batalha, this volume), and FK Comae stars (e.g., Hubl & Strassmeier 1995). Schüssler & Solanki (1992) and Solanki (this volume) discuss a possible theoretical underpinning for this observation.

Chromospheric extent: The solar chromosphere is compact, with a scale height approximately 2×10^8cm ($<0.01R_\odot$).

In addition to AR Lac and AB Dor, other active stars possess extended cool chromospheres. Guinan & Caroll (1990) used the white dwarf star in the eclipsing white dwark/K dwarf binary system V471 Tau to trace the vertical extent of transition region gas, finding C IV absorption with scale heights of 10^{10}cm (~0.3 R_*). Heuenemorder et al. (1989) showed that the $\frac{H\alpha}{H\beta}$ ratio in the RS CVn system UX Arietis is similar to that seen in solar prominences, and suggested that the emission is from low density, extended gas. Hall & Ramsey (1994) modeled the Hα profiles of four RS CVn systems in terms of prominence-like structures with scale heights of order R_*.

Rotation-activity relations: Solar-like stars exhibit very clear rotation-activity relations, with the activity level proportional to P_{rot}^{-n}, or V sin i^n. In the corona, n is approximately 2 (Pallavicini et al. 1981; Maggio et al. 1987). This relation breaks down for rapidly rotating dwarfs (e.g., Caillault & Helfand 1985, Stauffer et al. 1994), and for active subgiants in binary systems (including RS CVn systems). Walter & Bowyer (1981) found n=1.1 for RS CVn systems. Majer et al. (1985)

and Dempsey et al. (1993) have argued that that there is no rotation-activity relation in these stars, and the apparent relation is due to the dependence of the radius on period. In any event, in G dwarfs the activity appears to saturate for V sin *i* greater than about 15 km s^{-1}, where by "saturate" I mean that the activity level no longer increases as the P_{rot} decreases.

Coronal variability: The solar X-ray emission varies markedly over the course of the solar cycle. The solar soft X-ray flux has decreased by a factor of 100 from solar maximum to solar minimum (Acton 1995). A number of active stars have been the subject of repeated X-ray observations, and none have exhibited variability of this magnitude. The range of variability seems to be fairly small in active stars.

Activity cycles: Solar-like G-K dwarfs generally exhibit long term periodicities in their Ca II K flux (Baliunas et al. 1983; Donahue, this volume), with periods of 7-15 years. The full range of solar behavior seems to be echoed, including activity minima (Donahue et al. 1995). A significant fraction of the most active (and youngest, most rapidly rotating) stars in the Mt. Wilson sample do not show evidence for activity cycles (Baliunas et al. 1983). They tend to be highly variable. It is not clear whether the variability masks the activity cycles, or whether there are no coherent cycles in these stars. There is no evidence for stellar cycles in the RS CVn or FK Comae systems, but lack of homogenous, long term observations, coupled with the sporadic variability, may mitigate against the detectability of activity cycles.

The conclusion is simply stated: not all G-K stars should be considered as solar-like, if by solar-like we mean having magnetic activity and structures phenonenologically similar to that of the Sun. Those G-K dwarfs which rotate in 3 or more days do appear to be solar-like, but the more rapidly rotating G-K dwarfs, and rapidly rotating G-K subgiants (to longer periods) exhibit a number of un-solar-like behaviors. These behaviors are likely driven by the rapid rotation, and perhaps a change in the operation of the magnetic dynamo. The different thresholds in the dwarfs and subgiants (subgiants with periods up to at least 7 days exhibit these un-solar-like characteristics) may be attributable to surface gravity.

There is strong evidence for the great extent of the active chromospheres. These may be confined by centripetally-supported magnetic flux tubes. It is tempting to interpret the symmetric, non-modulating emission component not as network, but as low-lying plage with filling factors approaching unity. The extended discrete structures may not be analogous to any common solar structure, and may be phenomenologically akin to the giant solar prominences.

O.C. Wilson (1972), noted that:

> "It is important to realize that a chromosphere is a completely negligable part of a star. Neither its mass nor its own radiation makes a significant contribution to those quantities for the star as a whole."

Though true, the chromospheres also offer a window into the stellar interior. In future years the study of this completely negligable part of the star promises to yield further insights into the workings of stellar dynamos and the organization of the surface magnetic fields.

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References

Acton, L.W. (1995) in *Cool Stars, Stellar Systems, and the Sun*, ed. R. Pallavicini, ASP Conf. series, in press.
Baliunas, S.L. & Vaughan, A.H. (1985) *ARA&A*, **23**, 379.
Baliunas, S.L. et al. (1983) *ApJ*, **275**, 752.
Baliunas, S.L. et al. (1995) *ApJ*, **438**, 269.
Caillault, J.-P. & Helfand, D. J. (1985) *ApJ*, **289**, 279.
Collier-Cameron, A. (1982) *MNRAS*, **200**, 489.
Collier-Cameron, A., Duncan, D.K., Ehrenfreund, P., Foing, B.H., Kuntz, K.D., Penston, M.V., Robinson, R.D., & Soderblom, D.R. (1990) *MNRAS*, **247**, 415.
Collier-Cameron, A. & Robinson R.D. (1989) *MNRAS*, **238**, 657.
Collier-Cameron, A. & Unruh, Y.C. (1994) *MNRAS*, **269**, 814.
Dempsey, R.C., Linsky, J.L., Schmitt, J.H.M.M., & Fleming, T.A. (1992) *ApJ*, **413**, 333.
Donahue, R.A., Baliunas, S.L., Soon, W.H., & McMillan, F.M. (1995) in *Poster Proceedings: Stellar Surface Structure*, ed. K.G. Strassmeier, p. 72.
Guirado (1995), presented at *Radio Emission from the Sun and Stars.*
Guinan, E.F., & Carroll, S.M. (1990) in *Active Close Binaries*, ed C. Ibanoglu, p 7.
Gurman, J.B. (1992) in *The Sun, A Laboratory for Astrophysics*, eds. J.T. Schmelz & J.C. Brown (Kluwer:Dorderecht) p. 245.
Hall, J.C. & Ramsey, L.W. (1994) *AJ*, **107**, 1149.
Hubl, B.J. & Strassmeier K.G. (1995) in *Poster Proceedings: Stellar Surface Structure*, ed. K.G. Strassmeier, p. 96.
Heuenemoerder, D.P., Buzasi, D.L., & Ramsey, L.W. (1989) *AJ*, **98**, 1398.
Heuenemoerder, D.P., Ramsey, L.W., & Buzasi, D.L. (1990) *ApJ*, **350**, 763.
Innis, J.L., Thompson, K., & Coates, D.W. (1986) *MNRAS*, **223**, 183.
Joncour, I, Bertout, C., & Bouvier, J. (1994) *A&A*, **291**, L19.
Lanza, A.F., Pagano, I., Rodonò, M., & Catalano, S. (1995) in *Poster Proceedings: Stellar Surface Structure*, ed. K.G. Strassmeier, p. 75.
Lim, J., Nelson, G.J., Castro, C., Kilkenny, D., & vanWyk, F. (1992) *ApJ*, **388**, L27.
Linsky, J.L. (1980) *ARAA*, **18**, 439.
Linsky, J.L., Wood, B., Brown, A., Giampapa, M., & Ambruster, C. (1995) *ApJ*, in press.
Maggio, A., Sciortino, S., Vaiana, G.S., Majer, P., Golub, L., Bookbinder, J., Harnden, R.F. Jr., & Rosner, R. 1987 *ApJ*, **315**, 687.
Majer, P., et al. (1986) *ApJ*, **300**, 360.
Neff, J.E. (1991) *Memorie Della Società Astronomica Italiana*, **62**, 291.
Neff, J.E., Walter, F.M., Rodonò, M., & Linsky, J.L. (1989) *A&A*, **215**, 79.
Oranje, B.J. (1983) *A&A*, **124**, 43.

Pallavicini, R., Golub, L., Rosner, R., Vaiana, G.S., Ayres, T., & Linsky, J.L. (1981) *ApJ*, **248**, 279.

Pakull, M.W. (1981) *A&A*, **104**, 33.

Pagano, I., Rodonò, M., & Neff, J.E. (1992a) in *Surface Inhomogeneities in Late-Type Stars*, eds. P.B. Byrne & D.J. Mullan, (Springer-Verlag:Berlin), p. 315.

Pagano, I., Rodonò, M., & Neff, J.E. (1992b) in *Cool Stars, Stellar Systems, and the Sun*, ASP Conf. Series **26**, eds. M.S. Giampapa & J.A. Bookbinder (ASP:San Francisco), p. 352.

Pagano, I., Rodonò, M., Neff, J.E., & Walter, F.M. (1994) in *Cool Stars, Stellar Systems, and the Sun*, ASP Conf. Series **64**, ed. J.-P. Caillault (ASP:San Francisco), p. 450.

Pagano, I., Rodonò, M., Neff, J.E., & Walter, F.M. (1995) in IAU Colloquium 153, *Magnetodynamic Phenomena in the Solar Atmosphere – Prototypes of Stellar Activity*, eds. Y. Uchida, T. Kosugi, & H.S. Hudson (Kluwer:Dordrecht), in press.

Robinson, R.D. & Collier-Cameron, A. (1986) *PASA*, **6**, 308.

Rucinski, S.M. (1983) *A&AS*, **52**, 281.

Rucinski, S.M., Garrison, R.F., & Duffey, B. (1995) *IBVS*, **4156**, 1.

Rutten, R.G.M. (1986) *A&A*, **159**, 291.

Schrijver, C.J. (1988) *A&A*, **189**, 163.

Schrijver, C.J. (1995) *A&ARev*, **6**, 181.

Schüssler M. & Solanki S.K. 1992, *A&A*, **264**, L13.

Shcherbakov, A.G., Fernandez-Figueroa, M.J., Martin-Parra, F., de Castro, E., Cornide, M., Tuominen, I., & Ilyin, I.V. (1995) in *Poster Proceedings: Stellar Surface Structure*, ed. K.G. Strassmeier, p. 181.

Slee, O.B., Nelson, G.J., Innis, J.L., Stewart, R.T., Vaughan, A., & Wright, A.E. (1986) *PASA*, **6**, 312.

Skumanich, A., Lean, J.L., White, O.R., & Livingston, W.C. (1984) *ApJ*, **282**, 776.

Skumanich, A., Smythe, C., & Frazier, E.N. (1975) *ApJ*, **200**, 747.

Stauffer, J.R., Caillault, J.-P., Gagne, M., Prosser, C.F., & Hartmann, L.W. (1994) *ApJS*, **91**, 625.

Strassmeier, K.G., Welty, A.D., & Rice, J.B. (1994) *A&A*, **285**, L17.

Title, A.M., Topka, K.P., Tarbell, T.D., Schmidt, W., Balke, C., & Scharmer, G. (1992) *ApJ*, **393**, 782.

Vaughan, A.H., Baliunas, S.L., Middlekoop, F., Hartmann, L.W., Mihalas, D., Noyes, R.W., & Preston, G.W. (1981) *ApJ*, **250**, 276.

Vaughan, A.H. & Preston, G.W. (1980) *PASP*, **92**, 385.

Vilhu, O., Gustafsson, B., & Walter, F.M. (1991) *A&A*, **241**, 167.

Vogt, S.S., Penrod, G.D., & Hatzes, A.P. (1987) *ApJ*, **321**, 496.

Vogt, S.S. & Penrod, G.D. (1983) *PASP*, **95**, 565.

Walter, F.M. (1995) in *Astrophysics in the EUV*, IAU Colloquium 152, eds. R. Malina & S. Bowyer, in press.

Walter, F.M. & Bowyer, S. (1981) *ApJ*, **245**, 671.

Walter F.M., Matthews, L.D., & Linsky, J.L. (1995) *ApJ*, **447**, 353.

Walter, F.M., Neff, J.E., Gibson, D.M., Linsky, J.L., Rodonò, M. Gary, D.E., & Butler, C.J. (1987) *A&A*, **186**, 241.

Walter, F.M., Neff, J.E., Pagano, I., & Rodonò, M. (1993) in *UV and X-Ray Spectroscopy of Laboratory and Astrophysical Plasmas*, eds, E. Silver & S.M. Kahn (Cambridge:Cambridge), p. 403.

White, N.E, Shafer, R.A., Horne, K., Parmar, A.N., & Culhane, J.L. (1990) *ApJ*, **350**, 776.

White, N.E., et al. (1994) *PASJ*, **46**, L97.

White, O.R. & Livingston, W.C. (1981) *ApJ*, **249**, 798.

Wilson, O.C. (1972) in *Stellar Chromospheres*, NASA SP-317, eds. S.D. Jordan & E.H. Avrett, p. 305.

Wilson O.C. (1978) *ApJ*, **226**, 379.

Zirin, H. (1988) *Astrophysics of the Sun* (Cambridge:Cambridge).