PHOTOSPHERIC ACTIVITY IN MAIN-SEQUENCE STARS*

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ABSTRACT

We present an analysis of the effects of stellar activity on photospheric absorption lines. High-resolution echelle spectra, including nearly complete coverage between $\lambda 3800$ and $\lambda 5300$, were obtained for early K dwarfs with a range of activity levels. The spectra of active stars are divided by the spectrum of an appropriate inactive standard, resulting in a measure of the possible perturbations to the line profiles due to changes in the temperature distribution induced by nonradiative heating. Many of the medium to strong lines show effects of activity. This is measured quantitatively using the equivalent widths of the strongest of the resulting pseudoemission features, which we find are especially prevalent in strong lines with excitation potentials of less than 3.0 eV. The effects are much weaker than found in pre-main-sequence stars, even on the active stars. We conclude that very high-quality data will be necessary to conduct a precise study of the effects.

Two classes of effects are seen in the ratio spectra: simple pseudoemission profiles resulting from the filling in of the line core, and profiles indicating that lines in some active stars have broader wings but shallower cores than their inactive counterparts. We hypothesize that the effect of activity on the photospheric lines follows from a shallower average photospheric temperature gradient due to nonradiative heating in the upper photosphere and additional effects inside magnetic flux tubes. The effects correlate reasonably well with the activity measured in the chromosphere proper (the K-line emission), which implies that stellar activity affects the atmosphere both above and below the temperature minimum. There are many other features at the ~20% level in ratio spectra which will require a complex fine analysis to interpret.

Key words: stars—activity; stars—chromospheres

1. Introduction

Study of stellar activity has experienced great growth during the last two decades, with most of the attention on the emission due to nonradiative heating in the chromospheres, transition regions, and coronae of stars with outer convective envelopes. This energy originates in the convection zone and is apparently preferentially channeled to the surface through magnetic flux tubes which have their origin in a stellar dynamo also associated with the convection zone. Both magnetic and acoustic energy may be released at the top of the convection zone as a result of this (cf. Linsky 1980). Since the work of Wilson (1963) chromospheric emission has been measured quantitatively by the emission flux in the cores of the Ca II H and K lines (e.g., Vaughan et al. 1981; Soderblom 1986; Stauffer and Hartmann 1986; Noyes et al. 1984; Oranje 1983; Rutten 1986). The study of chromospheric activity has been linked to the study of stellar evolution (Vaughan and Preston 1980; Soderblom 1986), dynamo models (Durney, Mihalas, and Robinson 1981; Gray 1982), and stratification of stellar atmospheres (Linsky 1980). Correlations between stellar rotation, convective turnover time, age, and activity have been well established (Noyes et al. 1984; Simon, Herbig, and Boesgaard 1985; Basri 1987), and a general picture of the physical mechanism responsible for activity has been developed. Work on T Tauri stars (cf. Bertout 1989), main-sequence stars (Noyes et al. 1984; Simon and Fekel 1987), and post-main-sequence stars (Basri, Laurent, and Walter 1985; Rutten 1987) has confirmed that chromospheric activity is connected with the rotation of the star and the convection in its interior and that both activity and rotation decline with age as suggested by Wilson (1963), Kraft (1967), and Skumanich (1972).

Most of the previous work on stellar activity has involved the determination of the chromospheric contribution to the Ca II H and K lines, due to their accessibility from ground-based observatories. Generally, this process has involved the often complicated subtraction of the photospheric contribution to the HK line reversals (cf. Blanco et al. 1974; Middlekoop 1982). The determination
of the photospheric contribution is based on the assumption that the wings of the HK lines and a small but uncertain fraction of the cores are photospheric in origin (cf. Linsky and Ayres 1978; Noyes et al. 1984). Once the photospheric contribution has been determined, the remaining fraction of the HK flux is labeled as chromospheric and is used to measure the degree of stellar activity. The strength of the emission cores is used to quantify the level of stellar activity and the variation of the line is used to determine temporal changes in activity, as well as the stellar rotational period.

Although known in solar work (e.g., Athay 1976) and occasionally mentioned in stellar work (cf. Linsky 1985), it is underappreciated that most of the nonradiative dissipation that takes place in a stellar atmosphere actually occurs in the upper photosphere. Work on the dissipation of waves (e.g., Ulmschneider et al. 1978) makes this clear, but the fact is often overlooked because its effect on the emergent spectrum is much more subtle than those found in the chromosphere and above. This is due to the fact that the relatively high photospheric densities give it a high heat capacity, so the temperature changes due to a given heat input are much less extreme than in the lower-density upper atmosphere. That this is so is also demonstrated by LaBonte (1986) observationally for the Sun; he shows that the integrated amount of enhanced emission in the wings of Hα and Ca II H and K is actually much more than in the cores despite the illusion that the cores undergo the largest enhancements in solar plages. Other investigators have looked at lines which are essentially chromospheric for filling in of what are (except in the most active cases) absorption lines, including Linsky et al. (1979) in the Ca II IR triplet, Wolff, Heasley, and Varsik (1985) for the He I D3 line, and Herbig (1985) for Hα. The only previous work which looks in detail at observations of such effects in truly photospheric stellar lines is that of Finkenzeller and Basri (1987, hereafter FB), who examined some pre-main-sequence stars. This work concentrates on the effect of nonradiative heating on photospheric absorption lines and on the general question of photospheric activity.

There is an established correlation between the various spectral diagnostics of the chromosphere, transition region, and corona (Ayres, Marstad, and Linsky 1981; Oranje 1986), so apparently stellar activity has unified effects on all levels of the upper atmosphere. Among others, Chapman and Sheeley (1968) in the case of absorption lines and Skumanich, Smythe, and Frazier (1975) for Ca II H and K emission have shown that brightening is coincident with the observed photospheric magnetic fields. There seems little doubt that the average \( T - \tau \) gradient in the photosphere is perturbed in the presence of solar activity. There is a suggestion that a "basal" component of activity which does not depend on rotation (and therefore, by implication, not on magnetic fields) is present in most stars (Schrijver 1987); this could be a purely acoustic form of heating and Anderson and Athay (1989) argue that it is (the Sun as a star is at essentially the basal level of activity). While there are many diagnostics of chromospheric activity in addition to the traditional HK lines, few good photospheric diagnostics have been developed. Identification of such diagnostics will enable us to better understand how activity distorts the photospheric absorption profiles. One must also evaluate to what extent analyses of stellar parameters (gravity, abundance) may be effected by the filling in of the line.

In this paper we determine the effects of stellar activity on spectral lines originating below the temperature minimum and establish some lines as good spectral diagnostics of photospheric heating. We also investigate the question of how well the degree of photospheric activity correlates with the observed level of chromospheric activity. We detail the observations in Section 2, and follow that in Section 3 with a description of the data reduction and the differential analysis technique we use. Our results are presented in Section 4, and we offer a discussion of the implications of this work in Section 5.

2. Observations and Reduction

Our sample of stars was drawn partly from the work of Soderblom (1986). He used a part of the survey of Vaughan and Preston (1980), studying only stars with \((B-V)\) values between 0.5 and 1.00. These are northern stars, later than F5, and not known to be binary. Our primary sample consists of 20 early K dwarfs, though we observed an additional nine stars ranging from G8 to K4. We wanted to sample only a limited spectral range to allow good intercomparison between the stars and used the published measurements of the HK strength to select a range of activity levels, from the lowest to the highest (with several representatives at each level for each spectral type). Some stars were chosen because they were in the lowest range of observed HK strengths; these are used as our "standard" stars, meaning that they presumably reflect the state of stellar photospheres with as little nonradiative heating as can be found. It is probably true that no K stars exist with truly radiative equilibrium outer atmospheres. Although we used the data in Soderblom (1986) to select the stars by activity level, our echelle spectra included the HK lines, so we are able to assess the chromospheric activity at the same time as the photospheric activity.

The spectra were obtained with the Hamilton echelle CCD spectrometer (Vogt 1987) at the coudé focus of the Shane 3-m telescope at Lick Observatory. A list of the targets observed and some relevant data on them appear in Table 1. The observations were made in a run on 1987...
April 9 and 15. They were reduced using a reduction package developed by us with the ANA spectral reduction language. This fits a polynomial to each of the order weights. And then the order is extracted and compressed to a single value for each dispersion element. The flat fielding is obtained using a program from UC Santa Cruz which makes a global 2-D polynomial fit of a Th-Ar frame to the spectra of stars within a given spectral type will show pseudoemission features which correspond to the stronger lines in the original spectra. We select lines that are formed in the photosphere and use the strength of these virtual features in the ratio spectra to measure the degree of photospheric activity just as the strength of the Ca II K-line emission core is used to measure the chromospheric activity. FB found no significant qualitative difference between ratio and difference spectra of their T Tauri stars. The ratio spectra tend to enhance the virtual features in the bottoms of strong lines, while difference spectra minimize them. For this reason and because difference spectra require the continua of the two stars in question to be normalized to the same value, we have chosen to proceed with ratio spectra.

To determine which spectra were directly comparable, we first focused on wavelength regions without any strong features (to avoid a bias in our classification by activity effects). In looking at weak lines, we hope that any significant differences we see are a result of underlying physical differences in the stars, such as the effective temperature, surface gravity, and metallicity. We used a region between \( \lambda \lambda 4580-4615 \). The differences in radial velocity are taken out with a cross-correlation analysis which yields a shift applied to each spectrum relative to a chosen standard. The cross-correlation functions were also examined to see whether significant rotational broadening was present. Our intention was to broaden the inactive standard appropriate to each program star, but we found no convincing cases where such a correction was necessary.

### 3.1 Classification of Comparable Spectra

For this method of spectral analysis to be effective, it is critical that features in the ratio spectra reflect only differences between the activity levels of the active star and inactive standard. In order to facilitate this, we separate the observed stars into groups based on their spectral similarities. We chose not to classify the sample merely by their listed spectral types, since these do not accurately reflect differences in spectra at high resolution and with activity effects. One does expect, however, that the spectra of stars within a given spectral type will show strong similarities. For the most part we find this to be the case, although there are a few anomalies. This analysis led to the selection of three main groups and three others consisting of two or three stars each. In order to maintain statistical significance, we concentrate exclusively on the three major groups. The groupings are indicated in the fourth column of Table 1.

<table>
<thead>
<tr>
<th>Star</th>
<th>Sp. Type</th>
<th>B-V</th>
<th>Group</th>
<th>K-line E.W.</th>
<th>Activity</th>
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<td>HD106620</td>
<td>K2</td>
<td>0.87</td>
<td>I</td>
<td>0.22</td>
<td>I</td>
</tr>
<tr>
<td>HR 6806</td>
<td>K2</td>
<td>0.87</td>
<td>I</td>
<td>0.24</td>
<td>I</td>
</tr>
<tr>
<td>36 Oph A(S)</td>
<td>K1</td>
<td>0.86</td>
<td>I</td>
<td>0.24</td>
<td>M</td>
</tr>
<tr>
<td>HR 6553</td>
<td>K2</td>
<td>0.83</td>
<td>I</td>
<td>0.31</td>
<td>A</td>
</tr>
<tr>
<td>HD 11540A</td>
<td>K2</td>
<td>0.94</td>
<td>I</td>
<td>0.456</td>
<td>A</td>
</tr>
<tr>
<td>HD 82106</td>
<td>K2</td>
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<td>0.620</td>
<td>A</td>
</tr>
<tr>
<td>HR 6301</td>
<td>K6</td>
<td>0.94</td>
<td>I</td>
<td>0.028</td>
<td>I</td>
</tr>
<tr>
<td>HD 852488</td>
<td>K0</td>
<td>0.81</td>
<td>I</td>
<td>0.301</td>
<td>I</td>
</tr>
<tr>
<td>HD 14593</td>
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<td>I</td>
<td>0.364</td>
<td>A</td>
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<tr>
<td>HD 175541</td>
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<td>I</td>
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<td>12 Oph</td>
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<td>0.82</td>
<td>I</td>
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<td>M</td>
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<tr>
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<td>K0</td>
<td>0.86</td>
<td>I</td>
<td>0.208</td>
<td>M</td>
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<tr>
<td>70 Oph</td>
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<td>0.78</td>
<td>I</td>
<td>0.207</td>
<td>M</td>
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<tr>
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<td>I</td>
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<td>A</td>
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<tr>
<td>HD 45675</td>
<td>K0</td>
<td>0.90</td>
<td>III</td>
<td>0.018</td>
<td>I</td>
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<tr>
<td>HD 135323</td>
<td>K0</td>
<td>0.95</td>
<td>III</td>
<td>0.046</td>
<td>I</td>
</tr>
<tr>
<td>HR 4243</td>
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<td>0.99</td>
<td>III</td>
<td>0.025</td>
<td>I</td>
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<tr>
<td>HD 165346</td>
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<td>HD 110833</td>
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<tr>
<td>HD 175742</td>
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<td>HD 42250</td>
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<td>0.77</td>
<td>IV</td>
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<tr>
<td>11 LMi</td>
<td>G8</td>
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<td>IV</td>
<td>0.122</td>
<td>M</td>
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<tr>
<td>HD 12805</td>
<td>G8</td>
<td>0.75</td>
<td>V</td>
<td>0.013</td>
<td>I</td>
</tr>
<tr>
<td>61 UMa</td>
<td>G8</td>
<td>0.72</td>
<td>V</td>
<td>0.174</td>
<td>M</td>
</tr>
<tr>
<td>XI Boo A</td>
<td>G8</td>
<td>0.72</td>
<td>V</td>
<td>0.271</td>
<td>A</td>
</tr>
<tr>
<td>HR 5568</td>
<td>K4</td>
<td>1.11</td>
<td>VI</td>
<td>0.408</td>
<td>(A)</td>
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<tr>
<td>70 Oph B</td>
<td>K4</td>
<td>1.15</td>
<td>VI</td>
<td>0.826</td>
<td>A</td>
</tr>
<tr>
<td>XI Boo B</td>
<td>K4</td>
<td>(1.12)</td>
<td>VI</td>
<td>1.582</td>
<td>A</td>
</tr>
<tr>
<td>HR 4182</td>
<td>K1</td>
<td>0.88</td>
<td>?</td>
<td>0.021</td>
<td>I</td>
</tr>
</tbody>
</table>

* Equivalent width (Å) of core emission feature above minima.
  1. A: Active; M: Moderate; I: Inactive
The comparisons were made by first dividing the spectrum of each star by that of the star HD 175541 (K0) and studying the resulting ratios. HD 175541 was chosen as the standard of comparison because of its relative degree of inactivity as determined by the equivalent-width measurements of its HK cores. Note that this division is purely for the purpose of classification; the activity study is not performed on these ratio spectra. We found that the K2 stars in our sample all contained the same virtual features in their ratio spectra, thus leading to their classification in our analysis as group I. One K1 star, 36 Ophiuchi A(S), has also been included in this group since its ratio spectrum contains the same features as do the K2 stars. Another large group was formulated in a similar manner consisting largely of K0 stars and one G9 star. Further analysis of this group, however, revealed that there are significant enough differences between the spectra to warrant their separation into groups II and III. We found one set which suggests a higher effective temperature (weaker neutral lines), although not necessarily a higher activity level. This set was labeled group II, while the cooler set defines group III.

Our groupings do correlate well with the \((B - V)\) values given for these stars in the literature, with group II stars having \((B - V)\) values between 0.77 and 0.86 and group III stars between 0.90 and 0.99. The given values are listed in Table 1. There are two exceptions to the \((B - V)\) correlations with our grouping scheme: HR 6301 (0.94) and HD 175541 (0.90). Our spectra indicate that these two objects are probably hotter than their published \((B - V)\) values would indicate (since they closely resemble the objects with bluer colors). This is unlikely to be due to the different levels of activity since inactivity should make them redder, if anything, than their active counterparts with more flux tubes and hotter outer atmospheres.

### 3.2 Determination of Inactive Standards

Better results with the differential analysis are obtained by using an average of inactive spectra as the standard against which the program stars are to be compared. Such an average will tend to reduce any differences between the inactive spectra, allowing us to gain a more accurate portrayal of the relative strengths of the active stars. Comparisons were made only between stars within each group, and the process of determining the inactive standard for each group is detailed below. The initial determination of the level of activity of each star was made by calculating the equivalent widths of the Ca \(\Pi\) H and K lines. Stars with HK equivalent widths below 0.050 Å were said to be inactive. These refer to a continuum level fixed by the height to which the wings rise on either side of the emission core; the placement of this is uncertain by about 5%-10%. The degree of activity (inactive, moderate, or active) is specified in Table 1 along with the measured equivalent widths, and examples are shown in Figure 1 where the K-line emission cores of an active, moderate, and inactive star are pictured.

Within group I we defined two stars to be inactive: HD 166620 and HR 6806. The average of these two spectra is the inactive standard used for the analysis within this...
group. In group II the inactive pair was HR 6301 and HD 175541. A third relatively inactive star, HD 182488, was not used in the averaging because a number of its stronger profiles were markedly broadened compared with most stars in the group. In group III the pair was HD 135323 and HR 4243, with HD 145675 not included for similar reasons.

4. Results

The ratio spectra we analyze are the result of the division of each program spectrum by the appropriate inactive standard. The results are mildly encouraging. The most persistent features in the ratio spectra are the virtual emission profiles that could be the signature of filling in of the absorption profiles in active stars. The strength of the virtual features is, in most cases, not very much stronger than a host of other features with less ready explanations. This is unfortunate and unlike the situation in pre-main-sequence stars, where the filled-in lines were very obvious. It is only because they are apparent in most of the ratio spectra and correspond to changes in the cores of lines that we have chosen them for analysis. The continua of the ratio spectra generally contain several to numerous excursions at the 20% level. Some correspond to lines missing in one of the spectra, some to differences in one line wing or in “continuum” levels. Despite some noise spikes, the signal-to-noise ratio in the spectra is above 30:1, so we have mostly either real spectral differences or unexplained instrumental effects. Experience with repeated spectra of this quality on the same star leads us to believe that it is unlikely the differences are spurious, especially since the observations were often obtained on the same night. On the other hand, because the features are often of the same strength as others we pass over, one should view this study as more of a feasibility test than a final proof of photospheric activity. In particular, we have only tried to discover whether selected perturbations are correlated with stellar activity, rather than trying to identify all effects of the activity.

We searched the ratio spectra of each group for the strongest virtual features and used these lines for our subsequent analysis. As expected, the ratio spectra of the individual inactive stars show no significant virtual features (they are being divided by the average of themselves and one other). For the most part we restricted ourselves to features that were common to the ratio spectra of all three groups. These lines are listed in Table 2 with the wavelength of each line (Moore, Minnaert, and Houtgast 1966), the excitation potential of the lowest level of the corresponding transition, and value of log (gf) for each line (Kurucz and Peytremann 1975).

It is clear from studying Table 2 that lines with relatively low excitation potentials are those most often seen in the ratio spectra. This is not an unexpected result as such lines are generally formed closer to the temperature minimum where the perturbation of the temperature structure due to nonradiative heating should be greater than in the deep photosphere. For the Fe I multiplets the strongest transitions have excitation potentials less than about 1.6 eV. We also see the strong Mg I lines at \( \lambda \lambda 5167,5172,5183 \) which have excitation potentials of 2.71 eV. This is consistent with the results of FB. Examples of ratio spectra are shown in Figure 2. We show only a few of the orders and use the average ratio spectrum from group II.

Several things are clear from a detailed examination of these spectra. Many of the weak and medium-strength lines are not apparent in the ratios despite being very visible in the original spectra. We take this as an encouraging sign that the reduction was performed correctly and that differential analysis can be carried out with these stars. There are also several cases where some lines of equal strength in the active spectra show up in the ratio spectra while others do not. We show one in Figure 3, comparing the two lines at \( \lambda 3902.5 \) and \( \lambda 3905.5 \) One finds that the latter line is more filled in than the former and, therefore, present in the ratio spectrum while its companion is not. Two weaker lines between them are also filled in. This also indicates that we are really seeing the effects of stellar activity and not some problem with the zero level or background subtraction in the spectrum. The virtual features seen in the ratio spectra reflect differences between the stars that are the result of a source function or opacity perturbation at the line-forming levels of the active star. Note, too, that there is not a perfect match between the spectra outside of line cores. It is these other differences which make us cautious about the

<table>
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<th>Wavelength</th>
<th>Element</th>
<th>Low E.P.</th>
<th>log gf</th>
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<tr>
<td>3920.269</td>
<td>Fe I</td>
<td>0.12</td>
<td>-1.81</td>
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<td>3922.923</td>
<td>Fe I</td>
<td>0.05</td>
<td>-2.05</td>
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<td>3927.933</td>
<td>Fe I</td>
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<tr>
<td>3933.682</td>
<td>Ca II H</td>
<td>0.00</td>
<td>+0.15</td>
</tr>
<tr>
<td>3961.535</td>
<td>Al I</td>
<td>0.01</td>
<td>-0.45</td>
</tr>
<tr>
<td>3968.492</td>
<td>Ca II K</td>
<td>0.00</td>
<td>-0.15</td>
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<tr>
<td>4045.825</td>
<td>Fe I</td>
<td>1.48</td>
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<td>4063.605</td>
<td>Fe I</td>
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<td>+0.01</td>
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<tr>
<td>4071.749</td>
<td>Fe I</td>
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<td>-0.03</td>
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<tr>
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<td>Ca I</td>
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<td>+0.20</td>
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<tr>
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<td>-0.04</td>
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<td>5232.952</td>
<td>Fe I</td>
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<td>-0.32</td>
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Fig. 2.-Representative orders from group II. The upper panel (A) shows the average ratio spectra from group II for seven representative orders. The wavelength ranges for the orders are (from top to bottom): \( \lambda \lambda 4029-4056 \), \( \lambda \lambda 4087-4114 \), \( \lambda \lambda 4146-4174 \), \( \lambda \lambda 4208-4236 \), \( \lambda \lambda 4271-4300 \), \( \lambda \lambda 4336-4365 \), and \( \lambda \lambda 4403-4433 \). There is another order between each of the orders shown and further orders above and below them. The lower panel (B) shows the actual spectrum from an inactive star in this group (HD 175541) for the identical orders, so the original lines present can be seen. In both panels the individual traces have been divided by their mean values and are shifted by one unit for each adjacent order.

interpretation of spectral differences, although repeated core filling which is correlated with activity almost certainly has to be a real effect.

We measured the equivalent widths of only the most prominent and repeated virtual features in the ratio spectra. In this instance, "equivalent width" has its usual meaning but is applied to the ratio spectra. The measurement of these was rendered uncertain by the difficulty in defining what the local continuum should be. In cases where just the core was filled in, a flat continuum was apparent around it (at a value of unity for two spectra of equal intensity) and the equivalent width is in units of this continuum. When the strong line wings were depressed, the core emission feature appears in a pseudoabsorption trough; our measurement in these cases generally represents the flux above the local minima around a pseudo-emission feature (analogous to the measurements of the K-line cores). We have attempted to conduct the measurements in such a way that a relative comparison is meaningful; the absolute values certainly are not. These values are displayed for groups I, II, and III in Figure 4. Symbols correspond to the various moderate and active stars in each group, and each column of symbols corresponds to a particular line.

Using the measured equivalent widths of the Ca II H and K lines as a calibration of stellar chromospheric activ-
ity, we can clearly see that the photospheric emission generally follows this traditional measure of stellar activity. The results for group I are given in Figure 4a. The symbols correspond to the stars in the following way: triangles (HD 82106), crosses (HD 115404A), squares (HR 5553), diamonds (36 Oph A(S)), and inverted triangles (HD 166620). HD 166620 is an inactive star, and the virtual emission features in its ratio spectrum are quite weak. At the other extreme HD 82106 is clearly the most active star of the group, a result that is consistent with the strengths of its HK emission cores. The values given for the Ca H and K lines are scaled down by a factor of ten, and include pseudoemission from the near wings and in the case of the H line, from He.

In group II (Fig. 4b) we find very similar results. Here the triangles correspond to HD 82443, the crosses to HD 41593, the squares to 36 Ophiuchi A(N), the diamonds to 70 Ophiuchi A, and the inverted triangles to 12 Ophiuchi. For the most part we find that HD 82443 is the most active star of the group with the other moderate and active stars falling in a group at smaller equivalent widths. While the exact order of the group members is not preserved from line to line, the measured equivalent widths are quite clustered for many of the lines. This is particularly true for the Fe I lines at λ4957 and λ4383. Of course, the ordering is essentially meaningless when the lines do not have clearly different equivalent widths.

The unusual ordering in the λ4045 line points to another issue of interpretation. In this case, the active star has not only a filled core, but the entire wings out to ±2 Å are also brighter. An equivalent width in the ratio spectrum uses the local "continuum", which is higher all around the core in the active star. The area above this what we have measured, and that area turns out to be less than in the next-most-active star (where the wings are not brighter). Remeasuring these core features with the lower "continuum" level in both cases yields a line strength for the active star that is more than doubled. In this particular instance, it could be argued that the line is simply weaker overall in the active spectrum, leading to these effects. The issue of what is appropriate to measure is analogous to the long-standing dispute about the "photospheric correction" which should be made to HK measurements. We believe that absolute line profiles from models should be compared directly to observations in a final analysis, neatly avoiding the problem. For now, however, we have elected to use one consistent observational measure which is reasonable; other choices are also possible.

Figure 4c presents the measured equivalent widths for the group III stars. The HK strengths have again been reduced by a factor of ten. In this figure the triangles correspond to HD 175742, the crosses to HD 110833, the squares to HD 160346, the diamonds to HD 145675, and the inverted triangles to HD 135323. From the values of the H and K lines we expect to find that HD 175742 is the most active of the group III stars. This is generally confirmed by the equivalent widths of the virtual emission features of the photospheric diagnostics. We find that there is little spread in the equivalent widths of most of the lines but that HD 175742 consistently has the strongest virtual emission features. In all the groups, the...
very active stars tend to stand out, and moderate activity produces an effect of which we are really unable to measure the finer points. Presumably, with still higher-quality data this would be possible. Similarly, the least-active stars usually tend to lie at the bottom of the pile.

Several of the stars in our sample have broader strong absorption profiles than the inactive standards. Our initial suspicion was that the rotational velocities of the stars in question were high, despite the fact that we sampled main-sequence dwarfs which are typically slow rotators. A velocity-broadened line will mimic that of a line affected by activity, in that both profiles will have relatively shallow cores. An autocorrelation routine was used to determine the value of $v \sin i$ needed to match these broader spectra. We found that it is necessary to increase the rotational velocities of the narrow-lined stars by as much as 40 km s$^{-1}$ to account for the broadened profiles. Such rotational velocities are inconsistent with the current understanding of main-sequence K dwarfs. We also studied the weaker features in the spectra and found no indication that they are broadened. If the broadening was due to rotation all the lines would be broadened.

The line broadening is almost exclusively restricted to the strongest absorption profiles. In the ratio spectra we identify a broadened profile by the fact that its virtual opacity would show emission in the core and absorption in the wings. Note that one immediate implication of this is that the brighter cores are not due to a generally weaker opacity, as this is incompatible with the strengthening of the wings. The absorption profile in Figure 5a at $\lambda$4072 is clearly broader in the active spectrum (12 Oph) than for the group II inactive standard, and the result is the virtual feature seen in the ratio spectrum. The effect is somewhat less dramatic at $\lambda$4064. We compare three stars of varying degrees of activity in Figure 5b. Here two spectra are from active stars (HD 160346 and HD 110833) and one is again inactive (HD 135323). The same effect as above is seen again in $\lambda$4072 for both active stars; note that they are both much more similar to each other than to the inactive star, and, therefore, the differences with the inactive star are repeated for both stars (despite their being obtained on different nights, while the inactive star was observed on the same night as one of them). Note also that the Sr II line at $\lambda$4077 shows the opposite effect (narrower wings in the active stars), as though the ionized metals were weaker. These results seem somewhat contrary to the expectation if active atmospheres were simply hotter. Apparently the wing behavior is related to activity, but it is an unexpected effect. Of course, an alternate interpretation is that the particular lines involved are for some reason narrower and deeper in the inactive standards than in most stars.

5. Discussion

We have shown here that the photospheric line profiles of active stars are sometimes perturbed by a "filling in" of the line core. This is an effect seen by Chapman and Sheeley (1968) and LaBonte (1986) in solar plage regions where the distortion of the line profile due to nonradiative heating leads to a reduced value of the equivalent width. Giampapa, Worden, and Gilliam (1979) and LaBonte and Rose (1985) report similar findings for the Sun and Hyades, respectively. Previous authors (cf. Section 1) have demonstrated a strong correlation between the effects of stellar activity on many diagnostics in the outer atmospheres of a wide range of late-type stars. With this study we have shown that this correlation extends down into the photosphere as well. The relative strengths of the equivalent widths of the virtual features seen in the ratio spectra indicate that those stars which are chromospherically more active (as determined by the strength of their K-line emission cores) are photospherically more active as well. We have identified a number of diagnostics of photospheric activity. The most promising lines are those of neutral iron which are numerous and relatively strong. We find that lines with excitation potentials less than 3.0 eV are most easily seen in the ratio plots. The Mg b lines near $\lambda$5175 also seem to be reliable diagnostics of photospheric activity; they are probably formed nearest to the temperature minimum because of their greater strength.

From another point of view, our work also shows that many of the weak- and medium-strength absorption lines in a late-type spectrum are relatively unperturbed by even strong stellar activity. We do not see as dramatic effects, even in very active older stars, as have been seen in strong solar plages or in pre-main-sequence stars. In particular, many of the weak and moderate neutral metal lines look almost the same in active and inactive stars, as do some of the ionized metal lines. For accurate determinations of the relative gravities of main-sequence stars both the ionized and neutral lines of a particular element must show the same abundance. The abundance analyses of stars are usually based on a study of equivalent widths of lines with various strengths. Workers have tended to avoid the strongest lines in the spectrum because of the damping wings and concerns about NLTE effects. Thus, it seems unlikely that major revisions of the general results of such analyses are necessary in light of what we have found. On the other hand, fine analyses which included the stronger lines must be examined more closely, and certainly we sometimes do see disturbing effects (Fig. 5b).

In interpreting a differential analysis one can make a variety of assumptions of increasing complexity. The simplest is a one-component model which supposes that the source functions of the two stars in question are equivalent functions of depth, i.e., that the optical scales are equivalent and only the temperature structure in active regions is different. With this assumption the virtual features will reflect the relative differences in activity...
between the two stars and not be due to changes in how
the atmosphere maps onto the profiles. Assuming LTE,
and because the heat capacity decreases with density, the
effect of an increase of nonradiative flux will be to increase
the source function in the upper layers while leaving the
deeper layers unaffected. Given that the line profile maps
out the temperature stratification of the atmosphere with the wings of the line originating at a deeper layer, the cores of the absorption lines in an active star will be filled in relative to the cores of an inactive counterpart. The ratio of two such profiles with reveal a pseudoemission feature as the fingerprint of stellar activity. If the structure of the deep photosphere is relatively unperturbed, then the weak- and medium-strength lines should divide out completely while the strong lines will show pseudoemission. Such effects were found in moderately active Τ Tauri stars by FB.

Beyond this clearly oversimplified approach, the interpretation of the line core filling has several more complicated possibilities. One is that it is due to a reduction of opacity in the line. For example, a neutral line can be weakened if the magnetic region is hotter, causing greater ionization. In this case the wings should appear brighter along with the core, i.e., the whole line should become weaker. This is favored by Chapman and Sheeley (1968) who see some evidence for opposite behavior in lines of neutral and ionized metals. The temperature might be hotter either because of extra nonradiative heating (as in traditional facular models, e.g., Shine and Linsky 1974) or because the mass column density to a given photospheric temperature is reduced (flux-tube models, e.g., Steiner, Pneuman, and Stenflo 1986). This latter case supposes that flux tubes are thin enough that their temperature structure is dominated by the outside photosphere but that partial magnetic support inside the tube reduces the tube densities. Thicker flux-tube models in which the interior temperature does not match the exterior have also been considered.

The evidence that the solar atmosphere actually has several components is considerable. The solar magnetic field is known to be concentrated into kilogauss bundles (while the average surface field strength is of order 1 gauss). Ayres (1981), Ayres, Testerman, and Brault (1986), and others have made a good case for the presence of a very cool (radiative equilibrium?) component of the solar chromosphere on the basis of CO observations, and there is theoretical evidence (Muchmore and Ulmschneider 1985; Massaglia et al. 1988) that the solar plasma has a high/low temperature bifurcation instability. The facular models can be interpreted as average one-component models which reflect a mixture of the truly two-component quiet and flux-tube atmospheres. Flux-tube models lead to some confusion on the amount or need for nonradiative heating itself because evacuated tubes are likely to look hotter even without additional heating since one sees further into the photosphere in the tube. Evidence for a third "circumtubular" atmosphere comes from the disk center appearance of plage continuum, which is virtually the same as in the quiet Sun. This likely means that the hot tubes are surrounded by cooler rings due to the channeling of energy up through the tube. There are several excellent review papers on this topic for the solar case in Schröter, Vázquez, and Wyller (1987). The current consensus seems to be that flux tubes...
are both evacuated and heated in the upper photosphere. The most complete recent treatment of the problem in the Sun is by Walton (1987). He even begins to include the geometrical effects that must arise in small flux tubes on the emergent line profiles. The fact that the solar flux-tube problem is far from fully understood no doubt means that the stellar problem is even further from final solution. Indeed, it may turn out that the range of stellar activity observed is almost entirely due to the filling factor of flux tubes (or hot elements) compared with quiet atmosphere. 

The detailed interpretation of the perturbations seen in the line profiles must await modeling of the stellar atmospheres. Even if the temperature structure were the same inside and outside a flux tube at the same location, the optical depth scales will be different. Particle densities are different, leading to different ionization and excitation equilibria, and the collision broadening is also different. While effects in the line wings can probably be examined with LTE models, it may be risky not to include NLTE effects in the strong line cores. One virtue of a data
set like the one here is that there are several constraints on each part of the atmosphere due to the number of lines that can be analyzed. The broader wings that we see are rather mysterious. If interpreted as a change in just the temperature structure, they would imply that the mid-
photospheric temperatures are cooler where the wings are formed. This is both theoretically unexpected and would present a problem for the cores of lines which are somewhat weaker and therefore formed in the same place as the strong wings, yet whose profiles have not changed.

An alternative is that the line opacities in the broadened line wings have increased for some reason, so that the same point in the wing is now formed somewhat higher up at cooler temperatures than before. It is such an effect that causes the wings of the solar Hα line to actually darken in solar active regions, while the core brightens (Basri et al. 1979). The line-formation problem for Hα is somewhat special; it would not be clear that such an explanation can work for neutral iron lines until a detailed modeling analysis is performed. One means of increasing the wing opacity is through the collisional damping, although evacuated tubes tend to lead to narrower lines. Rather little work has been done on how multicomponent atmospheres will affect the appearance of photospheric lines in nonsolar stars, and we have begun to work on this problem.

Finally, this work has some bearing on the hypothesis of "basal" chromospheric fluxes. The suggestion by Schrijver (1986) that acoustic heating (which does not depend on stellar rotation) is the source of the minimum fluxes observed in cool stars in Mg II, for example, carries with it the implication that such heating should also be observed in the photosphere, where most acoustic flux should be dissipated (Ulemschneider et al. 1978). Anderson and Athay (1989) argue that there is good-evidence that this may be the dominant heating term throughout the solar chromosphere (with additional effects in magnetic regions).

Rutten, Lemmens, and Zwaan (1988) do not see a basal level in stellar transition region lines which, according to current understanding, should be formed almost exclusively at the footpoints of bright coronal magnetic loops. If acoustic waves were the dominant mode of photospheric heating in all cool stars (as it might be on the Sun), then we should not see a similar correlated variation of the photospheric perturbations within the narrow range of spectral types we have examined. In particular, they should not be so strongly associated with variations in Ca II H and K, which is known to be strongly correlated with stellar rotation (implying a magnetic component to the heating mechanism). We must conclude that either a major part of the photospheric heating has essentially the same origin as the chromospheric heating or that the photospheric and chromospheric changes result from the same structures, which in either case must have a definite magnetic component due to the clear rotation-activity connection.

This should not be regarded as a refutation of the basal flux idea. It only means that the photospheric heating is like heating in the upper atmosphere in that it may only be purely acoustic in the least active stars (like the Sun). The range of stellar activity observed is due to the non-acoustic component, and this component can be seen at photospheric levels. Indeed, it may be true in general that the amount of stellar activity is directly a result of the filling factor of this component (without the need to posit structural changes in either the acoustic or magnetically dominated atmospheres). The contrast of this component, though, is clearly lowest in the photosphere and increases as one moves upward in the atmosphere.

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