PHYSICAL PROPERTIES OF SOLAR CHROMOSPHERIC PLAGES

III. Models Based on Ca II and Mg II Observations

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Abstract. We compute a new grid of plage models to determine the difference in temperature versus mass column density structure $T(m)$ between plage regions and the quiet solar chromosphere, and to test whether the solar chromosphere is geometrically thinner in plages. We compare partial redistribution calculations of Mg II h and k and Ca II K to NRL Skylab observations of Mg II h and k in six active regions and Ca II K intensities obtained from spectroheliograms taken at approximately the same time as the Mg II observations. We find that the plage observations are better matched by models with linear (in \log m) temperature distributions and larger values of $m_0$ (the mass column density at the 8000 K layer in the chromosphere), than by models with larger low chromosphere temperature gradients but values of $m_0$ similar to the quiet Sun. Our derived temperature structures are in agreement with the grid originally proposed by Shine and Linsky, but our analysis is in contrast to the study by Kelch which implies that stellar chromospheric geometrical thickness is not affected by chromospheric 'activity'. We conclude that either the stellar Mg II observations upon which the Kelch study was based are of poorer quality than had been assumed, or that the spatial averaging of inhomogeneous structures, which is inherent in the stellar data, does not lead to a best fit one-component model similar in detail to that of a stellar or a solar plage.

1. Introduction

In this paper we model solar plages using observations of both the Ca II K and Mg II h and k lines. A previous grid of models proposed by Shine and Linsky (1974a; hereafter SL), derived by matching observations with complete redistribution calculations of the Ca II lines, led to the results that the chromospheric temperature gradient increases with increasing Ca II emission and that the chromosphere is geometrically thinner in plages. A consequence of increased $m_0$ in their plage models was larger densities at $\tau_{\text{Lyman cont.}} = 1.0$ and thus brighter Lyman continuum emission in agreement with the OSO-IV observations. However, the Ca II line strengths, as we will show, are insensitive to the value of $m_0$. Specifically, SL report observations of approximately a factor of 5 brightening of the Lyman continuum in active regions compared to quiet regions, indicating the Lyman continuum is formed at higher densities in active regions. Unfortunately one cannot accurately model the Lyman continuum without solving the L$\alpha$ radiative transfer equation simultaneously (Avrett and Vernazza, 1977), and to our knowledge no simultaneous L$\alpha$ and Lyman continuum observations exist for the regions for which we

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have simultaneous Ca II and Mg II observations. However, Munro et al. (1971) and Withbroe and Gurman (1973) used the ratios of singlet to triplet lines of C III and O V, which are formed in the transition region less than a scale height above the Lyman continuum, to derive electron density increases of factors of 4 to 10 in active regions, and Dupree et al. (1976) derived increases of factors of 2 to 5. These increases imply similar density increases where the Lyman continuum is formed, which is qualitative evidence that $m_0$ increases in solar active regions.

Recently Kelch et al. (1978) and Kelch (1978) have shown that the chromospheric structure of late-type dwarf and giant stars deduced from modeling Mg II h and k and Ca II K emission fluxes are quite different from what would be deduced using only Ca II data. This is because the Mg II lines thermalize further out in the chromosphere than the Ca II lines and are thus better diagnostics of the upper chromospheric structure. Specifically, Kelch’s (1978) models of the active chromosphere dwarf stars ε Eri (K2 V) and 70 Oph A (K0 V) imply that the difference between ‘active’ and ‘quiet’ chromosphere stars is in the lower chromospheric temperature gradient and that the chromospheric geometrical thickness (inversely proportional to the value of $m_0$) is the same in ‘active’ and ‘quiet’ chromosphere stars of the same gravity. We will, therefore, reexamine the conclusions of SL with both the additional information gained from modeling the Mg II resonance lines and the greater accuracy of the partial redistribution approach.

It is important to reexamine the chromospheric temperature structure in plages to aid in the understanding of the chromospheric mechanical heating and to establish tighter constraints on $T(m)$ and $m_0$ for future acoustic wave models and flux tube models of these regions. Besides the SL plage models, photospheric facular models have been proposed by Shine and Linsky (1974b) based on complete redistribution calculations of the same Ca II data used for their plage models, and by Morrison and Linsky (1978; hereafter ML) based on partial coherent scattering calculations of the wings of Mg II h and k. We use the same Mg II data as ML and, as we both use the partial redistribution approach, our plage models can be regarded as an extension into the chromosphere of their photospheric facular models.

2. Procedures

A. COMPUTATIONAL METHOD AND ATOMIC DATA

Our method of computing model atmospheres and our partial redistribution techniques for calculating profiles of the Ca II K and Mg II h and k lines have been described by Kelch et al. (1978). We use the solar abundances of Ross and Aller (1976), except for the Mount and Linsky (1975) carbon abundance, the Ayres and Linsky (1976) value of Mg/H = 3.89 × 10^{-5}, and the Ayres (1977) value of Ca/H = 2.40 × 10^{-6}. For all models we use a photospheric microturbulence of 2 km s\(^{-1}\), which increases linearly with log \( m \) to 10 km s\(^{-1}\) at \( m_0 \), as adopted by Ayres and
Linsky. We compute profiles for \( \mu = 0.83 \) and 0.50 to match data for the observed plage regions. We use a model photospheric structure interpolated linearly in \( \log m \) between the temperatures \( T = 5740 \text{ K} \) at \( \log m = 0.46 \), \( 5100 \text{ K} \) at \( \log m = -0.4 \), and \( 4600 \text{ K} (T_{\text{min}}) \) at \( \log m = -1.5 \). These model photosphere parameters are the mean of the six models derived by ML for the same six regions used for this study. Since we are primarily interested in analyzing the core emission intensities, our use of an approximate photospheric structure should introduce negligible error in the derived chromospheric models.

For both Ca\(^+\) and Mg\(^+\) we use three-level-plus-continuum representations, solving transfer equations explicitly for the Ca \( \text{II} \) K and Ca \( \text{II} \) \( \lambda 8542 \), and Mg \( \text{II} \) h and k lines. We do not use the more expensive five-level-plus-continuum representation for Ca \( \text{II} \) which would include a solution for Ca \( \text{II} \) H, because simultaneous plage observations in the H line are not available. Also, the computed line core (\( \Delta \lambda = \pm 0.25 \text{ Å} \)) emission ratio \( I(K)/I(H) \) should not differ from the previous complete redistribution solutions of Shine and Linsky (1974a) as the significant partial redistribution effects (outside of center-to-limb variations of \( \Delta \lambda_{K} \)) occur in the \( K_1 \) and inner wing region. We use the same collision cross sections, atomic parameters, photoionization cross-sections, and van der Waals broadening constants as Kelch et al. (1978). Photoionizations are treated as fixed rates using the solar chromospheric radiation temperatures of Ayres (1975).

B. THE OBSERVATIONS

The Mg \( \text{II} \) observations were made from Skylab in August and September 1973 with the Naval Research Laboratory spectrograph and are described by Doschek and Feldman (1977). The calibration to absolute intensities and the correction for instrumental reflectance are discussed by ML, who conclude that the uncertainty in the absolute scale is 10\%. The spatial resolution is 2\( '' \times 60'' \) and the spectral resolution is 0.12 Å. The observed integrated line intensities for each of the plage regions studied by Doschek and Feldman (1977) are given in Table I. These integrated intensities refer to the total energy above zero between the minimum features on either side of the emission core; for example, between \( k_1 \) blue (short wavelength side) and \( k_1 \) red (long wavelength side).

The Ca \( \text{II} \) K data were obtained from patrol K line spectroheliograms of 0.514 Å bandpass, centered on the K line and taken at the Sacramento Peak Observatory. These film images were microdensitometered using the Kitt Peak National Observatory PDS system with a slit size of 2\"\times2\". These spectroheliograms were taken within 12 h of the time of the Skylab observations. We microphotometered the areas corresponding to the NRL spectrograph slit positions as located on the K spectroheliograms by comparing companion Sacramento Peak H\( \alpha \) spectroheliograms with the Skylab H\( \alpha \) spectroheliograms on which the NRL experiment slit positions are indicated (cf. Figure 6 of Doschek and Feldman, 1977). The Ca \( \text{II} \) intensities were calibrated using the step wedge on the original image and the ratio of the mean intensity in the 2\"\times60\" slit to the mean intensity of a large area of quiet
### TABLE I

Observed and computed integrated emission intensities

<table>
<thead>
<tr>
<th>Region Model</th>
<th>$\mu$</th>
<th>$I(k)$(bandpass)$^b$</th>
<th>$I(h)$(bandpass)$^b$</th>
<th>$I(h+k)$</th>
<th>$I(k)$/$I(h)$</th>
<th>$I(K)$ (±0.257 Å)</th>
<th>$R = \frac{I(K)}{I(h+k)}$</th>
<th>log $n_0$</th>
<th>$n_e(m_0)$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.842</td>
<td>2.17(+5)(1.22)</td>
<td>1.63(+5)(0.93)</td>
<td>3.80(+5)</td>
<td>1.33</td>
<td>1.72(+5)</td>
<td>0.45</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>II</td>
<td>0.521</td>
<td>8.92(+5)(1.51)</td>
<td>7.35(+5)(1.37)</td>
<td>1.63(+5)</td>
<td>1.21</td>
<td>1.76(+5)</td>
<td>0.11</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>III</td>
<td>0.500</td>
<td>1.54(+6)(1.63)</td>
<td>1.05(+6)(1.30)</td>
<td>2.60(+6)</td>
<td>1.47</td>
<td>3.57(+5)</td>
<td>0.14</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>IV</td>
<td>0.819</td>
<td>1.65(+6)(1.86)</td>
<td>1.24(+6)(1.84)</td>
<td>2.88(+6)</td>
<td>1.33</td>
<td>4.68(+5)</td>
<td>0.16</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>V</td>
<td>0.826</td>
<td>1.46(+6)(1.58)</td>
<td>1.12(+6)(1.51)</td>
<td>2.58(+6)</td>
<td>1.30</td>
<td>3.44(+5)</td>
<td>0.13</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>VI$^c$</td>
<td>0.842</td>
<td>1.94(+6)(1.63)</td>
<td>1.71(+6)(1.48)</td>
<td>3.64(+6)</td>
<td>1.13</td>
<td>3.83(+5)</td>
<td>0.11</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>III–V</td>
<td>0.72</td>
<td>1.55(+6)(1.69)</td>
<td>1.14(+6)(1.55)</td>
<td>2.69(+6)</td>
<td>1.37</td>
<td>3.90(+5)</td>
<td>0.15</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1</td>
<td>0.83</td>
<td>2.4(+5)(1.2)</td>
<td>2.0(+5)(0.9)</td>
<td>4.4(+5)</td>
<td>1.20</td>
<td>1.66(+5)</td>
<td>0.38</td>
<td>−5.25</td>
<td>3.9(+10)</td>
</tr>
<tr>
<td>2</td>
<td>0.67</td>
<td>4.20(+5)(1.37)</td>
<td>3.61(+5)(1.12)</td>
<td>7.8(+5)</td>
<td>1.16</td>
<td>2.57(+5)</td>
<td>0.33</td>
<td>−5.25</td>
<td>3.9(+10)</td>
</tr>
<tr>
<td>3</td>
<td>0.67</td>
<td>6.85(+5)(1.42)</td>
<td>6.05(+5)(1.26)</td>
<td>1.29(+6)</td>
<td>1.13</td>
<td>4.21(+5)</td>
<td>0.33</td>
<td>−5.25</td>
<td>3.9(+10)</td>
</tr>
<tr>
<td>4</td>
<td>0.67</td>
<td>5.50(+5)(1.42)</td>
<td>4.48(+5)(1.08)</td>
<td>1.00(+6)</td>
<td>1.23</td>
<td>2.62(+5)</td>
<td>0.26</td>
<td>−4.5</td>
<td>2.2(+11)</td>
</tr>
<tr>
<td>5</td>
<td>0.67</td>
<td>1.47(+6)(1.62)</td>
<td>1.09(+6)(1.33)</td>
<td>2.56(+6)</td>
<td>1.35</td>
<td>4.27(+5)</td>
<td>0.17</td>
<td>−4.0</td>
<td>6.4(+11)</td>
</tr>
</tbody>
</table>

$^a$ All intensities are in cgs units (ergs cm$^{-2}$ s$^{-1}$).

$^b$ In Å, from, e.g., $k_1$ blue to $k_1$ red.

$^c$ The peaks of the Mg II emission lines are saturated in the Region VI data.
Sun near disk center. We derived a value of $1.278 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$ from the data of White and Suemoto (1968) for the integrated K line intensity in the quiet Sun at disk center for the spectroheliogram bandpass. The values of the integrated intensities thus found for the six regions are presented in Table I. We expect random errors of 10–20% due mainly to possible errors of a few arcseconds in aligning the microdensitometer slit to correspond with the NRL spectrograph slit.

C. THE GRID OF MODEL CHROMOSPHERES

Our line profile calculations were made using a grid of five model chromospheres designed to test the sensitivity of the Ca II K and Mg II h and k intensities both to increases in the lower chromospheric temperature gradient while keeping $m_0$ fixed, and to increases in $m_0$. (In the second experiment the chromospheric temperature gradient increases as well, and the larger values of $m_0$ force the Mg II lines to form at higher densities since optical depth unity in the h and k lines occurs at or just above 8000 K.) All models use the same photospheric structure, as mentioned earlier, including the same minimum temperature, $T_{\text{min}} = 4600$ K, located at $\log m(T_{\text{min}}) = -1.5$. All of our models also assume the same temperature at the top of the chromosphere, $T_0 = 8000$ K, and assume that the temperature rises very steeply above this point. Our model parameters are $T_{\text{hinge}}$ and $m_{\text{hinge}}$ (if used) and $m_0$. (A hinge point is a location where the chromospheric temperature gradient, $dT/d\log m$, changes.) The five models are shown in Figure 1, together with the Ayres and Linsky (1977) ‘Ca II’ and ‘Mg II’ (photosphere only) quiet Sun models and the VAL model (Vernazza, Avrett and Loeser, 1976).

![Figure 1](image_url)

Fig. 1. Shown are the grid models used in this paper, the Ayres and Linsky (1976) ‘Ca II’ and ‘Mg II’ (photosphere only) models, and the VAL model. For Models 2 and 3, $\log m_{\text{hinge}} = -4.0$ and $T_{\text{hinge}} = 7450$ K and 8000 K, respectively. For Models 4 and 5, $\log m_0 = -4.5$ and $-4.0$, respectively. For Models 1, 2, and 3, $\log m_0 = -5.25$. 

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3. Results and Discussion

In Table I we compare the computed integrated emission intensities for the five atmospheric models with observations for regions I–V, and an average of regions III through V, which appear to be a homogeneous set. In region VI the Mg II intensity is underestimated due to film saturation. Region I is basically a quiet Sun area and region II has line intensities intermediate between those of region I and typical plage regions. The computed intensities, except for Model 1, are an average of the intensities at $\mu = 0.83$ and 0.50. We give average intensities because the observations for regions III–V are at both $\mu$ values, and the differences between the $\mu = 0.83$ and $\mu = 0.50$ computed intensities are small compared to the range of observed intensities. (The $\mu = 0.50$ Ca II K integrated emission intensities are 12–15\% smaller than for $\mu = 0.83$, whereas the Mg II results are smaller by less than 5\%.) The Ca II K intensities are all integrated over a bandpass of 0.514 Å centered on the K line.

The computed Mg II integrated intensities are for the bandpass between the ‘blue’ and ‘red’ k$_1$ and h$_1$ features. Although the wavelength separation of the k$_1$ and h$_1$ features differs slightly from model to model and among the observations, our computed Mg II emission profile widths well match the observations for all regions, except for region IV which has broader emission lines. This discrepancy could result from the chromospheric turbulence being greater or of a different nature (macroturbulence or intermediate scale turbulence) than our assumed microturbulence, or perhaps $m(T_{\text{min}})$ being greater than assumed. No combination of these effects, however, could substantially alter our derived chromospheric parameters.

The computed intensities for Models 1, 2 and 3 strongly suggest that no model in which $T(m)$ is concave downward can match both the Ca II K intensities and the Mg II h and k intensities for any plage region other than region I, which is nearly quiet Sun. Also, neither Model 2 nor 3 show an increase in electron density where the Lyman continuum is formed. Region I could be matched by a model which has a small chromospheric temperature gradient similar to that of Model 1, and which has a hinge point in the upper chromosphere and log $m_0 \approx -5.5$. Region II appears to require a lower chromospheric model like that for region I, but concave upwards with a hinge point near log $m \approx -3.75$ and log $m_0 \approx -4.25$. All the other regions require models similar to Model 5.

The sensitivity of the Mg II intensities to the value of $m_0$, as contrasted with the insensitivity of the Ca II K intensity to $m_0$, is shown by comparing the results for Models 2 and 4 and especially Models 3 and 5. This conclusion is also evident from the $R = I(K)/I(h + k)$ ratios, for which only Model 5 is consistent with the observed value in the active regions. Also, values of $m_0$ larger than that for the quiet Sun are required to produce the observed $I(k)/I(h)$ integrated intensity ratios for Regions III–V. The agreement for both $R$ and $I(k)/I(h)$ between Model 5 and Regions III–V is strong evidence that Model 5 is a realistic model for spatially-averaged
typical plages. Also Model 5 exhibits an increase in electron density where the Lyman continuum is formed \([n_e(m_0) \text{ is proportional to } m_0]\), similar to that derived for plage transition regions.

Errors of 10% in the Mg \(\text{II}\) intensity scale and random errors of 10–20% in the Ca \(\text{II}\) intensities cannot affect the present conclusions regarding solar plages. However, the effects of spatial averaging by the \(2''\times60''\) slit must be considered. The slit size of the microdensitometer used to make the raster scans of the K spectroheliograms was \(2''\) square on the scale of the Sun's image. These scans show bright patches \(5''\) to \(10''\) across. The peak intensities in Regions IV and VI, which show the largest contrast across the \(2''\times60''\) slit, are about 1.6 times the average over the \(2''\times60''\) slit. The corresponding contrast in the Mg intensity may be similar. Hence, the observations we are using sample a range of conditions and our models represent the average chromospheric structure observed within the slit.

We conclude that the basic plage model grid proposed by SL is still valid when the Mg \(\text{II}\) lines are included in the analysis and the Ca \(\text{II}\) and Mg \(\text{II}\) lines are analyzed using partial redistribution diagnostics. The question arises as to what causes the increase in the chromospheric temperature gradient and the increase in \(m_0\) in plage regions. Withbroe and Noyes (1977) estimate that the total chromospheric radiative losses in typical plage regions are 5 times that of the quiet Sun. This result requires additional nonradiative heating in plage regions, which is consistent with a steeper temperature gradient. The increase in \(m_0\) in plage regions then follows from the ionization of hydrogen near 8000 K and resultant decrease in the radiative efficiency of this plasma.

Our picture of solar plages is self-consistent, but it lacks a detailed description of the nonradiative heating process. Withbroe and Noyes have summarized recent calculations of heating by hydromagnetic waves, but they also state that heating by the dissipation of magnetic energy is an alternative possibility. We feel that semi-empirical plage temperature structures are now sufficiently well understood that it is feasible to derive the spatially-averaged nonradiative heating as a function of mass column density for testing against the various proposed heating mechanisms.

4. Comparison with Stellar Active Chromosphere Models

Our plage temperature structures are not in agreement with the results implied by Kelch's (1978) study of the active chromosphere stars \(\epsilon\) Eri (K2 V) and 70 Oph A (K0 V). His models for these two stars are characterized by steep lower chromospheric temperature gradients (needed to match the observed Ca \(\text{II}\) K flux) and subsequent temperature plateaus near 7000 K out to \(\log m_0 = -6.0\) (needed to reduce the computed Mg \(\text{II}\) fluxes to values as small as observed). This value of \(m_0\) is somewhat smaller than the values obtained for other dwarf stars (including the Sun) which are 'quiet' chromosphere stars, as defined by their relatively small Ca \(\text{II}\) line emission. These models imply that 'active' chromosphere stars are characterized by steeper lower chromosphere temperature gradients but values of \(m_0\)
similar to 'quiet' chromosphere stars. Kelch noted that a factor of two error is required in the Mg II fluxes to change these conclusions. If the stellar Mg data are approximately correct, then we might conclude that solar plages and 'active' chromosphere K dwarf stars differ either in the magnitude or type of physical processes which cause the 'activity' we observe. For example, we do not know the magnetic field configurations and properties of other late-type stars, except that there is evidence that the global average field in certain apparently young dwarf stars may be stronger by two orders of magnitude (Boesgaard, 1974) than that for the Sun but similar to values commonly cited for plage regions at a spatial resolution of $2 \times 60$ arc sec.

There is an alternative explanation for the apparent discrepancy between the $T(m)$ shapes in solar plages and those for 'active' chromosphere K dwarf stars. The stellar observations are global averages presumably including both plage and nonplage regions. It is possible that by simulating this inhomogeneous atmospheric structure with a one component model, we have been led to a model which is not representative of either the plage or nonplage regions, and thus should not be compared with solar plages. We cannot comment further on the discrepancy until completion of a larger program now underway of comparisons between 'active' and 'quiet' chromosphere stars covering a range of spectral types.

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