CIRCULAR POLARIZATION OF THE Ca II H AND K LINES
IN SOLAR QUIET AND ACTIVE REGIONS

V. Martínez Pillet, R. J. García López, J. C. del Toro Iniesta,
R. Reboiro, M. Vázquez, J. E. Beckman, and S. Char
Instituto de Astrofísica de Canarias, La Laguna, Tenerife
Received 1990 March 2; accepted 1990 July 12

ABSTRACT

We present a representative set of profiles of the Ca II H resonance line in Stokes V and I, for the quiet Sun, plages, sunspot umbrae, and a flare, as well as one example of the Ca II K line in a sunspot penumbra. The degree of polarization is highest in the spots and zero in the quiet Sun, within error limits. The V profile asymmetries are, however, highest in the flare. From the spectra of the Ca II K line, we have obtained a linear relation between V(\lambda) and -dI/d\lambda, allowing us to derive a value for B, of 820 (+40) G using the weak field approximation. The availability of chromospheric polarization data is important in permitting comparison of chromospheric magnetic fields with those in the underlying photosphere.

Subject headings: Ca II emission — polarization — Sun: chromosphere — Sun: magnetic fields

I. INTRODUCTION

Much of our knowledge about the solar chromosphere is due to the observation and theoretical interpretation of the strong non-LTE Ca II H and K lines (see, e.g., the paper discussing these lines by Linsky 1970). The appearance of significant emission cores is related to the presence of magnetic activity (see, e.g., Skumanich, Smythe, and Frazier 1975; Schrijver et al. 1989), as measured in the photosphere in lines such as Fe i 5250.22 Å. It would be interesting to find a way to relate the behavior of the cores of the Ca II lines to the local magnetic field present at the height where the emission signature takes place, i.e., to measure the chromospheric magnetic field. Recently, Lites et al. (1988 and references therein) have studied the Stokes I, Q, U, and V parameters of some chromospheric lines showing how to obtain valuable information about the magnetic field via the analysis of the polarimetric properties of these lines. However, no observations of the polarization state of the calcium lines in magnetic areas have been presented in the literature. As pointed out by Lites et al. (1988), this could be due, in part, to the relative inefficiency of many of the modern detectors at the relevant wavelengths. As far as the Stokes V parameter (circular polarization) is concerned, we cannot expect an appreciable signal level from the far wings of these lines (Stenflo 1985). The steep features in the core of these lines on the other hand, both the emission peaks and the K self-reversals, should show measurable levels of polarization.

The polarization of the anomalously split Ca II K line was analyzed, from the theoretical point of view, first by Auer, Heasley, and House (1977) neglecting magneto-optical effects and, more recently, by Rees, Murphy, and Durrant (1989) who include these effects in the analysis. Both papers agree in establishing that the nonmonotonic dependence of the source functions on the optical depth for these lines gives rise not only to the K_2 (H_2) peaks and K_3 (H_3) self-reversal in the I profiles, but also to a complicated pattern in the V profiles. Rees, Murphy, and Durrant (1989) conclude that studies of the V reversals should be very useful when constructing models of the chromosphere in magnetic regions.

The Ca II H line is more suitable for circular polarization analysis than the K line because it has a slightly larger effective Landé factor (g_H = 1.333 while g_K = 1.167, in LS coupling) and because, being a \j = \j + \j transition, no linear polarization can be produced in the very core of this line as result of resonance scattering (Stenflo 1980; Landi Degl'Innocenti 1984). In this Letter we show I and V profiles of these two lines. As far as we are aware, this is the first time that such circular polarization profiles have been published. Some characteristic parameters of the profiles are determined and tabulated.

II. OBSERVATIONS AND DATA REDUCTION

The observations were made at the German Grégory-coudé Teleskop at the Spanish Observatorio del Teide. The observational period coincided with zero Sun declination, thus avoiding instrumental polarization effects (Wiehr 1971; Sánchez Almeida 1988). The circular polarimeter we used is similar to that described by Semel (1980). This instrument provides, as output, simultaneous I ± V images of a given zone of the Sun. In order to check this behavior we have performed laboratory measurements yielding, at \lambda = 4000 Å, an I_\text{output} of

\[
I_{\text{output}} \propto [I + (-0.10 \pm 0.04)Q + (0.03 \pm 0.06)U + (0.995 \pm 0.004)V], \tag{1a}
\]

\[
I_{\text{output}} \propto [I + (-0.10 \pm 0.04)Q + (0.03 \pm 0.06)U - (0.995 \pm 0.004)V], \tag{1b}
\]

where I, Q, U, and V correspond to the input Stokes parameters. Equation (1) allows us to obtain an estimate of the contamination of our observations due to linear polarization. To do this, we assume that the synthetic profiles given by Rees, Murphy, and Durrant (1989) form the input of the analyzer. These profiles correspond to a 3000 G magnetic field strength and an inclination of \pi/4 with respect to the line of sight. Using the maximum value for the polarization signals in Q, U, and V which are produced at \Delta \lambda = 120 mÅ from line center, the ratio between linear and circular polarization is...
The width of the entrance slit of the spectrograph was set at 170 μm (1.4”) allowing a spectral purity of 0.0197 Å. The dispersion, in the focal plane, was 0.116 Å mm⁻¹. The film used was Kodak 2415 which has good sensitivity in the blue and very small grain size, thus providing relatively high signal-to-noise ratios and not limiting the spectral resolution. An interference filter (λ₀ = 3942 Å; Δλ = 50 Å) was used to prevent contamination due to light from other spectral orders. Due to the low transmission efficiency of this filter, the exposure time, 70 s, was particularly high. However, the spatial resolution achieved in moments of good seeing was near 2″ or even better, exhibiting, in the best data, a conspicuous granulation “wiggle” on the photospheric lines. Slit-jaw video pictures were simultaneously obtained. We present data for the days 1989 September 20 and 21. The active region studied was located at E14-S24 (μ = 0.83) on the first day and at E05-S24 (μ = 0.85) on the following day. The associated spot group showed a δ-type configuration with a great amount of flare activity. Four different spots were easily discerned in the group, as well as several pores.

The spectrograms were digitized with the PDS microdensitometer of the IAC using a rectangular slit of 200 × 100 μm² (= 1′.6 × 0.01 Å). The data were converted into intensities using a step-wedge filter of known transmission. The reduction procedure after intensity calibration was somewhat complex. Due to gradients of illumination of the spectral direction of the images, the spectra showed small tilts after correction for the filter transmission. These tilts were corrected assuming the photospheric wings of the Ca II lines to be symmetric, as described by Rebolo et al. (1989). The last step in the data reduction was the wavelength calibration, which was made using several unblended photospheric lines located at either side of the line center; the wavelength values for these lines were taken from the solar atlas of Moore, Minnaert, and Houtgast (1966).

## III. RESULTS AND DISCUSSION

In Figure 1 we present a sample of profiles in I (left panels) and V (right panels) of the Ca II H line formed in different types of solar surface regions: quiet Sun, plage, a spot umbra, and a flare located in a plage; we have also included the Ca II K line profiles in I and V formed in a spot penumbra. Only the cores have been represented in the V plots. The first point to be noted is that we find nonzero V signal in the H and K line cores in each observed region, except in the quiet Sun (within error limits). It can be noted how emission cores and Stokes V signals are stronger, with respect to their adjacent pseudocontinuum, in spots than in plages. The more complicated pattern shown by the plage V profiles can be mostly attributed to the presence of self-reversals in the corresponding I profiles (cf. Auer, Hassey, and House 1977; Rees, Murphy, and Durrant 1989). In the figure we have also included the derivatives of the I profiles with respect to λ. These are to be compared with the V profiles, since the two quantities should be proportional if the weak field approximation is valid (see e.g. Landi Degl’Innocenti and Landi Degl’Innocenti 1973; Jefferies, Lites, and Skumanich 1989; Landi Degl’Innocenti 1990). The Ca II H and K cores are particularly suitable for the application of this approximation, since the effective Landé factors of their transitions are small, their FWHM are large, they are situated in the blue, and they are formed well above the photosphere.

In Table 1, some scale-independent parameters of the spectra that we have analyzed are listed. In column (2), δ is an indicator of the degree of polarization. It is calculated as the average value of the ratios between I and V at the wavelengths where the maxima and minima of the V profiles are reached. The degree of polarization is higher in spots than in plages and the flare and zero in the quiet Sun, within error limits. This is clearly interpretable qualitatively as a consequence of the presence of higher magnetic fluxes in the spots.

Columns (3) and (4) contain values of parameters related to the so-called V profile asymmetries in studies of sunspots and small-scale magnetic concentrations in the photosphere. It is well known that in absence of mass motions, V profiles must be strictly antisymmetric (Landi Degl’Innocenti and Landi Degl’Innocenti 1981). Photospheric profiles are asymmetric, so that the asymmetry properties provide valuable information about the physical conditions in the magnetic structures (Sánchez Almeida, Collados, and del Toro Iniesta 1989 and references therein). In this Letter, the definition of these parameters is a little different from the usual definitions, in order to make direct comparison between sunspots and plages. Aᵥ and \( aᵥ \) are defined as

\[
Aᵥ = \frac{\int_\lambda_1^{\lambda_2} V(\lambda) \, d\lambda}{\int_\lambda_1^{\lambda_2} |V(\lambda)| \, d\lambda}, \quad aᵥ = \frac{V_{max} + V_{min}}{|V_{max}| + |V_{min}|},
\]

where \( \lambda_1 \) and \( \lambda_2 \) are the wavelengths of the limits of the emission cores, and \( V_{max} \) and \( V_{min} \) are the maximum and minimum values of the V profile, respectively. These parameters indicate the asymmetries in integrated value and in the peaks, respectively, and are different from zero in all the spectra analyzed, except for plage 2. In the two quiet Sun regions observed, their

### Table 1

<table>
<thead>
<tr>
<th>Region</th>
<th>δ</th>
<th>( Aᵥ )</th>
<th>( aᵥ )</th>
<th>( Aᵢ )</th>
<th>( aᵢ )</th>
<th>( \lambda₁ (Å) )</th>
<th>( \lambda₂ (Å) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umbra 1</td>
<td>0.212</td>
<td>0.324± 0.004</td>
<td>-0.070± 0.006</td>
<td>19.5±0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Umbra 2</td>
<td>0.174</td>
<td>0.408± 0.008</td>
<td>0.04± 0.02</td>
<td>25.8±0.6</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Penumbra*</td>
<td>0.094</td>
<td>-0.040±0.010</td>
<td>-0.06± 0.01</td>
<td>26.9±0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Flare</td>
<td>0.079</td>
<td>0.43± 0.02</td>
<td>0.28± 0.04</td>
<td>32.5±0.9</td>
<td>3968.475</td>
<td>3968.479</td>
<td>...</td>
</tr>
<tr>
<td>Flare</td>
<td>0.065</td>
<td>0.0±0.1</td>
<td>0.0±0.2</td>
<td>45±4</td>
<td>3968.475</td>
<td>3968.478</td>
<td>...</td>
</tr>
<tr>
<td>Flare</td>
<td>0.084</td>
<td>0.12±0.05</td>
<td>0.21±0.14</td>
<td>45±4</td>
<td>3968.476</td>
<td>3968.480</td>
<td>...</td>
</tr>
<tr>
<td>Flare</td>
<td>0.109</td>
<td>-0.16±0.06</td>
<td>0.50±0.08</td>
<td>43±3</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Flare</td>
<td>0.038</td>
<td>-0.94±0.04</td>
<td>-0.78±0.16</td>
<td>34±2</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

* Ca II K line in a spot penumbra.
Fig. 1.—Six examples of $I$ (left panels) and $V$ (right panels) profiles obtained at different locations on the Sun for the H and K lines. Only the cores of the Ca II lines have been included to describe the observed $V$ profiles (solid lines). The derivatives of $I$ with respect to $\lambda$ are also plotted for comparison (dotted lines). They have been scaled to represent a 1000 G field strength, in the weak field approximation. The labels in each panel refer to Table 1.
values are, within the limits of our observational errors, compatible with zero. The highest values of both parameters were measured in the flare, where it is apparent that the $V$ profile does not show a zero crossing, an interesting observation which deserves further interpretation. The errors have been calculated after estimating the standard deviation of the spectra in their pseudocontinua which, in the $I$ profiles, are of the order of 1\%–2\%.

Theoretical synthesis of these lines by Auer, Heasley, and House (1977) and by Rees, Murphy, and Durrant (1989) does not show any asymmetry; indeed, they only model half of the Ca $\Pi$ profiles. However, the asymmetries found here strongly suggest that velocity fields are by no means negligible and should be considered as an important ingredient of future models. In particular, the flare, where very large velocities are known to occur (see, e.g. Canfield 1986), shows the strongest asymmetry among the observed $V$ profiles.

The intensity profiles, $I$, in the Ca $\Pi$ H cores are clearly asymmetric in sunspots and show double peaks in plages as already known (Linsky 1970; Shine and Linsky 1972; Mattig and Kneer 1978; Thomas, Cram, and Nye, 1984). Column (5) shows the integral of the $I$ emission core normalized to its maximum value. Its error has been calculated similarly to those of the other parameters. In Table 1 we have also tabulated our measurements of the positions of the self-reversals in three of the observed plages. They were obtained using a standard technique of fitting via two Gaussians, one in absorption (giving as its central wavelength the position $\lambda_{A}$) and the other in emission (giving as its central wavelength the position $\lambda_{E}$), as described by Crivellari et al. (1987). These two wavelengths were determined with an accuracy of $\pm 1$ m\AA. The self-reversal is displaced to the redward of the $\lambda_{E}$, with a difference $\Delta = \lambda_{E} - \lambda_{A} \approx 4$ m\AA, comparable to the values which were recently found by Rebolo et al. (1989) in late F-type to K-type stars in the solar neighborhood following the same technique. We also point out a notable feature in the $I$ profiles of sunspots: in these, the He line (3970.07 Å) appears in emission. Giampapa et al. (1981) already noted that He shows up in emission in dMe stars (the spectral type of sunspots is between late K and M). From our spectra one can infer a positive correlation, in sunspots, between the He intensity and that of the Ca emission cores. Moreover, in umbra 1, a small Stokes $V$ signal has been detected in He.

In previous studies, e.g. that by Rees, Murphy, and Durrant (1989), attention has been drawn to the importance of comparing the observed values of $V(\lambda)$ with $-dl/d\lambda$. Only in the observation of the Ca $\Pi$ K line do we find a clearly linear relationship between these quantities, shown in Figure 2a. In this case, the weak field approximation seems to be in order and allows us to infer a value of the longitudinal component of the magnetic field, $B_{z}$, of 820 ($\pm 40$) G. In the remaining spectra, these plots look more complicated. In the plages and the flare the scatter is large. In the two umbral observations, these plots look like Figure 2b. The fact that in the penumbra the $I$ profile shows the greatest degree of symmetry, and the $V$ profile the closest approach to antisymmetry suggests that the approximation is most applicable in this case. This could indicate that the explanation of the differences found between Figures 2a and 2b lies in the precise applicability of the weak field approximation and not in intrinsic differences between the H and K lines.

In conclusion, this first sample of $V$ profiles in the core of the Ca $\Pi$ lines demonstrates a varied phenomenology of the fourth Stokes parameter, which appears to be as rich as the hitherto better explored phenomenology of the first Stokes parameter, $I$. The acquisition of a statistically significant sample of characteristic parameters of the $V$ profile in different solar regions should be pursued. This will help toward a better understanding of the chromospheric magnetic field and, at the same time, provide information important for studies of stellar activity.

It is a pleasure to acknowledge Meir Semel, who kindly provided his polarimeter, and Egidio Landi Degl’Innocenti, who encouraged us after fruitful discussions. We thank the anonymous referee for his useful comments. This work was partially supported by the Spanish CICYT under project PB87-0521.

REFERENCES


J. E. BECKMAN, J. C. DEL TORO INIESTA, R. J. GARCÍA LÓPEZ, V. MARTÍNEZ PILLET, R. REBOLO, AND M. VÁZQUEZ: Instituto de Astrofísica de Canarias, E-38200 La Laguna (Tenerife), Spain

S. CHAR: Institut d'ASTrophysique Spaciale /L.P.S.P.B.P., 10-91371 Verrières Le Buisson Cédex, France