MEASUREMENT OF THE FULL STOKES VECTOR OF HE I 10830 Å

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Abstract. First observations of the full Stokes vector in the upper chromosphere are presented. The He I 10830 Å line, which has been shown to give reliable measurements of the line-of-sight component of the magnetic field vector, has been used for this purpose. It is shown that the difference between the appearance of chromospheric and photospheric magnetic structures observed close to the solar limb is largely due to the difference in height to which they refer and projection effects. The observations do suggest, however, that the magnetic field above sunspot penumbrae is somewhat more vertical in the chromosphere than in the photosphere.

Key words: Chromosphere – Polarization – Infrared – Magnetic Field

1. Introduction

Only few measurements of the upper chromospheric magnetic field exist. All of them are restricted to a single magnetic vector component, i.e. they are based on only a single polarized Stokes parameter. Simultaneous and cospatial measurements of all the components of the magnetic vector would be of great interest. In the upper chromosphere the ratio of magnetic to gas pressure is much larger than in the photosphere and consequently more closely representative of coronal conditions. Measurements of the magnetic vector in the upper chromosphere consequently are better starting values for the extrapolation of the magnetic configuration into the corona, or can at least be used to test the predictions of extrapolations that start in the photosphere.

The He I 10830 Å line has been shown to be a convenient and useful diagnostic of the line of sight component of the magnetic field vector (Penn *et al.*, 1995; Rüedi *et al.*, 1995a). Due to its narrow range of formation in the upper chromosphere it gives direct information on that layer, in contrast to

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lines such as, for example, Hα, which are formed over a much larger height range.

In the present paper we point out that He I 10830 Å is also suited for the measurement of the other components of the magnetic vector and demonstrate that simultaneous and cospatial measurements of all the components of the Stokes vector can be carried out using current detectors and polarimeters.

2. Observations

The observations presented here were carried out on 9 Feb. 1995 at Kitt Peak. The McMath-Pierce telescope was used with the main spectrograph and the visible grating in combination with ZIMPOL I (Povel, 1995; Povel *et al.*, 1990, 1994; Keller *et al.*, 1992), a vector polarimeter consisting of three separate CCD cameras that simultaneously records $I \pm V$, $I \pm Q$, and $I \pm U$.

The observations covered the wavelength range from 10823 Å to 10836 Å. The pixel size was $3.23 \cdot 10^{-2}$ Å in the spectral direction and 0.36″ in the spatial direction. The resolving power was 85 000.

The slit was positioned along the solar N-S direction. Stokes Q and U each made an angle of 22.5° to the slit. The observed feature was a sunspot (NOAA 7838) located close to the eastern solar limb at $\mu = \cos\theta = 0.3$ with the coordinates N 09 E 71. The slit was first placed through the umbra. Then it was moved to the outer edge of the eastern (limb-side) penumbra and stepped through the penumbra in the direction of the umbra in steps of roughly 3″. Spectra were recorded at a total of 6 slit positions. The integration time was 10 minutes at each position. The long integration time was needed because of the high S/N ratio required to measure linear polarization signals in the He I line and the low quantum efficiency of the CCD at this wavelength.

3. Data Reduction

The reduction procedure included the removal of the dark current, flat-fielding, correction for the difference of illumination of the CCD rows for each pair of opposite polarization and calibration of the relative positioning of the cameras. The modulation efficiency along the slit was determined and taken into account.

Every second row of the CCD is covered with an opaque mask (see Povel *et al.*, 1994). While this mask is very effective in providing a storage area for charges in the visible, the scattering of photons in the near-infrared in the silicon substrate leads to an apparent leakage under the mask. This reduction in the efficiency of the polarization measurements was calibrated and removed during the data reduction.

Strong *modulated* interference fringes affect our data. They are produced by the piezo-elastic modulators. The appearance of modulated interference fringes is a problem intrinsic to all variable retarders (Oakberg, 1995). Multiple reflections between the two surfaces, between which the optical path length is varied, lead to spectral fringes. The optical path length changes in synchrony with the polarization modulation, and this change results in a change of the fringe pattern. Even when the incoming light is unpolarized there will be a fringe-like polarization pattern in the polarized spectrum due to the fringe pattern varying in synchrony with the polarization modulation. Anti-reflective coatings and tilting of the modulators strongly reduce their amplitude. Generally these fringes are of no importance, since their amplitude is below the noise level when the coating is appropriate for the observed wavelength range. ZIMPOL is optimized for the visible, so that the anti-reflective coatings are not very efficient at 1.1 μm. In addition, the instrumental set-up did not allow us to tilt the modulators significantly.

Due to their polarized character these fringes cannot be removed by simple flat fielding. We removed (or reduced) them in the following way. First of all, those fringes that were neither parallel nor perpendicular to the slit direction were removed by 2D-Fourier filtering. If the spectrum is not known in advance, fringes parallel to spectral lines are hard to remove in this manner. We then employed the following approach: Since the polarization signal in the continuum is only due to the modulated fringes, we could fit an autoregressive model to the fringe pattern in the continuum and use this model to predict the fringe pattern at the location of spectral lines. This method is similar to linear predictive coding and represents a maximum entropy interpolation. We were not able to fit simple periodic functions because of optical distortions in the spectra. Using this procedure, the amplitude of the fringes could be reduced by at least a factor of 10.

4. Results

Sample CCD frames corresponding, from top to bottom, to the four Stokes parameters I, V/I_c, Q/I_c, and U/I_c are plotted in Fig. 1. They were recorded in the limbside penumbra of the sunspot ($\mu = 0.3$). The strong line in the left half of the plots is the Si I 10827.14 Å line, a photospheric line with a Landé factor of 1.5. The upper chromospheric He I line, which actually consists of three components, is located at 10830 Å. Two of these components are blended together at 10830.3 Å, the third is the very weak line that appears at 10829.0 Å. Some fringes are still present in Stokes Q at the position of these

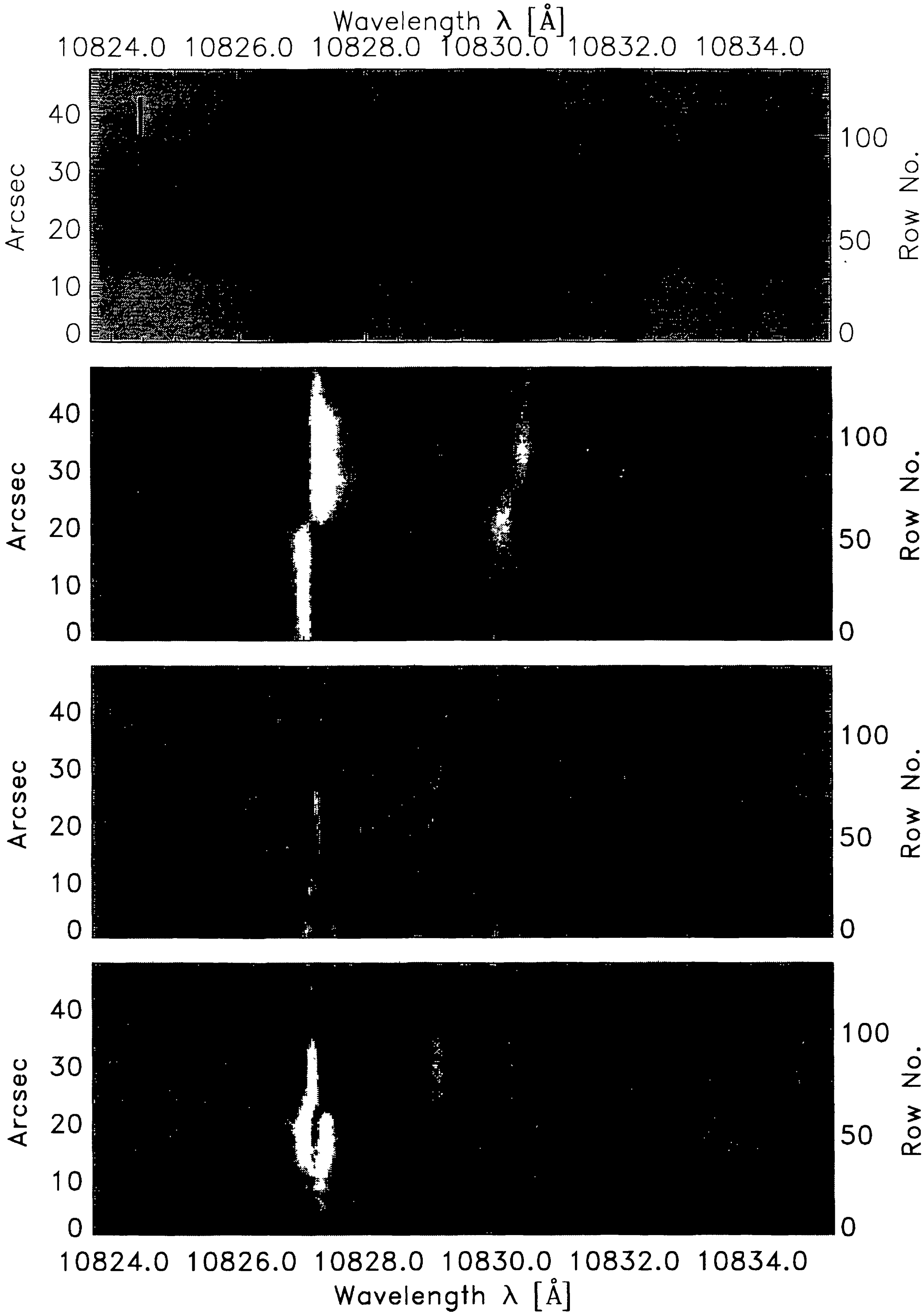

Fig. 1. CCD frames of Stokes I, V/I_c, Q/I_c, and U/I_c recorded simultaneously in a limbside sunspot penumbra at $\mu = \cos\theta = 0.3$. The vertical scale on the left of the plots gives the position along the slit in arcsec. The scale on the right indicates the row numbers of the CCD.

spectral lines, while they have been removed almost completely in Stokes V and U.

The photosphere and chromosphere (as represented by the Si I and He I lines, respectively) possess on the whole similar polarization signals. For example both lines show a sign reversal in Stokes V. In Stokes Q only little signal can be seen above the noise (or rather fringe) level in the helium line, while in Stokes U a distinct signal is seen in the upper part of the panel. In the lower part, a very weak signal can be distinguished in the helium line at a few places. Its weakness may be due to the reduced field strength expected in the chromosphere and the small Landé factor of this line. The He I Stokes U signal has the same sign as that of the silicon line, i.e. reversed relative to the upper part of the panel, although the S/N ratio is very low in the lower part (however, averaged profiles distinctly show the reversal of the sign of Stokes U).

In Fig. 2 we show a Stokes vector spectrum. The plotted profiles are averages over rows number 81–90 of Fig. 1. A distinct Stokes U signal is present in both apparent line components of the helium line (at 10829.0 and 10830.3 Å). The signal seen in Stokes Q is a mixture of true signal and fringes that could not be removed completely (the remaining fringes can be seen clearly in the Stokes Q panel of Fig. 1).

The plotted He I Stokes profiles represent the first detections of the full Stokes vector coming from the upper chromosphere and demonstrate that He I 10830 Å may be used to measure the full magnetic vector in the chromosphere.

One striking feature of Fig. 2 is the difference in relative strength between the weak and strong He I spectral components in the various Stokes parameters. The ratio of the 10829 Å component's amplitude (respectively line depth) to that of the 10830 Å component increases from the Stokes I profile, over Stokes V to Stokes Q and U, for which both components show almost equally strong signals. The main cause for this difference is the fact that the strength of the Stokes V profile is proportional to g_{eff}, while for Stokes Q and U it is proportional to g_{eff}^2. Since the 10829 Å component has $g_{\text{eff}} = 2$, while the 10830 Å component has $\langle g_{\text{eff}} \rangle = 1.22$ (weighted average over the two sub-components) it is clear that the increasingly strong weighting by g_{eff} when going from Stokes V to Stokes Q and U will lead to the observed effect.

Another factor which influences the relative strength of the two separate line components is saturation. It has a particularly large effect on the π-component of Stokes Q and U. The σ-components of the Stokes U profile at 10830 Å are considerably stronger than those of the 10829 Å line. The π-components are, however, almost equal in strength. This and the spectral shape of the Stokes U profiles suggest that the He I line in this sunspot is

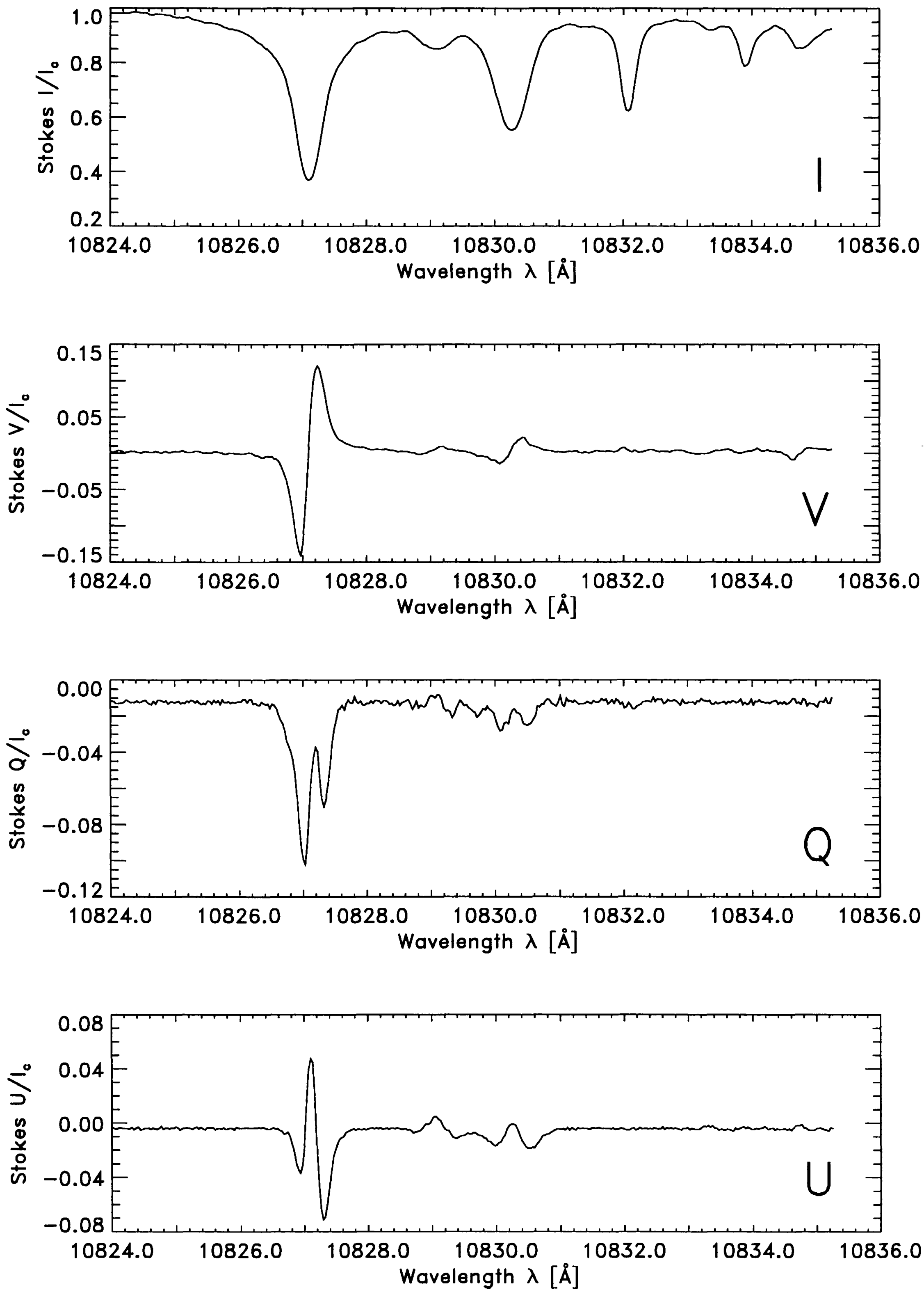

Fig. 2. From top to bottom: examples of Stokes I, V, Q, and U profiles extracted from Fig 1. They correspond to an average of spectra 81–90 of Fig. 1.

significantly saturated, confirming the suggestion by Rüedi *et al.* (1995b) that this may generally be the case above sunspots near the solar limb.

The Stokes Q and U profiles of the Si I line show very large asymmetries. In Stokes U, for which the fringes could be properly removed over the whole spectrum, both components of the He I line show an asymmetry similar to that of the Si I line. These asymmetries are produced by cross-talk from Stokes V into Stokes Q and U and have not been removed in the preliminary data reduction. *

In spite of the similarities the photospheric and chromospheric Stokes profiles exhibit significant differences. In Stokes V, for example, the polarity reverses at row number 57 in the photosphere but at row 75 in the chromosphere. Fig. 3 shows Stokes V profiles corresponding to different spatial positions in Fig. 1. The top panel corresponds to row numbers 84–88. At that position both lines show the same magnetic polarity. In the second panel from the top, corresponding to row Nos. 73–77, the Si I line still shows a strong signal of the same polarity as above, while the He I line Stokes V profile has disappeared. The apparent neutral line in the chromosphere is located at this position. In the third panel of Fig. 3 (corresponding to row Nos. 55–59 in Fig. 1) the Si I line shows hardly any signal, while the He I Stokes V profile exhibits the opposite polarity to that in the first panel. The neutral line in the photosphere is located here. Finally at row Nos. 46–50 (bottom panel) both lines show a signal again.

Is the different position of the neutral line in the chromosphere and photosphere produced by a strong height evolution of the magnetic structure of the sunspot penumbra or is it just due to a projection effect? In order to settle this point we consider the whole Stokes V scan through the penumbra. Four adjacent Stokes V CCD frames are plotted in Fig. 4. The top panel was recorded closest to the solar limb at the outer edge of the penumbra, while the lowest panel was recorded closest to the sunspot umbra. Firstly, closer to the umbra the position of the neutral line in the Si I line is shifted upwards suggesting that the neutral line runs at an angle to the slit, which cuts it at different latitudes as the slit is moved in the E-W direction. This phenomenon can also be seen in the helium line in the two uppermost frames where the neutral line position is clearly defined. In effect, the chromospheric neutral line positions in the two topmost frames correspond closely to the photospheric neutral line positions in the third and fourth frames (which have been recorded further from the solar limb). In summary, the neutral line in the chromosphere lies closer to the white-light limb than the apparent

* In principle this cross-talk can be calibrated by observing the nearby phosphorus line at 10597 Å. This line has a Landé factor $g_{\text{eff}} = 1.333$. Due to the configurations of its atomic levels, this transition produces no linear polarization (Vela Villahoz *et al.*, 1994). Consequently, any signal observed in its Stokes Q or U spectrum has to be produced by cross-talk from Stokes I or V and can thus be used to directly determine the amount of cross-talk also affecting the Si I and He I lines.

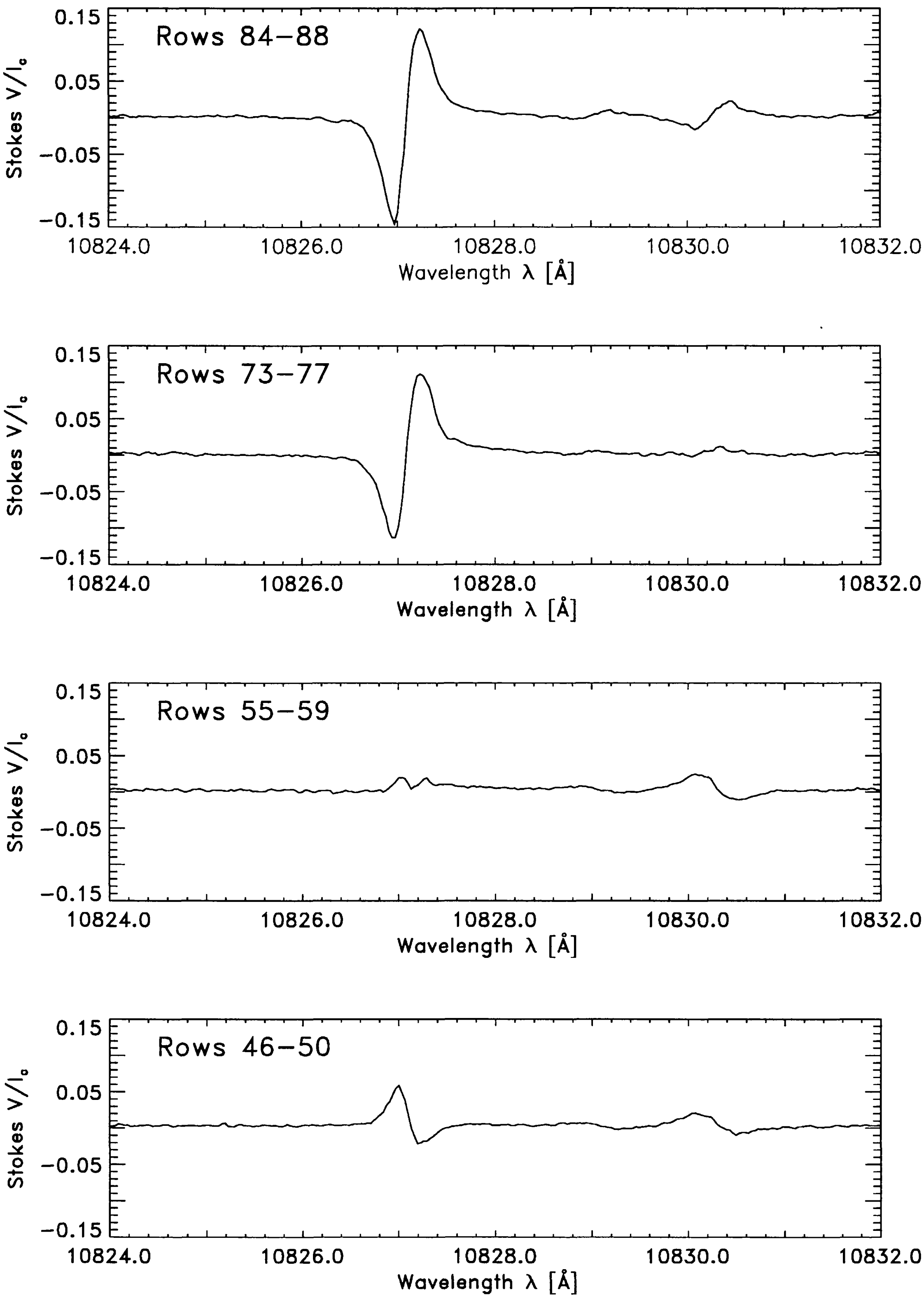

Fig. 3. Sample of Stokes V profiles extracted from Fig. 1. From top to bottom the plotted spectra correspond to averages over rows 84–88, 73–77, 55–59, and 46–50, respectively.

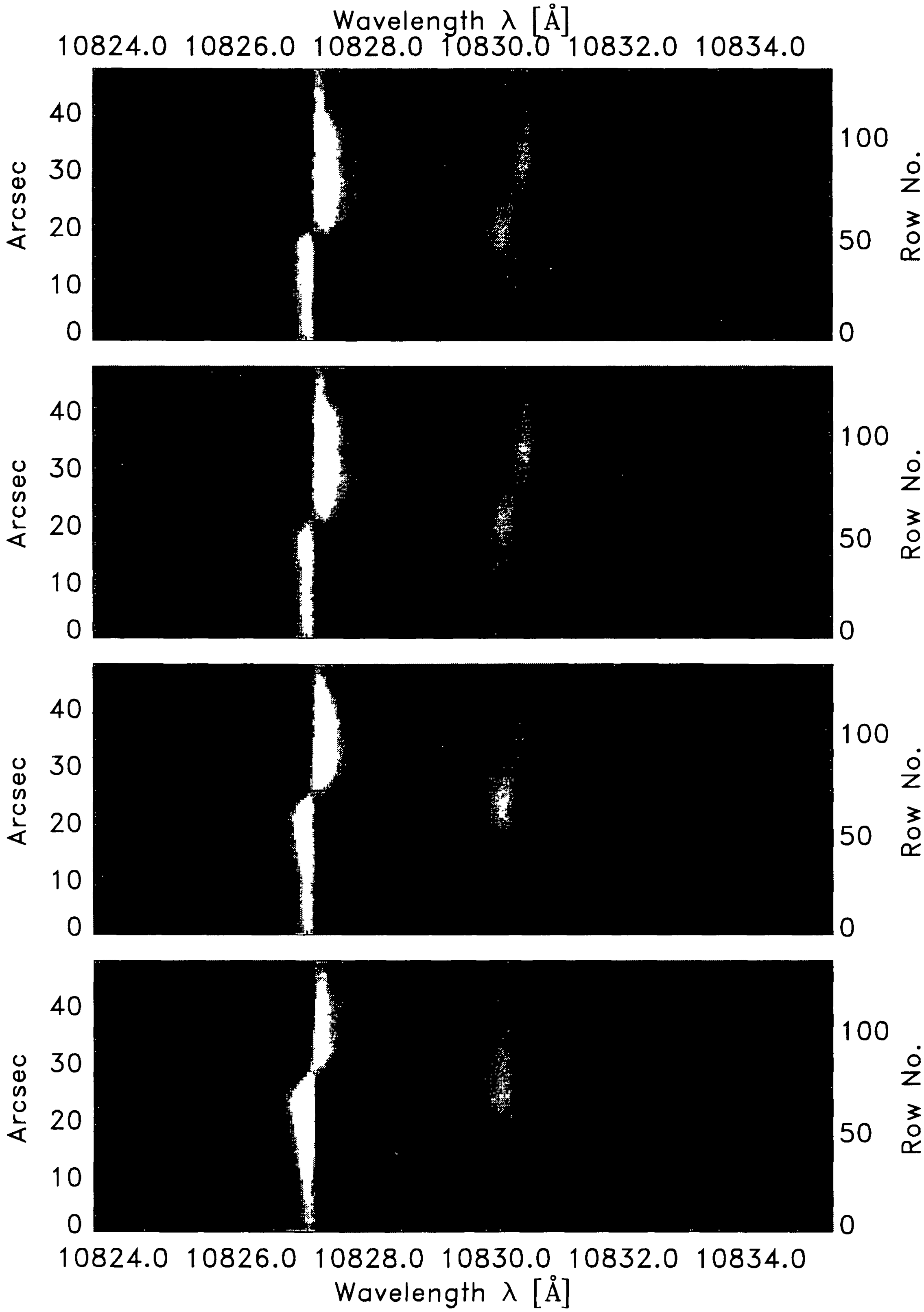

Fig. 4. Stokes V CCD frames recorded at different positions in the limb-side penumbra of the sunspot. The top frame was recorded closest to the limb. Equidistant steps of approximately 3″ separate the frames.

neutral line in the photosphere. The shift between the neutral line position in the chromosphere and the photosphere can be explained by a projection effect. Consider the simple case of a neutral line lying at the same horizontal position at all heights in the atmosphere. Further, consider it to be located near the solar limb, so that the line of sight makes only a small angle to the solar surface. If we now observe this neutral line in two spectral lines formed at different heights, then it will be seen along two different rays, with the one passing through the neutral line in the upper atmosphere intersecting the solar surface closer to the solar limb. Thus the neutral line *apparently* lies closer to the limb in the upper chromosphere than in the photosphere.

Assuming that the difference in location of the neutral line in the two spectral lines is due only to projection, we can estimate the difference in height of formation of the two spectral lines. This difference, determined in the described manner from the current data set is 4500 km, which is significantly larger than theoretical predictions (Avrett *et al.*, 1994; Fontenla *et al.*, 1993) and off-limb observations (Schmidt *et al.*, 1994). This suggests that, although the magnetic structure in the upper chromosphere is similar to that in the photosphere, the two are not identical. For example, previous investigations have suggested that the chromospheric structures appear diffuser than the photospheric structures (Harvey & Hall, 1971; Giovanelli, 1980; Giovanelli & Jones, 1982; Solanki& Steiner, 1990; Rüedi *et al.*, 1995a). In the case of the observed sunspot the chromospheric neutral line appears to be located closer to the limb (even after removal of projection effects) by approximately 2000 km if we employ the He I 10830 Å height of formation quoted by Schmidt *et al.* (1994). This implies that the magnetic field is somewhat more vertical in the chromosphere than in the underlying photosphere, in agreement with the general picture of a sunspot as an expanding flux tube, e.g. with a potential field.

5. Conclusions

The Helium 10830 Å line can be used for complete magnetic field vector measurements in the upper chromosphere.

ZIMPOL I has been successfully used to measure the complete Stokes vector in the He I 10830 Å line in a sunspot region. Observations in a filament, not discussed here, also show linear polarization signatures. The modulated fringes will be strongly reduced in future observations by tilting the piezo-elastic modulators by a considerable amount. The low quantum efficiency of the CCD at these wavelengths remains a problem, however. Future efforts will address the accurate determination of chromospheric vector magnetic fields from observed Stokes spectra.

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