NATIONAL OPTICAL ASTRONOMY OBSERVATORIES

SCATTERING POLARIZATION IN THE CHROMOSPHERE

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Abstract. Scattering polarization from the photosphere observed close to the solar limb has recently become of interest to study turbulent magnetic fields, abundances, and radiative transfer effects. We extend these studies by measuring the scattering polarization off the limb, i.e. in the chromosphere. However, instrumental effects are much more pronounced and more complicated than those affecting on-disk measurements. In particular, scattered light from the telescope mirrors leads to a new type of instrumental polarization that we describe in detail. The differences between the linearly polarized spectra on the disk and off the limb are often very substantial. Here we show the profiles of HeI D_3, the OI triplet at 777 nm, and the NaI D lines. The change in the latter is in reasonable agreement with the recent modeling efforts of atomic polarization in the lower level by Landi Degl'Innocenti (1998).

Key words: scattering, polarization, chromosphere, observations

1. Introduction

Almost all scattering polarization measurements on the sun have been obtained on the disk, i.e. in the middle to upper photosphere. The linear polarization spectrum due to scattering on the solar disk is now often referred to as the second solar spectrum (Stenflo and Keller, 1996). Early observations already showed that several singly ionized rare-earth elements, such as the NdII line at 525.0 nm (Stenflo and Keller, 1997), show strong scattering polarization. Singly ionized rare-earth elements are also responsible for a large number of lines in the flash spectrum (e.g. Pierce, 1968), which shows chromospheric emission lines. Even molecular features in the second solar spectrum such as C_2 show considerable emission in chromospheric spectra (Pierce, 1968). Since the scattering polarization is solely due to the

emission term in the radiative transfer equation, one might expect stronger photospheric and maybe chromospheric scattering polarization in lines that show emission above the limb. This was the idea that led one of us (NRS) to initiate the observational study of scattering polarization above the limb. Other absorption lines show emission features in their wings, sometimes with large differences between the emission in the red and the blue wings. The relation between these emission features and the scattering polarization profiles was another topic that we wanted to study.

Here we report initial findings from our attempts to study the scattering polarization in the chromosphere. We describe a new type of instrumental effect that has an overwhelming influence on our data. While we have obtained a large number of spectra, these instrumental effects cannot always be successfully removed. We therefore restrict ourselves to presenting examples that we expect to be relatively free of instrumental effects.

2. Observations

We used the same optical setup as the one used in earlier observations of the second solar spectrum (Stenflo and Keller, 1996, 1997), i.e. the McMath-Pierce main 1.5 m telescope, the vertical spectrograph, and ZIMPOL I. A tilted glass plate in front of the slit is used to minimize the instrumental polarization before the light enters the polarimeter. The plate is tilted and rotated until the average polarization on the solar disk is smaller than 10^{-3}. This minimizes various instrumental effects due to inaccuracies in the determination of the dark current and non-linearities in the read-out electronics of the CCD cameras (see Keller, 1996 for details). Hundreds to thousands of frames are averaged to achieve the required large signal-to-noise ratio (SNR).

The slit-length is about $50''$, covering a little more than one supergranule in diameter. The present observations have been obtained about $1''$ from the limb, on and off the disk. Good seeing is required to see the emission features in the chromosphere.

Telescope motion and seeing move the solar image across the entrance slit of the spectrograph. Instead of averaging frames online, as was done in the measurements of the second solar spectrum, we sometimes recorded every single frame and then binned and averaged the frames off-line according to their average intensities in the continuum. Because the continuum intensity decreases monotonically crossing the limb, this technique provides some information about the height variation of the spectra. Of course, the decrease is rapid and non-linear, and the observed intensities depend on seeing and scattering in the Earth's atmosphere as well as in the telescope, so that the height information provides a qualitative trend rather than a
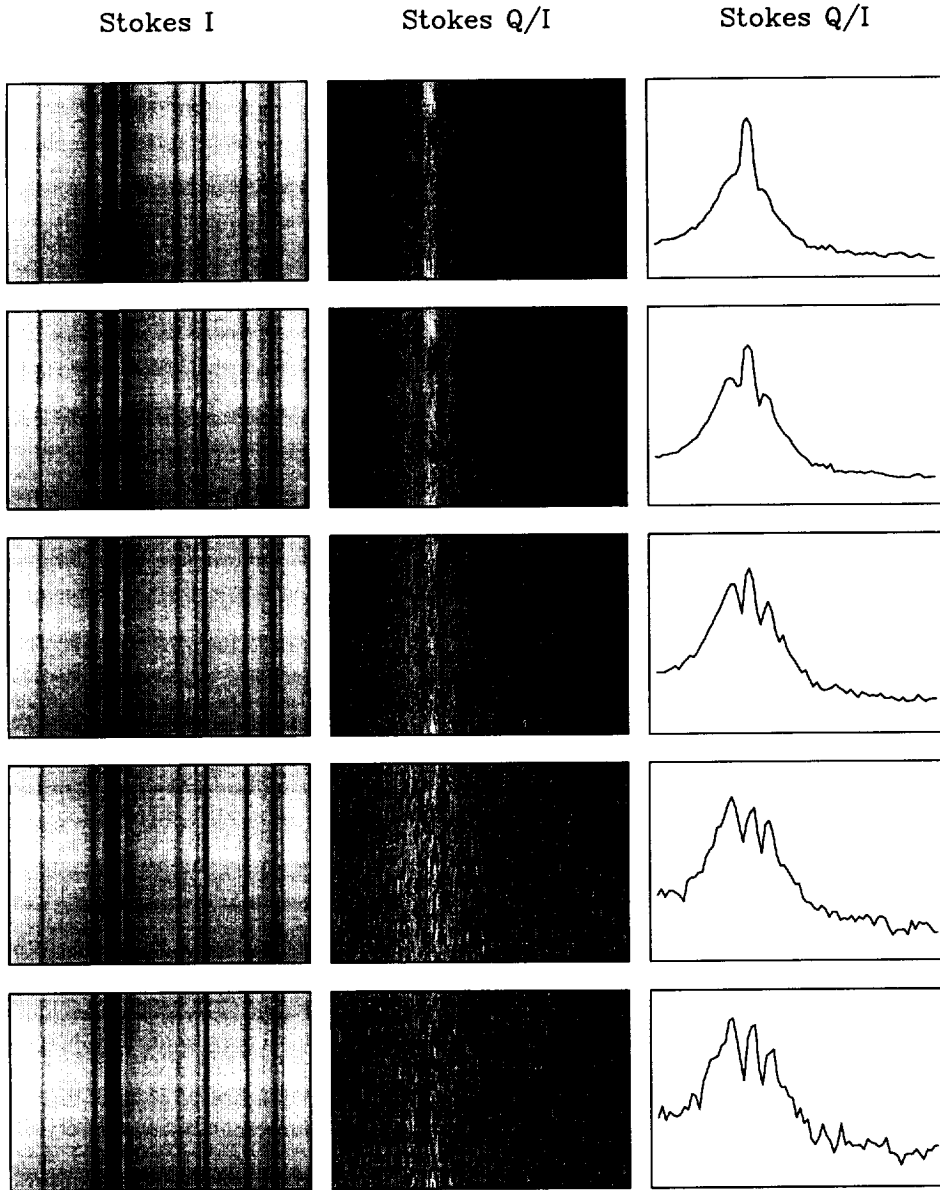
Stokes I   Stokes Q/I   Stokes Q/I

Figure 1. Variation of the intensity and the Stokes Q/I spectra of the NaI D_2 line from the photosphere (bottom) to the chromosphere (top) on June 19, 1998. Note the faint emission in the wings of the NaI D_2 line. Lighter-than-average shading indicates polarization parallel to the limb. The average Stokes Q/I spectra on the right are all shown at the same scale. These observations are not affected by polarized scattered light (see Sect. 3) because they have been obtained at 45° from the geographic north direction where this effect vanishes for the McMath-Pierce telescope.

calibrated height dependence. Figure 1 shows this trend in the intensity and linear polarization for the NaI D_2 line.

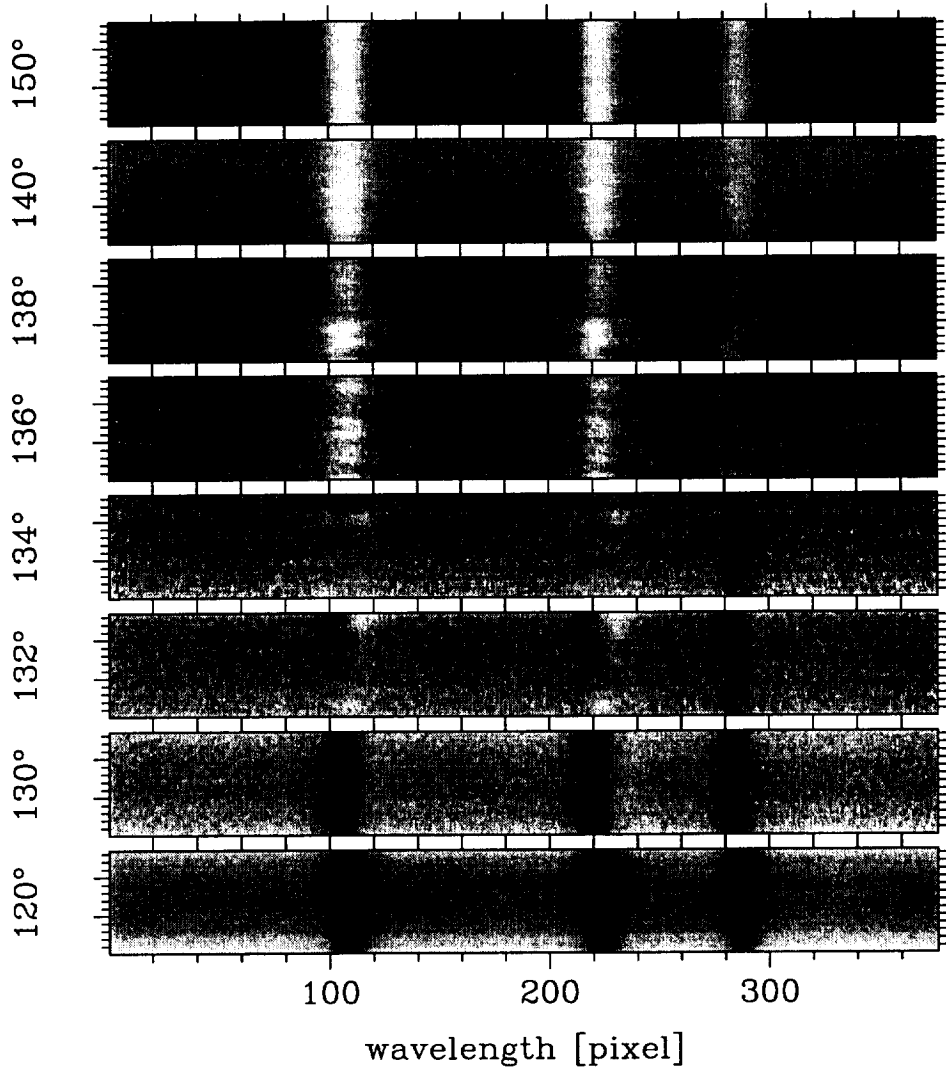## 3. Effects of polarized, instrumentally scattered light

3.1. DESCRIPTION OF THE EFFECTS

Already in our first observations of scattering polarization above the solar limb, we detected strong changes in polarization. Even the sign of the polarization (compared to the continuum polarization) changed from one place along the limb to another. Although we considered the possibility that these changes might be associated with particular solar features like coronal holes at the poles and strong active regions, we recently obtained observations that point to scattered light from the heliostat mirror as the origin of this effect.

Figure 2 is taken from our June 1998 run and shows how the polarization of the OI 777 nm triplet varies with geocentric position around the solar limb. Clearly, the effect reverses sign at a position angle near 135° from the geographic north direction, giving positive polarization at high latitude and negative polarization at low latitude. However, the reversal does not occur at the same position angle for all three lines, as if the instrumental effect were being supplemented by different scattering polarizations from each line. In fact, the maximum theoretical scattering polarization of the OI 777.5 nm line is only 0.75% compared to 19% and 29% for the OI 777.2 and 777.4 nm lines (Beckers, 1974), so that its reversal at 136° is probably closest to the location where the instrumental effect vanishes. Our other limb scans during this observing run also showed OI 777.5 nm reversals within only one or two degrees of the 45° and 135° locations, but several degrees from the zero points of the combined instrumental I to Q crosstalk for the entire telescope system (which wandered by about 6 degrees from the 45° and 135° points as the heliostat rotated relative to the final flat mirror). It is interesting to note in Fig. 2 that the polarization of the OI 777 nm lines seems to resolve into spicule-like features near 136°, which suggests that we will be able to study scattering polarization from chromospheric fine structures in the future when we have found a way to remove the instrumental effects.

The magnitude of this effect is on the order of 10^{-3} to 10^{-2}, i.e. it is comparable to any true solar scattering polarization signal. The magnitude also indicates that it must be a first-order effect, i.e. not a combination of two first-order effects such as instrumental polarization, dark-current variations, or non-linearities in the CCD read-out electronics (see Keller, 1996 for a discussion of those effects). Regular instrumental polarization cannot be the explanation since the Q/I signal due to instrumental polarization
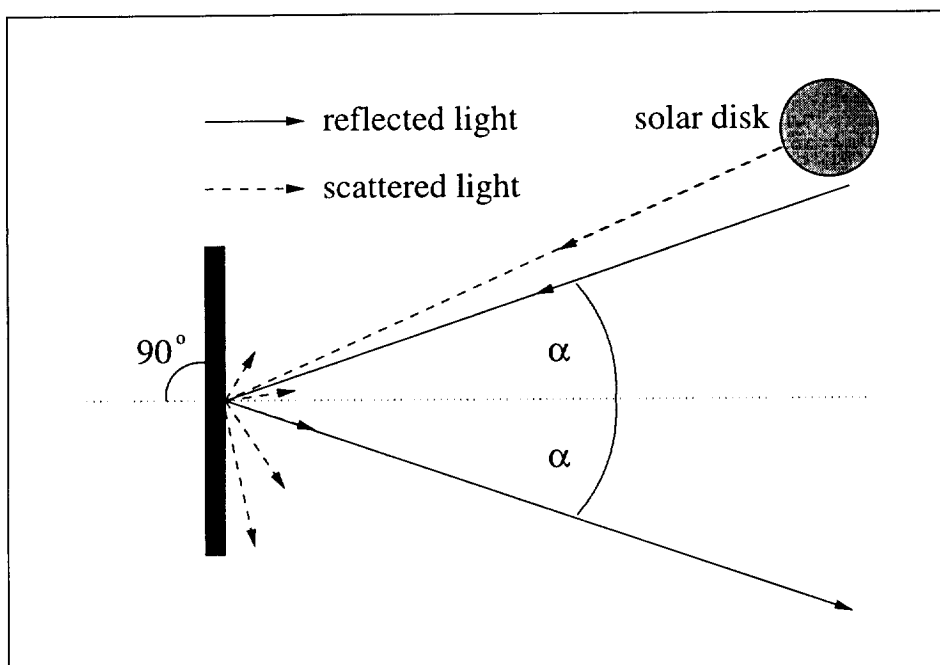
Figure 2.   Observed Stokes Q/I signal in the OI 777 nm triplet about $1''$ above the limb as a function of position angle, measured clockwise from geographic north, during 1400-1520 UT on June 18, 1998. Lighter-than-average shading denotes polarization along the limb and darker-than-average shading denotes polarization perpendicular to the limb.

has no spectral signature. Because of the variation of the effect with the position angle on the limb, it cannot be due to an unknown effect in ZIM-POL I, i.e. it has to be an effect that should be seen by any polarimeter. As mentioned above, the effect vanishes at $\pm 45°$ and $\pm 135°$, rather than at the zero points of the telescope instrumental polarization. Empirically, the effect seems to be most pronounced for lines that are in absorption near

disk center, but which weaken toward the limb and then go into emission above the limb. However, it also occurs for HeI D₃, which is virtually absent on the disk but very strong in emission above the limb. Also, telluric lines do not seem to show this effect at all, which was very puzzling and initially hinted at a true solar phenomenon. It therefore had to be an effect unknown to us. After many unsuccessful attempts to understand this effect, we came up with an explanation that can account for all the observed properties mentioned above.

3.2. MODELING OF THE EFFECTS

Figure 3. Light paths for obliquely reflected (from above the solar limb) and scattered light (from all over the solar disk) on a flat mirror in an optical system. Note that scattered light does not follow the rule of equal angles of incidence for the incoming and outgoing beams. Part of the scattered light goes in the same direction as the reflected light, thus contributing to the measured signal.

When observing above the solar limb, there is a contribution to the signal due to scattered light from the solar disk. While scattered light from the solar limb due to seeing and telescope motion will have the same telescope Mueller matrix as compared to the chromospheric light, there will also be large-angle scattered light from all over the solar disk. Since the latter is not following the same path in the optical system as the true chro-

mospheric spectrum (see Fig. 3), it exhibits a different instrumental polarization. Furthermore, the Mueller matrix describing the scattering process is not equivalent to the regular Mueller matrix for oblique reflection on a metallic coating with a different angle of incidence (e.g. Harvey & Vernold, 1997). The Mueller matrix for scattering has to be calculated by performing a Fourier decomposition of the mirror surface profile. The diffraction from each sinusoidal grating (corresponding to one Fourier component) has to be determined. The coherent sum of all these sinusoidal diffraction gratings has to be considered when calculating the Mueller matrix for the scattering process. This is obviously a demanding job that is outside the scope of this investigation.

In the following we construct a model of the influence of polarized, instrumentally scattered light on precision linear polarization measurements above the limb. For simplicity we will assume that there is only instrumental cross-talk between I and Q, i.e. we assume that there are no U and V signals. The instrumental cross-talk can then be described by

$$\begin{pmatrix} i \\ q \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} I \\ Q \end{pmatrix} , \tag{1}$$

where lower case letters indicate the measured quantities and upper case letters indicate the true solar signal. With the Mueller matrices M^r and M^s describing the reflected and scattered light, respectively, the observed Stokes q/i signal is given by

$$\frac{q}{i} = \frac{M_{21}^r I_r + M_{21}^s I_s + M_{22}^r Q_r + M_{22}^s Q_s}{M_{11}^r I_r + M_{11}^s I_s + M_{12}^r Q_r + M_{12}^s Q_s} , \tag{2}$$

where I_r, Q_r, I_s, and Q_s are the solar Stokes I and Q signals for the reflected and the scattered beams, respectively.

This equation can be simplified by realizing that the terms $M_{12}^r Q_r$ and $M_{12}^s Q_s$ in the denominator are about three orders of magnitude smaller than the other terms in the denominator. $M_{12}^{r,s}$ as well as $Q^{r,s}$ are all on the order of a few percent or less as compared to $M_{11}^{r,s}$ and $I^{r,s}$, which are of order unity. Furthermore, since the instrumentally scattered light comes from all over the solar disk, we would not expect any net contribution to the true polarization signal, i.e. $Q_s = 0$ is a good assumption. Finally, $M_{11}^{r,s} = M_{22}^r = 1$ is a reasonable assumption that has no influence on our analysis. We then obtain

$$\frac{q}{i} = M_{21}^r + \Delta M \frac{I_s}{I_r + I_s} + \frac{Q_r}{I_r + I_s} , \tag{3}$$

where $\Delta M = M_{21}^s - M_{21}^r$. M_{21}^r is the linear polarization induced by the telescope mirrors and simply adds an offset that is independent of wavelength

(over a range of 0.5 nm, which is a typical range for ZIMPOL I spectra at the McMath-Pierce telescope) and independent of the exact height above the solar limb. Likewise the difference, ΔM, between the linear polarizations of the light scattered from the heliostat and the light reflected from the telescope mirrors is also independent of wavelength. Moreover, ΔM does not change with time as the heliostat rotates because the scattered and reflected light share the same optical path after leaving the heliostat. As discussed below, this causes ΔM to have the same $\cos 2\beta$ dependence on solar position angle β that the reflected light from the heliostat has. Finally, I_s is expected to show a spectral dependence similar to the integrated photospheric flux spectrum and should be independent of the exact height above the solar limb because it is due to large-angle (on the order of 0.25 degrees) scattering that should not vary rapidly over small angles of the order of $1''$.
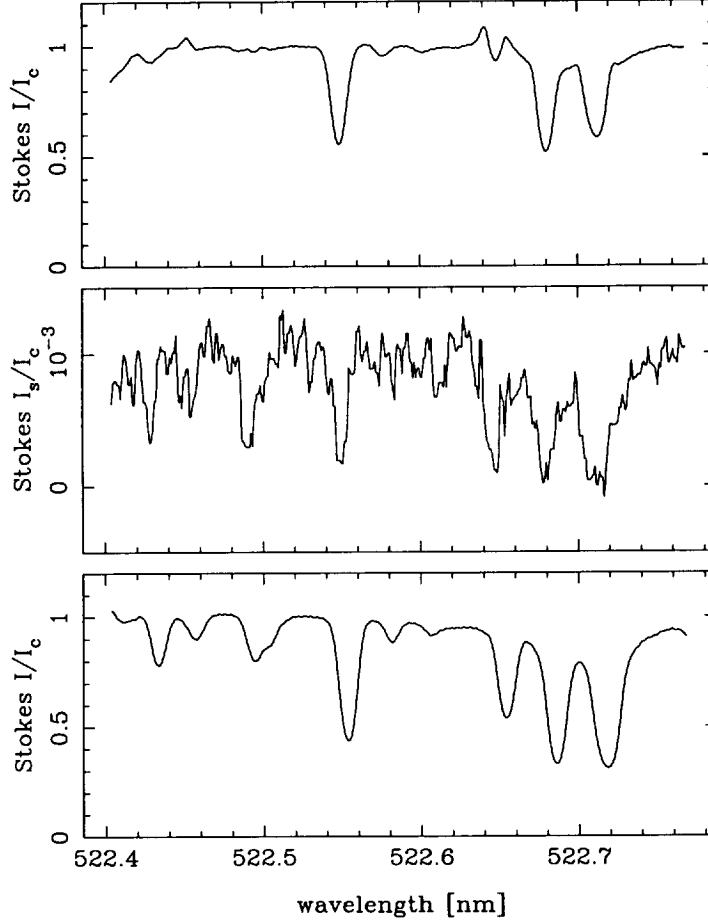
Although the $Q_r/(I_r + I_s)$ term may cause slight variations in q/i, the main influence of instrumentally scattered polarized light is contained in the term $\Delta M I_s/(I_r + I_s)$. For telluric lines, this term is independent of wavelength because they have the same shape for reflected and scattered light, which explains why they do not show the effect. Also, the spectral variation of this term is largest for lines that show a large difference between the photospheric and the chromospheric spectra, which explains why the effect is largest for strong emission lines that are in absorption on the disk.

So far we have not looked at the detailed reasons for the origin of ΔM. The McMath-Pierce main telescope consists of a heliostat mirror (angle of incidence between 34° and 57°, depending on the declination of the sun), a spherical mirror under almost normal incidence, and a fold mirror close to the final focus with an angle of incidence of 29°. The spherical mirror produces scattered light similar to the heliostat mirror, both being close to the pupil plane, but the almost normal incidence on the spherical mirror leads to a negligible difference between the Mueller matrices for reflected and scattered light. The final fold mirror does not contribute much to ΔM because it is close to the final focus, i.e. only a small part of the solar disk can actually scatter into the reflected beam, and because the angle of incidence is smaller than for the heliostat. To a very good approximation, only the scattering on the heliostat mirror has to be considered.

The dependence of ΔM on position angle β of the polarimeter with respect to the geographic north direction can easily be understood. The combined Mueller matrices for all telescope elements for reflected and scattered light have all reflections in common after the heliostat mirror. Under the assumption of weakly polarizing elements, the multiplication of the Mueller matrices can be approximated by the sum of the Mueller matrices (see Stenflo, 1994). The difference between the two Mueller matrices for the

whole telescope is therefore almost equivalent to the difference between the Mueller matrices for reflection and scattering at the heliostat alone. These two matrices depend on the sun's declination (which can be assumed to be constant during a day) and on the angle, β, of the positive Stokes Q direction with respect to the geographic north direction. The latter corresponds to a simple rotation of the Stokes coordinate system, hence ΔM is proportional to $\cos 2\beta$.

Figure 4. Using polarization measurements at various heights above the limb in September 1997, the shape of the scattered light was determined (see the text for a description of the technique). The top spectrum is the average intensity spectrum used in the analysis, the spectrum in the middle is the deduced scattered light spectrum, and the bottom spectrum is an on-disk spectrum for comparison. Note the absorption lines in the deduced scattered light spectrum that are absent or even in emission in the measured spectrum. These deduced absorption lines indeed correspond to real absorption lines shown in the on-disk spectrum.

A close examination of Eq. (3) shows that we should be able to deduce the shape of the scattered light spectrum with a regression analysis. Using observations that have been binned according to the intensity in the continuum and assuming that the polarization due to scattered light is much larger than the true solar signal, we can rewrite Eq. (3) in the form

$$\frac{q}{i} = c + \frac{1}{i}\left(\Delta M I_s\right) , \tag{4}$$

where c is a constant independent of wavelength and position above the limb. We recall that $i = I_r + I_s$. A linear regression between q/i and $1/i$ therefore renders $\Delta M I_s$. Figure 4 shows the results of such an analysis of FeI lines and a TiII line around 522.7 nm for a position angle of $\beta = 0$ on September 17, 1997. In the spectra observed above the limb, some of the lines in absorption on the disk vanish or are even in emission. Nevertheless, the linear regression analysis reveals these absorption lines, in excellent agreement with the on-disk spectrum, which is expected to be very similar to the scattered light from all over the disk. The magnitude of $\Delta M I_s$ of 1×10^{-3} in the continuum is also of interest. Since the observed intensity $1''$ above the limb is about 20 times smaller than on the disk, $\Delta M I_s$ is on the order of 5×10^{-5} of the disk center intensity. With an upper limit on the scattered light level of 5×10^{-3} (Pierce, 1991), we estimate ΔM to be of the order of 0.01, which is significantly larger than what would be estimated based on the different angles of incidence for Fresnel reflection of the reflected and scattered light on the heliostat.

3.3. REMOVING THE EFFECTS

The simple dependence of ΔM on position angle can be used to determine the true solar signal. Since M_{21}^r includes the tilting glass plate, which is adjusted for each position angle to avoid other instrumental effects, the measured q/i will have an unknown offset that varies from one position angle to the next. By subtracting the observed q/i in the continuum, we obtain a quantity $\delta(q/i)$ that is independent of such an offset, i.e.

$$\delta\left(q/i\right) = \Delta M \left(\frac{I^s(\lambda)}{I^s(\lambda) + I^r(\lambda)} - \frac{I_c^s}{I_c^s + I_c^r}\right) + \frac{Q^r(\lambda)}{I^s(\lambda) + I^r(\lambda)} - \frac{Q_c^r}{I_c^s + I_c^r} , \tag{5}$$

where the subscript c stands for the quantity measured in the continuum. This equation has the form of a linear equation in $\cos 2\beta$, i.e.

$$\delta\left(q/i\right) = \cos 2\beta \left(c_1 \frac{I^s(\lambda)}{I^s(\lambda) + I^r(\lambda)} - c_2\right) + \frac{Q^r(\lambda)}{I^s(\lambda) + I^r(\lambda)} - c_3 , \tag{6}$$

where the constants $c_{1,2,3}$ are independent of position angle, β, and wavelength, λ. If q/i is measured at two or more position angles, we can remove

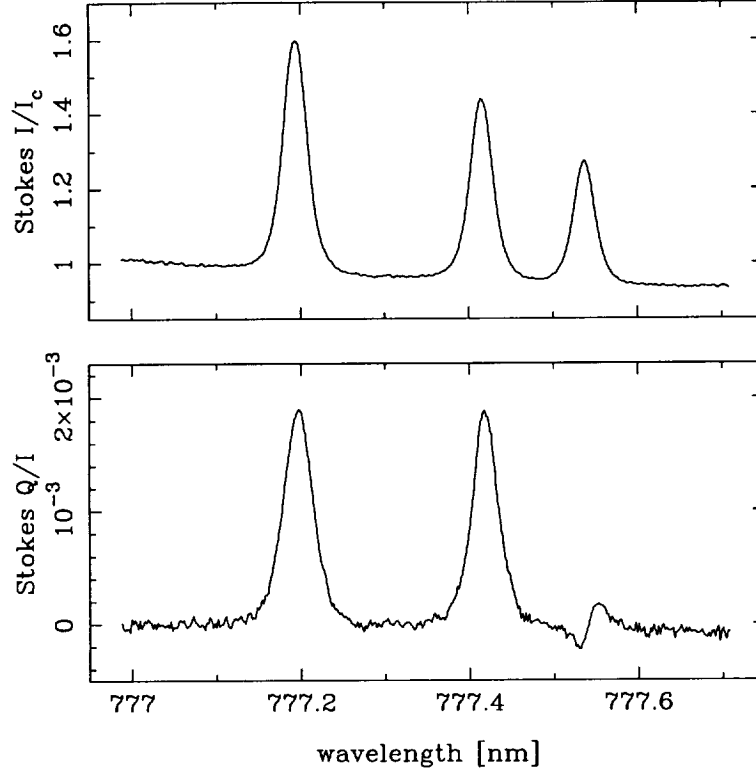*Figure 5.* True scattering polarization in the OI triplet at 777 nm about 1″ above the limb as observed on June 18, 1998.

the β-dependence by performing a linear regression with respect to $\cos 2\beta$, and obtain the polarization $Q^r(\lambda)/(I^r(\lambda) + I^s(\lambda))$ up to a constant that corresponds to the continuum polarization. Figure 5 shows this quantity for the OI triplet, and, as expected, indicates much less scattering for the 777.5 nm line than for the other two lines. However, Fig. 5 also shows a near equality of polarization for the 777.2 and 777.4 nm lines, whose theoretical maximum scattering polarizations are different (19% compared to 29%). This raises the question of whether the discrepancy may arise from our plot of $Q^r(\lambda)/(I^r(\lambda)+I^s(\lambda))$ rather than the true polarization $Q^r(\lambda)/I^r(\lambda)$, and emphasizes the importance of removing this remaining instrumental effect. At present, the best solution is to observe at the position angles where $\Delta M = 0$, and to keep the heliostat clean. And finally, there is the effect of seeing and telescope aberrations, which smears both Q and I in the same way. However, the ratio of two smeared quantities is not necessarily the same as the smeared ratio.

4. NaI D_1 and D_2

NaI D_2 on disk   NaI D_1 on disk
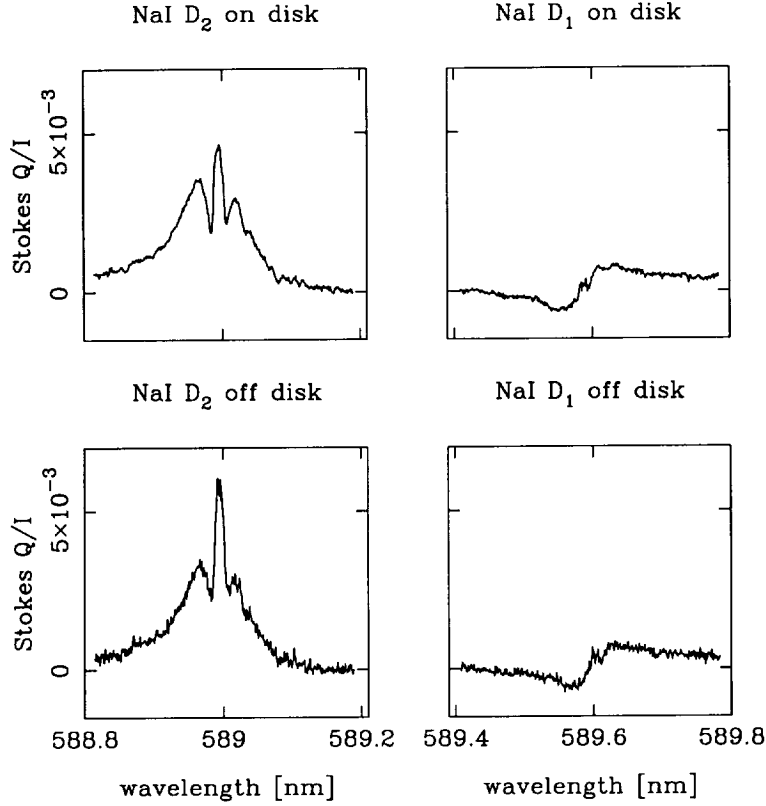
NaI D_2 off disk   NaI D_1 off disk

Figure 6. Scattering polarization in the NaI D lines on the disk and above the limb, each about $1''$ away from the limb as observed in September 1997.

Figure 6 shows the polarization signals of the NaI D_1 and D_2 lines on the disk and above the limb. There is some change in the polarization structure between photospheric and chromospheric spectra similar to what is seen in Fig. 1. The main change is due to the enhanced central component in the line core. The D_1 line shows no significant difference between photosphere and chromosphere. The spectra are in reasonable agreement with the theoretical calculations for photospheric and chromospheric measurements by Landi Degl'Innocenti (private communication).

5. HeI D_3

Figure 7 shows an example of a chromospheric emission line that shows measurable scattering polarization in the on-disk spectrum, while no absorption or emission due to the HeI D_3 line is visible in the intensity spectrum.

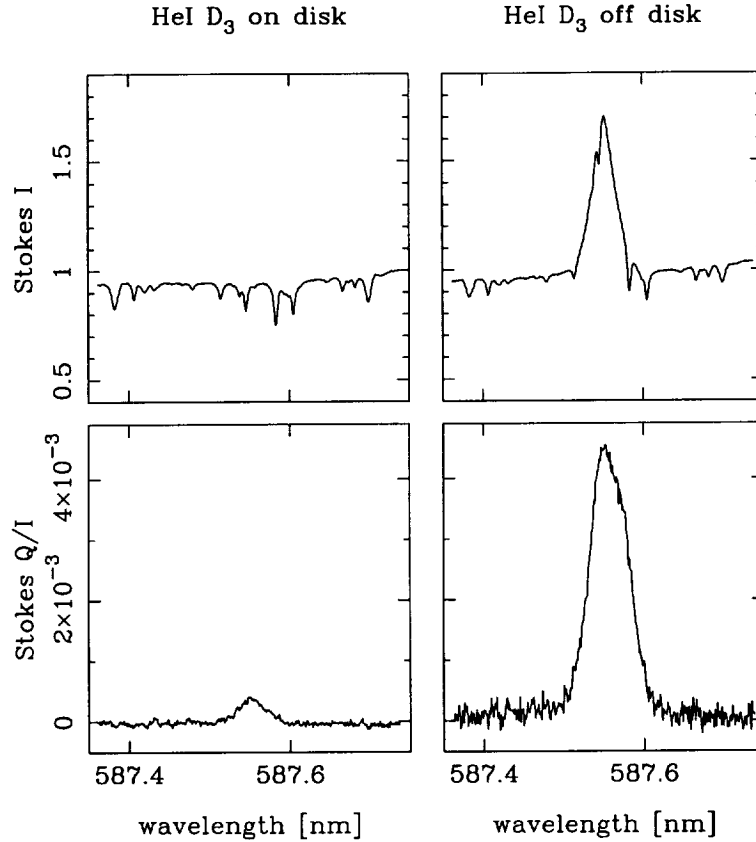HeI D$_3$ on disk   HeI D$_3$ off disk

Figure 7.   Stokes I and Q/I spectra of HeI D$_3$ on and off the disk on September 16, 1997 after the heliostat had been re-aluminized. Note the absence of the line in Stokes I on the disk. However, a clear signal is detected in Q/I.

Above the limb, the emission is associated with substantial polarization. In contrast to the HeI D$_3$ triplet line, the HeI singlet line at 492.2 nm (detected on September 17, 1997 in a post-flare loop region) shows no visible polarization on or off the disk.

6. Discussion

High-precision polarization measurements outside of the solar disk are much harder to obtain than on the disk. First of all, good seeing is required to reduce the influence of light from the disk, which is strongly polarized due to scattering polarization close to the limb. In addition, there is a new effect due to the wide-angle component of instrumental stray-light, which has a different Mueller matrix as compared to the reflected light. We now

understand this effect and found ways to reduce its influence. Observations taken at the McMath-Pierce telescope in September 1997 only weeks after the mirrors were freshly aluminized hardly show any sign of this effect. Observing at the position angles where $\cos 2\beta = 0$ minimizes the influence of scattered light. Although it tends to maximize the Stokes V to Q cross-talk, this cross-talk is mainly antisymmetric with respect to line center and can be removed or greatly reduced by decomposing each line into its symmetric and antisymmetric parts.

The adverse effects of polarized, instrumentally scattered light are particularly large for observations above the limb. We do not expect it to significantly affect on-disk measurements because the reflected light completely dominates the scattered light there.

The intensity binning has proven to be a powerful technique to study the height variation of the scattering polarization in a qualitative way. Apart from scattering polarization, many lines exhibit clear Stokes V cross-talk due to the Zeeman effect. By decomposing the observed Q/I profiles into their symmetric and anti-symmetric parts and using the theoretical amount of cross-talk due to the telescope, we obtain a good estimate of the true Stokes V signal. The height variation of these Zeeman signals reveals magnetic canopies directly (Sheeley and Keller, in preparation).

Acknowledgements

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