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Anomalous polarization effects due to coherent scattering on the Sun

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Abstract. The richly structured linearly polarized spectrum that is produced by coherent scattering in the Sun's atmosphere contains a number of spectral features for which no explanation has been found within the standard scattering theory. According to this quantum-mechanical framework, the intrinsic polarizability of a given line should be determined by the total angular momentum quantum numbers of the atomic levels involved in the scattering transition (which may be resonant or fluorescent). Well defined polarization peaks have been observed in many lines, which according to these theoretical concepts should be intrinsically unpolarizable. A possible explanation for these anomalous spectral structures could be that the initial ground state of the scattering transition becomes polarized by an optical pumping process. However, such an explanation is contradicted by other observations, since it seems to require that much of the solar atmosphere must be filled with extremely weak magnetic fields ($\lesssim 10$ mG). We have searched through the whole visible solar spectrum for lines with the quantum numbers that should normally make them unpolarizable, and have carried out a systematic observing program for the most prominent of these lines. Here we report on the observed properties of the polarized line profiles of these lines and explain in what respect their behaviors are anomalous and cannot be understood within current conceptual frameworks.

Key words: polarization – scattering – Sun: magnetic fields – atomic processes – techniques: polarimetric

1. Introduction

The linearly polarized spectrum of the Sun that is produced by coherent scattering processes has been called the "second solar spectrum", since it is as rich in spectral structures as the ordinary intensity spectrum, but its appearance is entirely different. It is as if the Sun has presented us a new spectral face, and we have to start over again to identify the new structures that we see. Due to the small polarization amplitudes, typically 0.1 % or below, most of the second solar spectrum has remained hidden from view until recently (Stenflo & Keller 1996, 1997), when its unexpected spectral richness began to be exposed. The breakthrough came with the implementation of the new polarimeter system ZIMPOL (**Z**urich **Im**aging **Pol**arimeter, cf. Povel 1995), which allows us to routinely obtain spectral recordings with a polarimetric accuracy of 10^{-5} in combination with high spectral resolution and high photon flux. At this level of accuracy everything (including the continuous spectrum) is polarized.

In 1994 we embarked on a program to systematically explore the second solar spectrum, using ZIMPOL with the McMath-Pierce facility at the National Solar Observatory (Kitt Peak), which is the solar telescope with the largest light-gathering power in the world. A large telescope is important for high-precision polarimetry when the limiting factor as here is due to the photon noise statistics. With this program we have identified polarization signatures of molecular scattering, isotope effects and hyperfine structure splitting, quantum interference between fine-structure components, fluorescent scattering, Hanle effect, scattering by the lithium atoms, etc. (Stenflo & Keller 1996; Stenflo 1997a,b; Stenflo et al. 1998).

The theory that has generally been used when trying to make sense of the new polarization data is based on the concept of coherent scattering from an initial atomic state that is assumed to be unpolarized, via an intermediate state into a final state that can either be the same as (Rayleigh or resonant scattering) or different from (Raman or fluorescent scattering) the initial state. The terms resonant and fluorescent refer to scattering near a resonance, while the terms Rayleigh and Raman are more general and cover scattering at any distance from the resonance. The polarization of the scattered light is explained as due to the anisotropic illumination of the scattering particle. In the case of a spherically symmetric Sun such an anisotropy arises as a consequence of the limb darkening. Thereby atomic polarization is induced in the excited, intermediate atomic state. This upper-state polarization then gets "imprinted" on the emitted radiation.

The term "coherent" here refers to scattering processes that are undisturbed by collisions, so that the phase relations between the incident and scattered radiation are preserved. Collisions depolarize the atom and redistribute the scattered frequencies. The theory of scattering in the presence of collisions is a theory for the partial frequency redistribution of polarized radiation. It was developed for the non-magnetic and weak-field case by Omont et al. (1973), Domke & Hubeny (1988) and Bommier (1997a), and for the case of magnetic fields of arbitrary strength and direc-

tion (the "mixed Hanle-Zeeman regime") by Bommier (1997b) and Bommier & Stenflo (1999). However, all these theories are based on the assumption that the initial state is unpolarized, and that the only source of polarization in the excited state is the anisotropic excitation process.

While the above-mentioned theoretical concepts have been very useful and successful for explaining much of what we see in the second solar spectrum, we have also identified a number of polarization features that we have been unable to explain, even qualitatively. In the present paper we will present our main observational examples of "anomalous" polarization features, for which the underlying physical processes have not yet been identified. The data have been obtained during various observing runs from November 1994 through October 1997. The observing run in October 1997 was in particular devoted to a systematic search for anomalous effects and to explore the behavior of scattering transitions that should according to the standard theory be intrinsically unpolarizable. For this purpose we searched the atomic multiplet tables (Moore 1945) combined with the table of solar line identifications (Moore et al. 1966) in a merged computer version that had been compiled (unpublished) by Axel Wittmann of Göttingen, to select all the observable solar lines with the desired combination of quantum numbers for the lower and upper states. The selected lines were then observed with ZIMPOL. Here we report on the results of these observations, combined with similar observations from various previous runs.

All the recordings presented here have been made using ZIMPOL at NSO/Kitt Peak with the spectrograph slit 5 arcsec inside the solar limb, where μ, the cosine of the heliocentric angle, equals 0.1. The slit has always been parallel to the nearest limb, and positive Stokes Q is defined as linear polarization with the electric vector parallel to the slit. Spatial averaging has been made along the 50 arcsec long slit to enhance the polarimetric accuracy. The position angles for the slit along the limb have varied, but all recordings have been made at heliographic latitudes far above the zones of solar activity. Wavelet smoothing has been applied to the presented spectra.

2. Arguments for and against lower level atomic polarization

The existence of a number of unexplained polarization features in the second solar spectrum suggests that the theoretical framework previously used is insufficient and needs to be enlarged, in particular to allow for the possibility that atomic levels other than the intermediate state of the scattering process may also be polarized, and that polarization transfer between the states may occur. Such a generalized framework for multi-level coherences has been developed by Landi Degl'Innocenti (1983) within a density-matrix quantum formalism. He has repeatedly stressed the potential importance of initial, lower-state atomic polarization (e.g. Landi Degl'Innocenti 1996). Trujillo Bueno and Landi Degl'Innocenti (1997) used the density-matrix formalism to derive polarized line profiles and could demonstrate how lines with $J = 1 \rightarrow 0 \rightarrow 1$ transitions that are intrinsically unpolarizable in the absence of lower-state atomic polarization may indeed exhibit polarized profiles with amplitudes in the observable range.

The mechanism for the generation of this type of scattering polarization is the following: The atomic polarization that is induced in the excited state by the anisotropic illumination is partly transfered to the lower state when the excited state decays via spontaneous emission. If this lower-state polarization survives until the next scattering process, then the atomic polarization of the excited state will receive a contribution due to polarization transfer from the lower state, in addition to the direct contribution from the anisotropic illumination. Part of this modified upper-state atomic polarization will be transfered back to the lower state, and so on, until a statistical equilibrium for the polarizations of the different atomic states has been established. The process of creating lower-state atomic polarization is called *optical depopulation pumping*, and the resulting polarization effects are found by solving the statistical equilibrium equations for the density matrices of the various atomic levels.

One type of polarization feature that has long remained enigmatic and unexplained is the narrow polarization peak in the Doppler core of the Na I D_1 5896 Å line, observed by Stenflo & Keller (1996, 1997) and displayed in Fig. 1. This line, being a $J = \frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{1}{2}$ transition, should be intrinsically unpolarizable according to standard quantum scattering theory that assumes zero atomic polarization for the initial state. The intrinsic polarizability of a transition is generally expressed in terms of the parameter W_2, which represents the fraction of scattering processes that occur as polarizing, dipole-type scattering (like a classical oscillator). The remaining fraction, $1-W_2$, then occurs as unpolarized, isotropic scattering. For the D_1 line $W_2 = 0$, while for the D_2 line at 5890 Å, which is a $J = \frac{1}{2} \rightarrow \frac{3}{2} \rightarrow \frac{1}{2}$ transition, $W_2 = \frac{1}{2}$. Quantum interference between the $J = \frac{1}{2}$ and $\frac{3}{2}$ states leads to the sign reversal with negative polarization between the two lines (Stenflo 1980), but it cannot explain the core polarization peak in the D_1 line, where instead a polarization zero crossing would be expected.

Recently Landi Degl'Innocenti (1998) provided an elegant explanation of the D_1 polarization in terms of optical depopulation pumping. However, this mechanism alone is unable to do the job, since a $J = \frac{1}{2}$ state is intrinsically unpolarizable by any means. The situation is saved by the hyperfine structure splitting, due to the nuclear spin of $\frac{3}{2}$ for sodium. This nuclear spin I couples to the electronic angular momentum J, resulting in splitting of the $J = \frac{1}{2}$ and $\frac{3}{2}$ states into levels with other total angular momentum quantum numbers F, which now determine the intrinsic polarizability W_2 for scattering transitions between the different levels. Through optical depopulation pumping of the split, lower levels Landi Degl'Innocenti (1998) could successfully model the polarization core peaks of both the Na I D_1 and D_2 lines. The effects of collisions were not accounted for.

Although this elegant theory significantly advances our physical understanding and may be on the right track, there are grave doubts that it represents the whole story. For the effects of lower-level atomic polarization to be significant, this polarization needs to survive the depolarizing threats from both

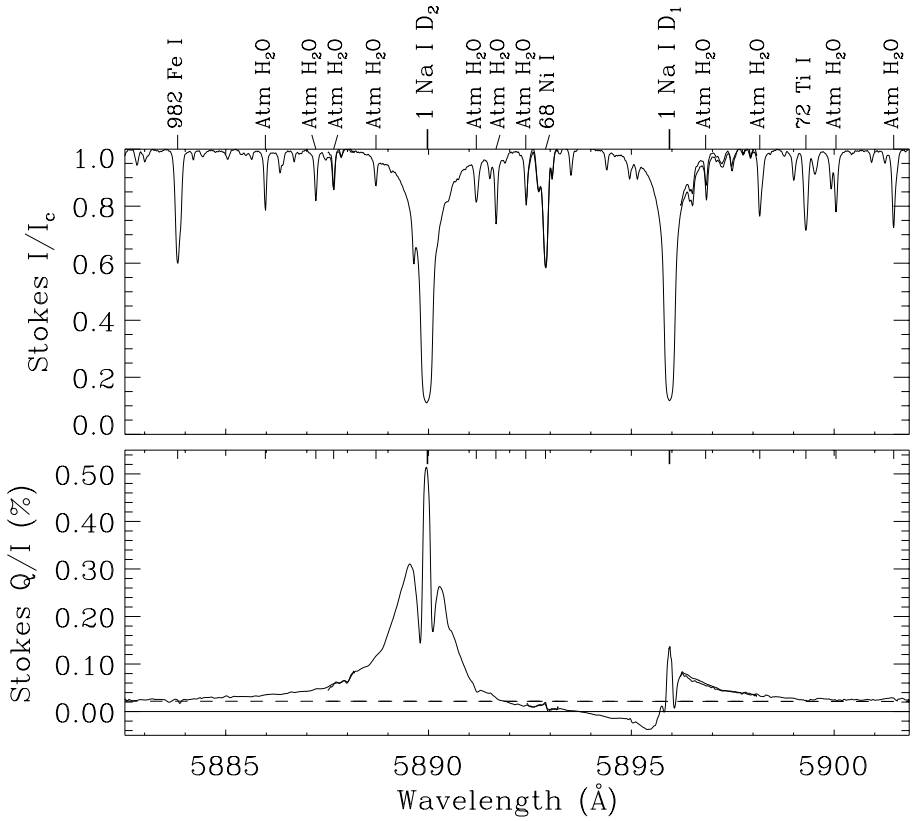

Fig. 1. Intensity (top panel) and degree of linear polarization (bottom panel) for the spectral region around the Na I D_2 5889.97 and D_1 5895.94 Å lines, obtained near the north polar limb on April 3, 1995. The level of the continuum polarization, obtained from Fluri & Stenflo (1999), is given by the horizontal dashed line. The polarization peaks in the line cores, in particular that of the D_1 line, remain enigmatic.

collisions and magnetic fields (Hanle depolarization). Since the lifetime of the lower state is longer by about two orders of magnitude as compared with the excited state (approximately the ratio between the rates of spontaneous and stimulated emission), the lower state is correspondingly much more vulnerable to depolarization effects. In particular, magnetic fields stronger than about 10 mG would wipe out most of these polarization effects. Since there is abundant evidence from Hanle-effect observations ruling out the possibility that a sufficiently large fraction of the solar atmosphere could be occupied by that weak magnetic fields (e.g. Bianda et al. 1998a,b, 1999), we seem to be led to the conclusion that the explanation by Landi Degl'Innocenti of the D_1 polarization peak in terms of lower-state polarization must also be ruled out (cf. Stenflo 1999). The Hanle-effect observations refered to include lines like Ca I 4227 Å, which has $J = 0$ for the lower level and no nuclear spin, and therefore cannot be subject to optical depopulation pumping effects.

For these reasons the observed D_1 and D_2 polarization peaks still remain an enigma, a challenge for the theorists. It is hard to see how lower-state atomic polarization can really play a significant role at all in the magnetized and highly conductive solar atmosphere. A variation of the optical pumping scheme could be that other, more short-lived atomic states than the initial one can couple and transfer atomic polarization to the intermediate state of the scattering transition. This possibility needs to be looked into, but until then, the D_1 polarization will remain a mystery.

3. Comparison between the D_1 polarizations of Na I and Ba II

The polarization peak in the Doppler core of the Na I D_1 line is prominent in our various recordings at different disk positions and in different observing runs, but the polarization amplitude varies, while the amount of wing polarization remains more constant (but of course varies with limb distance). Fluctuations in the Doppler core with invariant wing polarization is a characteristic signature of the Hanle effect (cf. Stenflo 1994, 1998), as was demonstrated for the Na I D_2 line in Stenflo et al. (1998), for the Ca I 4227 Å line in Bianda et al. (1998a, 1999), and for the Sr II 4078 Å line in Bianda et al. (1998b).

Fig. 2 illustrates how the wing polarization of the Na I D_1 line can stay the same, while the core polarization varies. The thicker curve is the same as that of Fig. 1, obtained in April 1995 near the solar north pole, while the two thinner curves were obtained in September 1996 at two different locations near the solar south pole. The September 1996 recordings have a polarization amplitude that is almost twice that of the April 1995 recording. We also have recordings with smaller or almost vanishing core peaks, but we have here chosen to illustrate the higher peaks, because they accentuate the mystery and constrain the possible theoretical models more. Such high peaks do not allow much room for depolarizing effects (e.g. due to weak magnetic fields).

Fortunately there exists a strongly polarizing multiplet with the the same J quantum numbers as that of multiplet no. 1 of neutral sodium, namely multiplet no. 1 of ionized barium. The

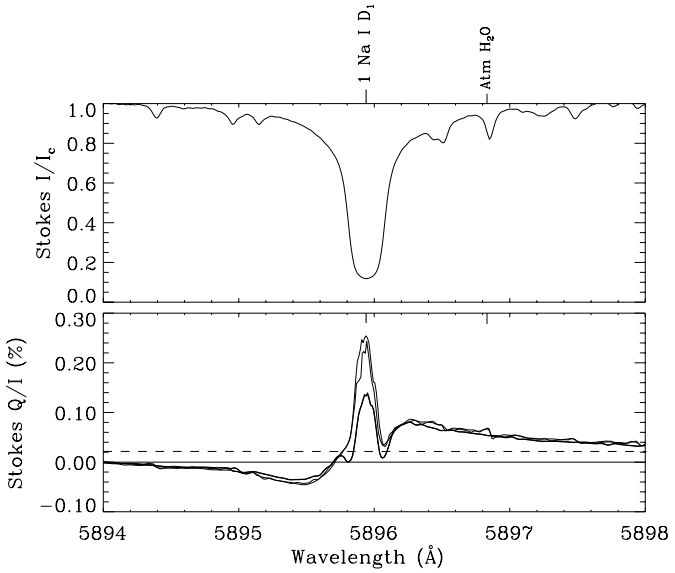

Fig. 2. Portion of the second solar spectrum around the Na I D_1 line. The thicker solid curve (with the smaller amplitude) in the bottom panel is the same as the corresponding curve in Fig. 1. The other two polarization profiles were obtained on September 12, 1996, at two different locations near the south polar limb of the Sun.

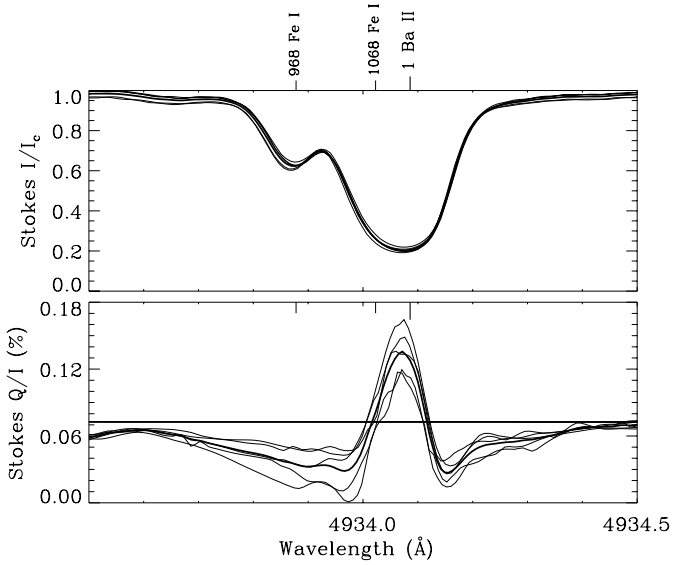

Fig. 3. Five recordings of the intensity and polarization profiles of the Ba II D_1 4934 Å line. Two of them were obtained on April 4 and 5, 1995, near the solar north pole, the remaining three on September 12, 1996, at various positions near the solar south pole. The thicker curve is an average of the five thinner curves. The horizontal line represents the level of the continuum polarization.

D_2 line of Ba II is at 4554 Å, the D_1 line at 4934 Å. With this large separation between the two fine-structure components of 380 Å, as compared with 6 Å for Na I, quantum interference between the fine-structure components can be completely neglected, so the two lines can be considered to be formed independently of each other.

Another similarity between these two multiplets is that the odd isotopes of barium (mainly the isotopes with nucleon numbers 137 and 135) have the same nuclear spin as sodium, namely $\frac{3}{2}$, although the magnitude of the hyperfine structure splitting is larger by a factor of about five in barium. However, only 18 % of barium is in the form of the odd isotopes. The remaining 82 % of the total barium abundance is in the form of the even isotopes, dominated by isotope 138. The even isotopes have zero nuclear spin and thus no hyperfine structure splitting. According to the theory of Landi Degl'Innocenti (1998), any observed polarization feature in the Ba II D_1 4934 Å line must then be exclusively due to the 18 % of barium that is in the form of the odd isotopes.

The behavior of the Ba II D_2 4554 Å line has previously been illustrated (Stenflo & Keller 1996, 1997) and interpreted (Stenflo 1997a). Recordings of the region around the Ba II D_1 line have also been illustrated before (Stenflo & Keller 1997; Stenflo et al. 1998), but in Fig. 3 we display the observed behavior in greater detail, to allow better comparison with the Na I case. The thin curves in Fig. 3 represent five different recordings, the thicker curve being the average of the thin curves. As before, the horizontal line represents the level of the continuous polarization, obtained from the theoretical work of Fluri & Stenflo (1999). Since the zero point of the polarization scale is not well determined (as compared with the relative polarization accuracy of the curves), the observed curves are always vertically shifted until the continuum portions agree with the theoretical continuum level. Since our recordings covered a much larger spectral range than that displayed here, we have sufficient continuum portions to determine the appropriate shift this way.

The five polarization curves in Fig. 3 illustrate the typical variability and reproducibility of the polarization profiles. Two of them were obtained on different days in April 1995 near the solar north pole, the other three in September 1996 at various locations near the solar south pole. The general appearance of the polarization profile is very similar to that of Na I. The core peak is well defined and narrow (as compared with the intensity profile), and it is surrounded by local minima in the near wings. In this comparison one should ignore the anti-symmetric behavior of the Na I profile in the far wings, which is entirely due to the quantum interference with the D_2 scattering transition. Such interference vanishes for Ba II since the D_2 line is so far away. Disregarding this interference for Na I, the polarization profiles for the two lines are indeed strikingly similar.

The wavelength marking for the Ba II line in Fig. 3 represents the value of 4934.086 Å listed in the multiplet tables of Moore (1945). The polarization peak appears slightly shifted to the left of this marking, but the center of gravity of the intensity profile is also shifted to the left by a similar amount, so the relative shift between the intensity and polarization profiles is substantially smaller. Since iron lines generally depolarize, the weak blend from the 1068 Fe I line would be expected to depress the left side of the polarization peak and make it appear somewhat red-shifted, which is not the case, so this blend seems to be insignificant. According to the Kitt Peak FTS archive of laboratory spectra, Ba II has, besides a strong component at 4934.083 Å, also a weak component at 4934.031 Å.

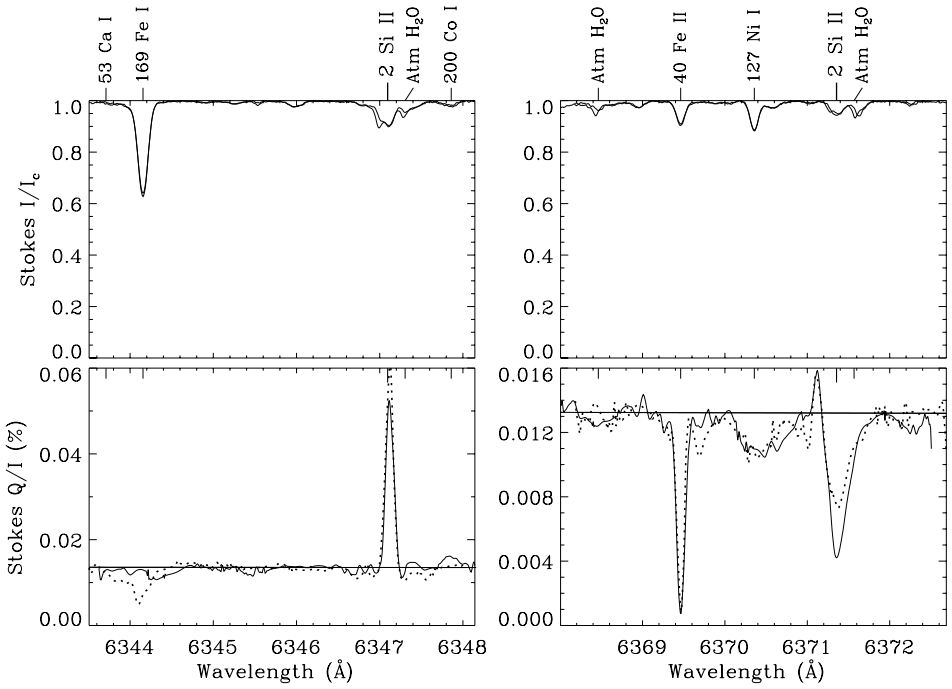

Fig. 4. Recordings around the Si II D_2 6347.090 (left panels) and D_1 6371.360 Å (right panels) lines. Note the difference in polarization scale used. The solid curves in the left and right Q/I panels were both obtained on October 3, 1997, near the solar south pole. The dotted curve in the left panel was obtained on October 5, 1997, near the solar south, the dotted curve in the right panel on October 9, 1997, near the solar north pole.

If this additional component really belongs to barium, then the center of gravity of the combined line may be expected to lie a bit lower than the value of 4934.086 Å taken from the multiplet tables. Another factor of considerable importance is the hyperfine structure splitting, which is asymmetric and shifts the center of gravity towards the blue. Due to this splitting the line contributions from the odd barium isotopes will appear in two groups, one that is shifted by about 38 mÅ towards the blue side from the central wavelength of the even isotopes, another that is shifted by about 25 mÅ towards the red (cf. the corresponding structure of the Ba II 4554 Å line in Stenflo 1997a). Note that the Stokes I profile is mainly produced by the even Ba isotopes, while the Q/I profile is due to the odd isotopes (see below). These effects could easily account for the apparent slight shift of the polarization peak with respect to the wavelength marking in Fig. 3.

For the even barium isotopes, which make up 82 % of the total barium abundance, there is presently no known way to make the D_1 line polarizable, since with nuclear spin zero optical depopulation pumping of the lower atomic state does not help. We would therefore expect the effect of the even isotopes to be exclusively depolarizing, depressing the continuum polarization. Possibly the depressed wing polarizations in Fig. 3 could be due to this. If the theory of Landi Degl'Innocenti is correct, then the core peak must be exclusively due to the odd isotopes, because it is their hyperfine structure splitting that makes the lower state polarizable in principle. Nevertheless we are still facing the same riddle how this atomic polarization in the long-lived ground state could possibly survive depolarization in the ubiquitously magnetized solar atmosphere.

4. Other $J = \frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{1}{2}$ transitions

Since the polarization features in the Na I and Ba II D_1 lines remain enigmatic, and a $J = \frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{1}{2}$ scattering transition should be intrinsically unpolarizable (if we disregard the effects of nuclear spin), we have searched for these types of solar lines and then observed them with ZIMPOL. We summarize the results in this section.

To allow useful answers the selected lines should be relatively unblended and in the observable range of ZIMPOL (above 4500 Å). For each given combination of quantum numbers there are in fact only few lines that satisfy these criteria, and each of them appears to exhibit an individual behavior. We now report on each observed line combination, ordered according to their apparent relevance to the present discussion.

4.1. The Si II D_2 and D_1 lines

Multiplet no. 2 of Si II has the same quantum numbers as the Na I and Ba II multiplets that we have discussed in the preceding section. In analogy with Na I the two lines can therefore be labeled as D_2 (at 6347.090 Å) and D_1 (at 6371.360 Å). 4.7 % of the Si ions consist of the odd isotope Si^{29}, which has nuclear spin $\frac{1}{2}$ (in contrast to the 18 % odd isotopes of Ba with nuclear spin $\frac{3}{2}$), while the rest of the ions are made up of the even isotopes Si^{28} with no nuclear spin. According to our discussion in the preceding section, if a positive polarization signal in the D_1 line of Si II is found, it must get its contribution exclusively from the 4.7 % of odd isotopes.

Fig. 4 shows some ZIMPOL observations of these two lines. The left panels show the region around the D_2 line, the right panels the region around the D_1 line. The D_2 line has a strong and well defined, single polarization peak, as may be expected,

since this line is polarizable (with $W_2 = \frac{1}{2}$) also in the case of the even isotopes with no hyperfine structure.

The D_1 case is less clear. Since the signals here are much weaker, the polarization scale has been greatly magnified in comparison with the D_2 diagram. The Si II D_1 line appears to be depolarizing, which suggests no intrinsic line polarization. However, the depolarizing profile is unusually broad, for instance much broader than the neighboring, depolarizing Fe II 6369.5 Å line, also when accounting for the difference in thermal line width due to the difference in atomic weights of Fe and Si. The polarization peak on the blue side of the D_1 line is too far from the line center to be explainable in terms of isotope shifts, and the very broad and rather shallow depolarization feature on the blue side of this peak appears to be much too broad (in comparison with the Fe II feature) to have anything to do with the Ni I line there.

We trust the reality of these various observed features around the Si II line, since they were all well reproduced in recordings made on different days and in opposite regions on the Sun (south and north poles), as shown by the solid and dotted curves in Fig. 4. Still these features remain mysterious, and we presently cannot say whether or not they are directly related to the D_1 line.

4.2. The Na I D_1 and "inverse D_2" lines of multiplet no. 5

The Na I, Ba II, and Si II lines that we have discussed in the preceding sections are all scattering transitions between the levels ${}^2S_{\frac{1}{2}} \rightarrow {}^2P_{\frac{3}{2},\frac{1}{2}} \rightarrow {}^2S_{\frac{1}{2}}$. In multiplet no. 5 of Na I we encounter two lines with the inverse level structure, namely ${}^2P_{\frac{3}{2},\frac{1}{2}} \rightarrow {}^2S_{\frac{1}{2}} \rightarrow {}^2P_{\frac{3}{2},\frac{1}{2}}$. The Na I 6154.220 Å line is a $J = \frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{1}{2}$ transition and can therefore be called a D_1-type line. The Na I 6160.750 Å line on the other hand, being a $J = \frac{3}{2} \rightarrow \frac{1}{2} \rightarrow \frac{3}{2}$ transition, can be regarded as an "upside-down" or "inverse" D_2-type transition.

In the absence of hyperfine structure splitting, the D_1-type line has polarizability $W_2 = 0$ as usual, but the inverse D_2 transition has $W_2 = 0$ as well (in contrast to the normal D_2 transitions, which have $W_2 = \frac{1}{2}$). Thus, in contrast to the normal $D_1 - D_2$ line pairs that we have discussed before, *both* lines should in this case be unpolarizable in the absence of hyperfine structure. However, since sodium has nuclear spin $\frac{3}{2}$, the hyperfine structure splitting may change the situation in the same way as for the usual $D_2 - D_1$ lines in Fig. 1.

The observations that we have give a confusing and inconclusive picture, so we refrain here from showing plots of these results. Both lines show no emission-like polarization peak in the Q/I spectra, but the D_1 line does not show any depolarizing, absorption-like profile either. The continuum polarization simply remains flat at the position of the line. This might be taken as evidence for intrinsic line polarization of an amount that just compensates the otherwise depolarizing effect. However, the two lines are surrounded by a large number of both emission- and absorption-like polarization features at locations where no lines in the intensity spectrum are seen, and there are no identified molecular lines in this spectral region. More observations are needed before we can feel confident about these features.

4.3. The Al I D_2 and D_1 lines

Multiplet no. 5 of Al I has the same quantum numbers as multiplet no. 1 of Na I and Ba II and is therefore of the "classical" $D_2 - D_1$ type. The D_2 line is at 6695.970 and the D_1 line at 6698.630 Å. Since the wavelength separation is only 2.66 Å, in contrast to 6 Å for the classical sodium case in Fig. 1, we may expect that quantum interference between the $J = \frac{3}{2}$ and $\frac{1}{2}$ excited states could play a significant role. Furthermore, since aluminum has nuclear spin $\frac{5}{2}$ (in contrast to $\frac{3}{2}$ for sodium), hyperfine structure splitting could make the D_1 line polarizable, but in a different way than for sodium, because of the different quantum numbers of the hyperfine structure multiplet.

Unfortunately the polarization signals in this spectral region, including the possible signals from the Al I lines, are on the order of 4×10^{-5} or below, too weak to give us results about which we can have any confidence at the present time. Conclusive observations would require much longer integration times.

4.4. The V I D_1 and "inverse D_2" lines of multiplet no. 34

Similar to multiplet no. 5 of Na I, multiplet no. 34 of V I contains a line pair with J quantum numbers of the transition type D_1 (at 6111.652 Å) and "inverse" D_2 (at 6135.370 Å). The L and S quantum numbers are however different. The transitions are thus ${}^4D_{\frac{1}{2},\frac{3}{2}} \rightarrow {}^4P_{\frac{1}{2}} \rightarrow {}^4D_{\frac{1}{2},\frac{3}{2}}$. Without hyperfine structure splitting both line transitions should be unpolarizable, but as vanadium has nuclear spin $\frac{7}{2}$, it has an unusually rich hyperfine structure multiplet.

Our observations of the D_1-type line show no significant polarization feature but rather depolarization of the continuum. We have also two recordings of the inverse D_2 line, but both suffer from infiltration of the Zeeman effect due to instrumental cross talk and are therefore inconclusive.

4.5. Fe II 6149.240 Å

The Fe II 6149.240 Å line has lower state ${}^4D_{\frac{1}{2}}$ and upper state ${}^4P_{\frac{1}{2}}$ and thus represents a D_1-type transition. Except for 2.2 % in the form of Fe^{57}, iron has no nuclear spin or hyperfine structure.

The observations show no significant intrinsic polarization in this line but instead a depolarizing, absorption-like feature.

5. The Li I 6708 Å D_2 and D_1 lines

Because of the abnormally low abundance of lithium in the Sun due to mixing of the surface layers to depths, where nuclear burning of lithium can take place, the Li I 6708 Å line of multiplet no. 1 is extremely weak in the unpolarized spectrum of the quiet Sun (Brault & Müller 1975), but it stands out with high contrast in the polarized spectrum, as shown by Fig. 5. Muliplet no. 1 of lithium contains two lines with the same quantum

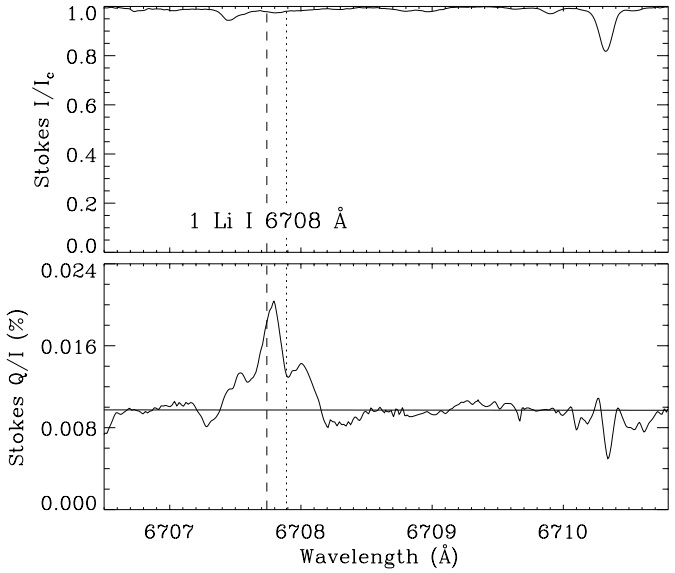

Fig. 5. Polarization profile of the Li I 6708 Å line, which shows up with a high-contrast triplet structure (lower panel) although it is barely visible in the intensity spectrum (upper panel). The wavelength positions of the two fine-structure components, which are of the D_2 and D_1 types, are indicated by the dashed and dotted lines, respectively. The recording was made on September 8, 1996, near the south polar limb.

numbers as the Na I and Ba II D_2 and D_1 lines, but the separation between them is only 0.15 Å (in contrast to 6 Å for Na I and 380 Å for Ba II). Therefore the feature that we see in Fig. 5 is produced by a coherent superposition of the scattering transitions in the two lines. It was the quantum interference from such a coherent superposition that gave rise to the sign reversal between the Na I D_2 and D_1 lines in Fig. 1. Because of the much smaller fine-structure splitting for lithium, we can expect quantum interference between the two lines to play a more dominating role for Li than for Na. On top of this, the hyperfine structure splitting adds to the coherent superposition of quantum states.

Isotope Li^7 makes up the dominant part (92.6 %) of the lithium abundance. It has the same nuclear spin ($\frac{3}{2}$) as sodium and the odd barium isotopes. Therefore we expect the 6708 Å feature to embody the same kind of physical system that was also responsible for the D_1 and D_2 lines of Na and Ba. We must caution, however, that 7.4 % of the lithium abundance is in the form of the isotope Li^6, which has nuclear spin 1. The isotope shift of the Li^6 lines towards the red with respect to the Li^7 lines is of the same magnitude as the fine structure splitting (cf. Brault & Müller 1975).

The wavelength positions of the D_2 and D_1 lines of Li^7 are marked in Fig. 5 by the vertical dashed and dotted lines, respectively. The observed polarization feature has a triplet structure that bears a curious qualitative resemblance to the Na I D_2 polarization feature in Fig. 1. Similar to the sodium case, the Li I 6708 Å line contains a concentrate of largely unexplored, enigmatic and not yet understood polarization physics, and may therefore guide us to a deeper understanding of the second solar spectrum.

6. $J = 1 \rightarrow 0 \rightarrow 1$ scattering transitions

Scattering transitions of the type $J = 1 \rightarrow 0 \rightarrow 1$ should be entirely unpolarizable (with polarizability $W_2 = 0$, see Sect. 2) in the absence of ground-state atomic polarization. Trujillo Bueno & Landi Degl'Innocenti (1997) have selected this type of transition to demonstrate how optical depopulation pumping can lead to scattering polarization in the observable range. We have searched all the useful solar lines of this type and tried to observe the polarization in the most promising lines. We report the results here, beginning with the positive evidence for ground-state polarization, and ending with the null results. Due to the highly individual behavior of the different lines, we need further future clarification of the circumstances under which these types of lines will exhibit intrinsic line polarization.

6.1. The C I 4932 Å line

This $^1P_1 \rightarrow ^1S_0 \rightarrow ^1P_1$ line, which is the single member of multiplet no. 13, was seen to have a very clear polarization signal already in Fig. 1 of Stenflo et al. (1998). However, according to Moore et al. (1966) the C I line at 4932.068 Å is blended by a V I line at 4932.016 Å. Accurate wavelengths for C I are hard to find because of the required very high temperature for the laboratory measurements. Johansson (1966) lists the wavelength of the C I line as 4932.050 Å, while Davis & Andrew (1978) list the V I line at 4932.032 Å. We have made a spectral decomposition of our ZIMPOL intensity data (see below) and find, under the assumption of two symmetric line contributions, that the wavelengths are 4932.053 Å for the C I line, in excellent agreement with the Johansson (1966) value, while the blend line is found to be at 4932.066 Å, i.e., it occurs in the red wing of the C I line instead of in the blue wing. We have made a similar decomposition of a solar FTS spectrum at disk center, which also shows that the blend occurs on the red rather than the blue side. The conclusion that the main line is due to C I rather than the other way around has strong support from the much larger line width of the main line, which can only be expected from a light element like carbon (see below).

There are thus strong reasons to believe that the identification of the C I line is correct, while there is some doubt concerning the identification (and even existence) of the blend line. If there is a blend that is due to multiplet no. 50 of V I, then this blend line should have the very low polarizability $W_2 = 0.02$, i.e., it should also be practically unpolarizable. With these identifications the polarization feature at 4932 Å could only exist as a result of ground-state atomic polarization, regardless of whether the feature is produced by the C I line or by the blend line. Our spectral decomposition below however provides evidence that it is really the C I line that is responsible for the polarization feature.

Fig. 6 shows five ZIMPOL recordings of the 4932 Å feature made in different solar regions (5 arcsec from the limb) and on

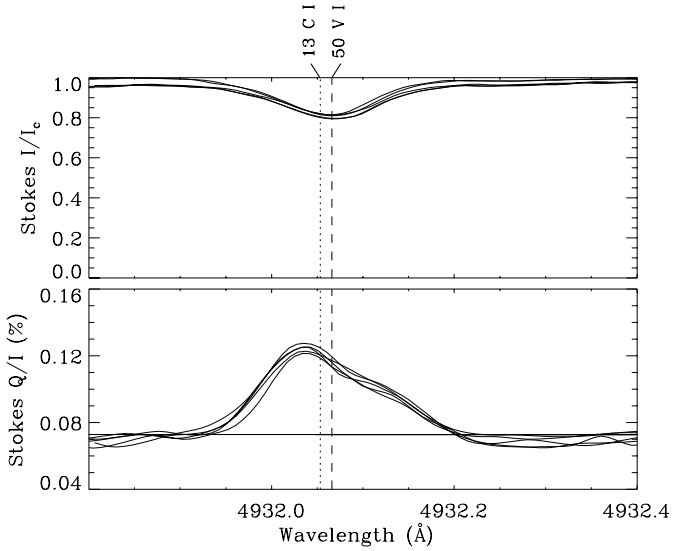

Fig. 6. Five recordings of the polarization feature at 4932 Å. Two of them were obtained on April 4 and 5, 1995, near the solar north pole, the remaining three on September 12, 1996, at various positions near the solar south pole. They are part of the same recordings that also included the Ba II 4934 Å line in Fig. 3.

different days. The vertical lines show the locations, determined from spectral decomposition of our data, of the C I line and the blend line, which for labelling purposes here is assumed to be due to V I. We notice the pronounced asymmetric shape of the polarization feature, which is well reproduced in all five recordings. The maximum is shifted towards the blue, while the red wing is suppressed. Through spectral decomposition of both the intensity and polarization profiles we will now make the case that it is the C I line that is polarizing, while the blend line, if it exists, depolarizes.

For the spectral decomposition we select one of the recordings, namely that of April 5, 1995, rather than the average of all five, since the average is spectrally smeared as compared with the individual profiles, due to small, relative shifts between the different recordings. We begin with a decomposition of the Stokes I profile, assuming that there are two contributing lines, governed by two Voigt-type profiles for the absorption coefficient: $H(a, v_{1,2})$, where $v_i = (\lambda - \lambda_i)/\Delta\lambda_{D,i}$. We model the observed Stokes I with a Milne-Eddington type solution:

$$(I/I_c)_{\rm model} = \frac{1}{1 + d_1 H(a, v_1) + d_2 H(a, v_2)} \,. \qquad (1)$$

The denominator contains the superposition of the opacity contributions from the continuum, represented by the Fig. 1, and the two lines, with relative weights d_1 and d_2. The model contains 6 free parameters: $\lambda_{1,2}$, $\Delta\lambda_{D,1,2}$, and $d_{1,2}$. To limit the degrees of freedom the damping parameter a is kept fixed at 0.004, which is a typical value for many spectral lines.

The result of the non-linear, iterative least-squares fit is that line 1 has a wavelength of 4932.053 Å and a Doppler width of as much as 88.6 mÅ, while line 2 is found to be at 4932.066 Å and has a Doppler width of 56.3 mÅ. The large Doppler width of line 1 shows that this must be the C I line, since only an element of low atomic weight can have such broad, unsaturated lines. The atomic weights of carbon and vanadium are 12.01 and 50.94, respectively. The ratio between the thermal widths of the two lines is expected to be approximately the square root of the inverse ratio between their atomic weights. Thus the C I line is expected to be broader by a factor of 2.1 if this were the only effect. Our spectral decomposition gives a width ratio of 1.9, which is very close and deviates as expected when one accounts for turbulent and instrumental broadening, which are independent of atomic weight. The d_1/d_2 ratio is found to be 1.44, i.e., the C I line is the stronger line.

To model the polarized spectrum (Q/I) we assume that the C I line is intrinsically polarizing, contributing with an emission-like feature in Q/I, while the blend line is assumed to be purely depolarizing (and thus contributing with an absorption-like feature). This choice of model is strongly suggested by Fig. 6, since the observed asymmetry shows that the polarization must be enhanced by the left line and rather suppressed by the right one. The natural choice for the analytical form of the model is then

$$(Q/I)_{\rm model} = p_c \, \frac{1 + a_1 H(a, v_1)}{1 + a_2 H(a, v_2)} \,. \qquad (2)$$

p_c is the continuum polarization, obtained from the theoretical work of Fluri & Stenflo (1999), which is also used in all the plots here. If there were no depolarizing line 2, then line 1 would add to the continuum polarization with a line contribution $p_c a_1 H(a, v_1)$, which shows that $a_1 H(a, 0)$ is the line polarization amplitude in units of the continuum polarization. The Voigt profile function is assumed to be centered around the already determined wavelength (4932.053 Å), but the Doppler width need not be the same as for the Stokes I profile (our experience is that the Q/I profiles are systematically narrower than the I profiles).

The depolarizing profile of line 2 is assumed to have a relative shape, in units of the "quasi-continuum" (the total background polarization, which contains the superposed contributions from the continuum and from line 1), of a Milne-Eddington type: $1/[1 + a_2 H(a, v_2)]$. Like in Eq. (1) the denominator consists of a continuum and a line contribution with relative amplitude parameter a_2. Also here the Voigt profile function is assumed to be centered around the already determined wavelength (4932.066 Å) but is allowed to have a different Doppler width.

The model for Q/I therefore contains 4 free parameters: The relative amplitudes ($a_{1,2}$) and the Doppler widths for the two lines. The fit gives for a_1 and a_2 1.06 and 0.27, respectively, for the Doppler widths 73.5 and 50.8 mÅ. Thus also the Q/I fit shows that the profile of the C I line is considerably broader than that of the blend line. In comparison with the Stokes I profiles, the width of the Q/I profile contribution is reduced for the intrinsically polarizing C I line, enhanced for the depolarizing blend line. This is a typical behavior for other lines when comparing their either polarizing or depolarizing profiles. The decomposition procedure thus yields entirely consistent results.

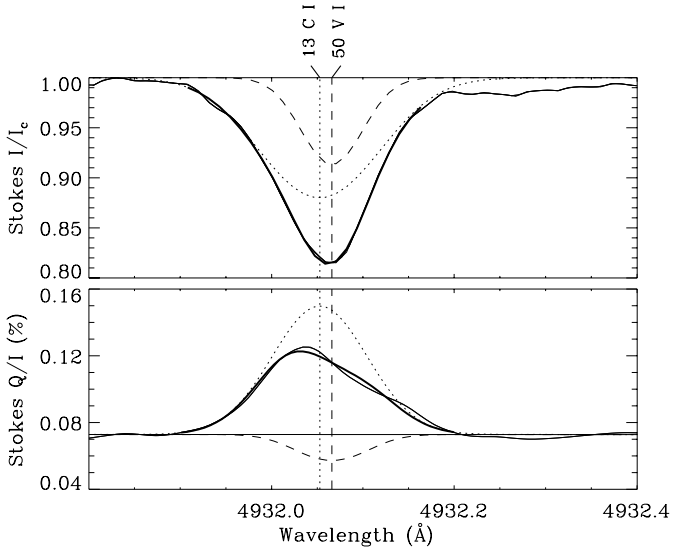

Fig. 7. Comparison between the observations (from April 5, 1995, represented by the thin, solid curves) and the model fit (thicker, solid curve). The individual contributions from the two spectral lines are given by the dotted (for C I) and dashed (for the depolarizing blend) curves.

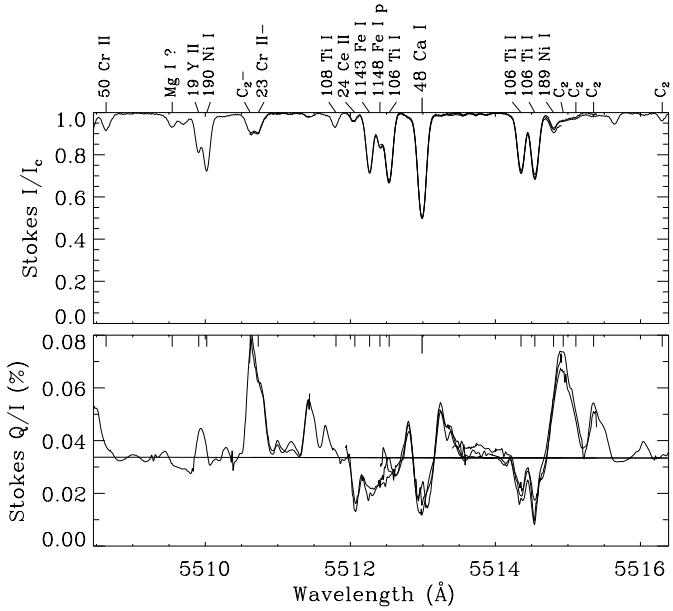

Fig. 8. Superposition of five partially overlapping recordings with ZIMPOL at the heliographic south pole, obtained on October 4 and 5, 1997. The Ca I 5513 Å line is surrounded by polarizing molecular lines due to C_2.

Fig. 7 shows a comparison between the model and observed spectra. The thin solid curves represent the observations, while the thick solid curve shows the model fit. For the Stokes I profile the model curve is practically indistinguishable from the observed profile, and also for Q/I the fit is nearly perfect, at least within the errors of the observations. The separate contributions in the fit from the two lines are shown by the dotted (for the C I line) and dashed (for the blend line) profiles. Thus the dotted curves are obtained from Eqs. (1) and (2) by letting d_2 and a_2 be zero, while the dashed profiles are obtained if instead d_1 and a_1 are set zero. Note the great difference between the line widths of the two lines, which is the main argument used to identify which of the two lines is due to C I.

Although the agreement between the model and the observed Stokes I profile is as perfect as it could possibly be, it does not necessarily mean that the decomposition correctly locates the blend line. It could instead be that we are dealing with one, single, but asymmetric line, and that this asymmetric shape could be mathematically represented in the form of a superposition of two symmetric contributions. Such asymmetries can arise from correlations between the intensity and Doppler velocity of the solar granulation. In this case the weaker (and much narrower) blend line could be an artefact of the assumption that we have two symmetric line components. However, in this single-line scenario, in which no significant blend line exists, we are still dealing with a line that is much wider than lines from heavier elements, so there can hardly be any doubt that this line must be due to C I. The conclusion, also in this single-line interpretation, is that the observed polarization feature is caused by scattering in the C I line.

The quantitative details of the decomposition should not be given much weight here, since they depend on the model assumptions for the analytic functional forms of the line contributions. The aim of the whole exercise is rather to qualitatively make sure which line is due to C I, and to verify that it is this line that is the source of the observed polarization signal. We are confident that this objective has been reached through this analysis.

We note here that carbon has zero nuclear spin and thus no hyperfine structure splitting. The observed polarization may thus represent the effect of ground level polarization due to optical pumping for a scattering transition with the total angular momentum quantum numbers $J = 1 \rightarrow 0 \rightarrow 1$.

6.2. The Ca I 5513 Å line

Like carbon, calcium has no nuclear spin, so the Ca I 5512.980 Å line should be another "clean" case of a $J = 1 \rightarrow 0 \rightarrow 1$ scattering transition. It is of type $^1P_1 \rightarrow ^1S_0 \rightarrow ^1P_1$ and is the single member of multiplet no. 48. In comparison with the C I 4932 Å line it has the great advantage of being unblended and considerably stronger (while not being saturated). It therefore would seem to be an ideal test case for lower-level atomic polarization.

Fig. 8 shows our spectral recordings of this line and its surroundings. As we noticed unexpected and prominent polarization features surrounding this line, which could confuse the interpretation, we made repeated and partially overlapping spectral recordings to increase the spectral coverage and check the reproducibility of the polarization features. Fig. 8 illustrates five different, superposed recordings, made with ZIMPOL at the heliographic south pole on October 4 (3 recordings) and 5 (2 recordings), 1997. The reproducibility of the polarization features is excellent, so we have no doubt about their reality.

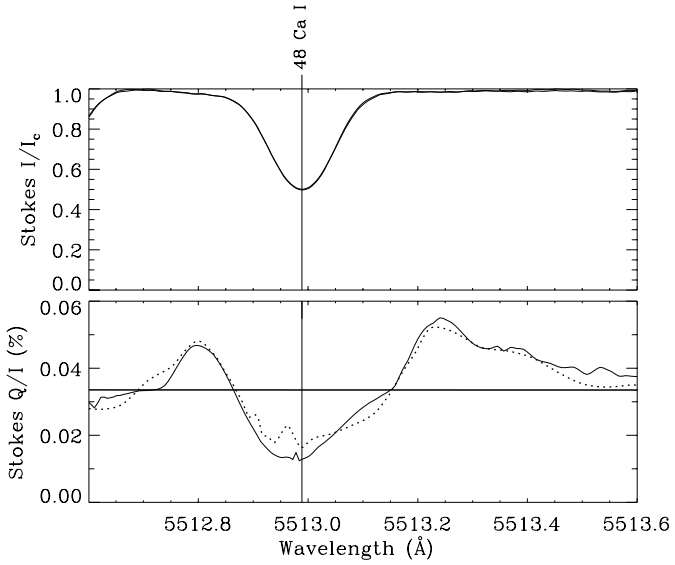

Fig. 9. Magnified portion of the spectrum in Fig. 8 around the Ca I 5512.980 Å line. The two overlapping recordings were both obtained with ZIMPOL on October 4, 1997.

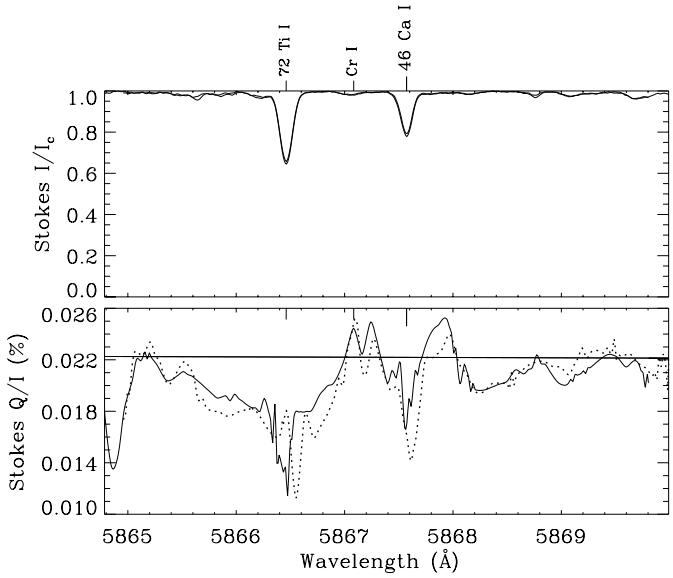

Fig. 10. Two superposed recordings of the region around the Ca I 5867.570 Å line, made in two different regions near the solar south pole on October 4 and 5, 1997.

As seen from the line identifications, the most prominent surrounding polarization features are due to molecular C_2. From previous recordings of the "second solar spectrum" (Stenflo & Keller, 1996, 1997; Stenflo 1997b) we know that weak and inconspicuous molecular lines like C_2 generally show up with high-contrast polarization features in the Q/I spectra. It is possible that some of the not identified, less prominent polarization features are due to molecular lines that are so weak in the intensity spectrum that they have not been listed among identified solar lines. However, we have the impression that the immediate neighborhood of the Ca I 5513 Å line is not contaminated by molecular lines, but that the polarization feature that is centered on the Ca I line with a depolarizing minimum in the line core and maxima in the line wings is really due to this line.

For all our recordings the relative positioning of the Q/I spectra with respect to the level of the continuum polarization always introduces some uncertainty, but since we in Fig. 8 have quite well defined continuum portions around 5508 and 5514 Å, it is highly unlikely that this uncertainty is of significance for the present discussion.

Fig. 9 shows a magnified detail from the previous Fig. 8 of the spectral portion around the 5513 Å line with two superposed recordings (solid and dotted curves), both obtained on October 4, 1997. If the wing maxima are really due to the Ca I line (and we have no alternative explanation what else they could be due to), then the profile shape is fundamentally different from that of the C I 4932 Å line that we analysed in the preceding section. The theoretical modelling by Trujillo Bueno & Landi Degl'Innocenti (1997) has illustrated how the polarized profile shapes may depend on the values of various parameters in the radiative-transfer problem, although none of the computed profile shapes was qualitatively similar to that of Fig. 9.

A somewhat speculative interpretation of the observed profile is that a broad polarization signal without central depression would be produced in the absence of magnetic fields by the Ca I line due to optical pumping of the ground state, but that the ubiquitous magnetic fields, as soon as they are stronger than about 10 mG, depolarize in the line core. Since the Hanle depolarization only operates in the Doppler core of the line but not in the wings, we obtain a depolarization feature in the central portion of the line, while the wing polarization survives. As the polarization must asymptotically approach the continuum level in the far wings, we will in this way get well-defined polarization maxima in the two line wings. Obviously careful theoretical work with radiative transfer, optical pumping, and Hanle depolarization is needed to verify whether this proposed explanation of the observations is correct.

6.3. The Ca I *5868 Å line*

The type of polarization profile that we saw for the Ca I 5513 Å line in Figs. 8 and 9 does not seem to be an isolated case but is suggested by a Ca I line of another multiplet, at 5867.570 Å. It is also a $^1P_1 \rightarrow ^1S_0 \rightarrow ^1P_1$ transition, and is the single member of multiplet no. 46. Fig. 10 shows a superposition of two ZIMPOL recordings, made in two different solar regions near the solar south pole on two different days, October 4 and 5, 1997. Here the reproducibility is not as good as in Figs. 8 and 9. We believe that the main reason for this is a subtle infiltration of Stokes V (circular polarization) signals from the longitudinal Zeeman effect due to instrumental polarization in the telescope. Since the instrumental polarization varies strongly during the day and the amount of high-latitude magnetic flux varies spatially, some Q/I recordings may be contaminated by such cross-talk while others are not. Due to the special signature of the longitudinal

Zeeman effect, the difference between the two curves in Fig. 10 should have anti-symmetric features around the two main spectral lines, which is at least qualitatively the case (within the observational errors).

Still the reproducibility in Fig. 10 is good enough to suggest the presence of a qualitatively similar polarization feature as that of the Ca I 5513 Å line, namely with a depolarizing contribution (possibly due to the Hanle effect) and wing polarization maxima (possibly due to lower-level atomic polarization produced by optical pumping). Due to broad, depolarizing, and unidentified Q/I features both to the blue and red sides of the Ca I line the results for this spectral region are not convincing by themselves and require further observational work, but taken together with the Ca I 5513 Å case, they lend support to the existence of polarizing profiles for $J = 1 \rightarrow 0 \rightarrow 1$ "null" lines of the type exhibited by the 5513 Å line.

6.4. The Mg I 5711 Å and Si I 5772.150 Å lines

Both these lines are also $^1\mathrm{P}_1 \rightarrow ^1\mathrm{S}_0 \rightarrow ^1\mathrm{P}_1$ scattering transitions and are single members of multiplets 8 and 17, respectively. The Mg I 5711.070 Å line appears as if it would be a rather ideal choice in the search for ground-level polarization, since it is an unblended and medium-strong line, similar in appearance to the Ca I 5513 Å line, and it is a $J = 1 \rightarrow 0 \rightarrow 1$ scattering transition with no hyperfine structure splitting for 90 % of the Mg atoms (while 10 % of Mg is in the form of isotopes with nuclear spin 5/2). We have made three recordings of the spectral region around this line in different solar regions (both at the south and north poles) on October 3, 5, and 9, 1997. All the recordings reproduce very well and show a broad and deep depolarizing profile throughout both core and wings of the line. There is no evidence for intrinsic line polarization.

Apart from 4.7 % of Si isotopes with nuclear spin $\frac{1}{2}$, the Si I 5772 Å $J = 1 \rightarrow 0 \rightarrow 1$ transition is not subject to hyperfine structure splitting. It is a relatively weak and unblended line of similar strength as the Ca I 5868 Å line (cf. Fig. 10). We have made two recordings with ZIMPOL of the 5772 Å region at different spatial locations (near the south pole) on October 3 and 5, 1997. Both recordings reproduce very well, and like in the Mg I 5711 Å case, we see no sign of significant intrinsic line polarization, only a broad depolarizing profile throughout core and wings.

6.5. The Ti I 4645 and Sc II 5669 Å lines

These two lines are somewhat different from the previously discussed $J = 1 \rightarrow 0 \rightarrow 1$ lines, since they are $^5\mathrm{P}_1 \rightarrow ^5\mathrm{D}_0 \rightarrow ^5\mathrm{P}_1$ and $^3\mathrm{P}_1 \rightarrow ^3\mathrm{P}_0 \rightarrow ^3\mathrm{P}_1$ transitions, respectively. This means that they are not the single members of their multiplets, but there are a number of other members. However, none of these other members have $J = 0$ as their upper state. Thus no fluorescent contributions with radiative excitation in other lines of the respective multiplet are possible, only the resonant contribution from the single line needs to be considered.

The observations indicate that the situation is the same as for the two previous cases described: Both the Ti I 4645 and the Sc II 5669 Å lines (which were both recorded with ZIMPOL on October 8, 1997) show a depolarizing profile, with no sign of intrinsic line polarization. 83 % of Ti has nuclear spin zero, while practically 100 % of scandium is in the form of the isotope Sc^{45}, which has nuclear spin $\frac{7}{2}$.

7. Anomalous multiplet patterns

When we compare the observed polarization amplitudes for all the different spectral lines of a given atomic multiplet, we expect the relative amplitudes to scale with the intrinsic polarizability W_2, which is determined by the total angular momentum quantum numbers J of the respective transitions. We have however found a number of multiplets, which very conspicuously violate this type of scaling. Even when accounting for all possible fluorescent contributions within the multiplet (when the initial and final states may be different) and using the weight factors of these different contributions as free parameters, one cannot come close even to a qualitative representation of the observed relative polarization amplitudes. It has not yet been explored to what extent lower-state atomic polarization produced by optical pumping could in principle provide an explanation for these cases, but so far they remain intriguing mysteries. We will now present the main outstanding cases.

7.1. Multiplet no. 2 of Mg I and multiplet no. 3 of Ca I

The three strong lines at 5167, 5173, and 5184 Å that constitute multiplet no. 2 of Mg I have the identical J quantum numbers as the medium strong lines at 6103, 6122, and 6162 Å of multiplet no. 3 of Ca I. Calcium has no nuclear spin (and thus no hyperfine structure splitting), while for magnesium 90 % is in the form of isotopes with no nuclear spin. The scattering transition is of the type $J = 0, 1, 2 \rightarrow 1 \rightarrow 0, 1, 2$, which allows for 9 different fluorescent combinations between the three initial and the three final states. Emission from $J = 1 \rightarrow 0$ produces the 5167 or 6103 Å lines, $J = 1 \rightarrow 1$ gives 5173 or 6122 Å, $J = 1 \rightarrow 2$ gives 5184 or 6162 Å. Since resonant scattering with $J = 0 \rightarrow 1 \rightarrow 0$ has a polarizability $W_2 = 1$, while resonant scattering with $J = 2 \rightarrow 1 \rightarrow 2$ has $W_2 = 0.01$, one might at first expect that the polarization amplitude of the 5184 Å line should be one hundred times smaller than that of the 5167 Å line, and similarly the amplitude of the 6162 Å line should be hundred times smaller than that of the 6103 Å line. The observations, presented in Figs. 11 and 12, show that it is instead the 5184 and 6162 Å lines that have the larger amplitudes. The expectations are thus in error by more than two orders of magnitude.

The next possibility to try is that there could be some combination of fluorescent scattering, which, when weighted appropriately, could explain the observed relative amplitudes. To examine whether this could work in principle, we list below all the fluorescent possibilities with their respective polarizabilities W_2, derived from the J quantum numbers according to the algebraic formulae given in Stenflo (1994, pp. 188–189). For

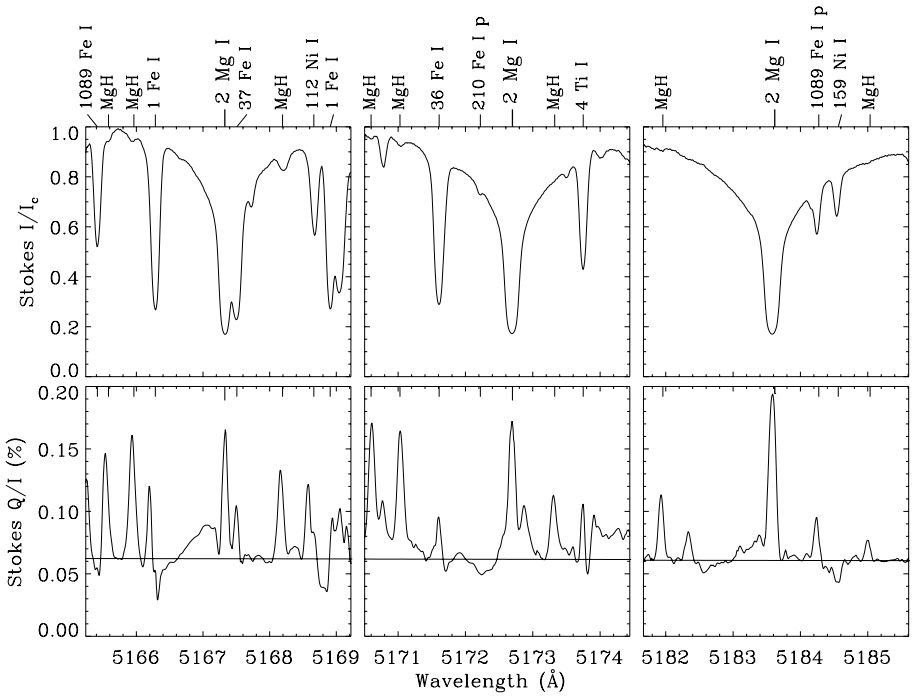

Fig. 11. Recordings of the spectral regions around the three lines of multiplet no. 2 of Mg I made with ZIMPOL at the same place near the solar north pole and on the same day, April 4, 1995. The Mg I lines are surrounded by weak but strongly polarizing lines of molecular MgH.

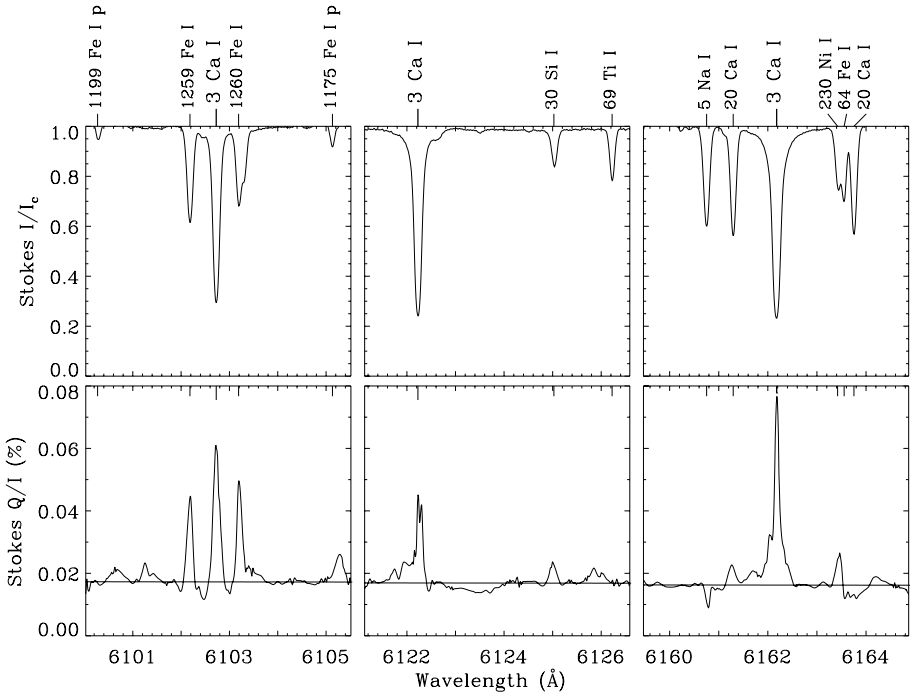

Fig. 12. Recordings of the spectral regions around the three lines of multiplet no. 3 of Ca I made with ZIMPOL at the same place near the solar north pole and on the same day, April 3, 1995.

each line there are three fluorescent possibilities, one of which is resonant and highlighted by giving its W_2 in bold face.

For the 5167 and 6103 Å lines we have

$J = 0 \rightarrow 1 \rightarrow 0 : \boldsymbol{W_2 = 1.00}$,
$J = 1 \rightarrow 1 \rightarrow 0 : W_2 = -0.50$,
$J = 2 \rightarrow 1 \rightarrow 0 : W_2 = 0.10$.

For the 5173 and 6122 Å lines we have

$J = 0 \rightarrow 1 \rightarrow 1 : W_2 = -0.50$,
$J = 1 \rightarrow 1 \rightarrow 1 : \boldsymbol{W_2 = 0.25}$,
$J = 2 \rightarrow 1 \rightarrow 1 : W_2 = -0.05$.

For the 5184 and 6162 Å lines we have

$J = 0 \rightarrow 1 \rightarrow 2 : W_2 = 0.10$,
$J = 1 \rightarrow 1 \rightarrow 2 : W_2 = -0.05$,
$J = 2 \rightarrow 1 \rightarrow 2 : \boldsymbol{W_2 = 0.01}$.

For a given line, the relative weights of the three fluorescent contributions are determined by the relative absorption oscil-

lator strengths for the three radiative excitations $J = 0 \rightarrow 1$, $J = 1 \rightarrow 1$, and $J = 2 \rightarrow 1$, as well as by the intensities of the radiation field at the three wavelengths, where the excitations take place. Let us begin by assuming that we single out the $J = 0 \rightarrow 1$ absorption and give zero weight to the other two excitations. Then we would expect a strong *negative* amplitude of the 5173 and 6122 Å lines, while the amplitudes of the 5184 and 6162 Å lines should be an order of magnitude smaller than those of the 5167 and 6103 Å lines. This clearly has no qualitative resemblance at all to the observations.

Next, let us single out the $J = 1 \rightarrow 1$ excitation transition and give zero weight to the other two. In this case we would expect negative amplitudes for both the 5167, 6103 and 5184, 6162 Å line pairs, again with an order of magnitude smaller (but negative) amplitude for the 5184, 6162 Å pair. Also this has no qualitative resemblance to the observations. Finally we single out the $J = 2 \rightarrow 1$ absorption transition. This should result in overall small polarization amplitudes, again an order of magnitude smaller for the 5184, 6162 Å pair as compared with the 5167, 6103 Å pair, and the 5173, 6122 Å lines should appear with small but negative polarization amplitudes. Also here there is no similarity to the observations.

If instead of this idealized discussion that has singled out one absorption transition at a time we allow arbitrary weight combinations with three free parameters, we immediately see that it is impossible, even with these three artificially allowed degrees of freedom, to come remotely close to a qualitative fit to the observed relative polarization amplitudes. The reason is that the intrinsic polarizability of the 5167, 6103 Å line pair always remains larger by an order of magnitude than that of the 5184, 6162 Å pair. In contrast, it is the latter pair that has the largest observed polarization amplitudes.

The above discussion demonstrates that the observations cannot be explained within the theoretical framework used to calculate the intrinsic polarizabilities W_2, which implicitly assumes zero initial-state atomic polarization. The question whether or not ground-state polarization induced by optical depopulation pumping can indeed provide the explanation can only be answered by future theoretical work with detailed modelling of this possibility.

7.2. The Ca II *infrared triplet*

Another enigmatic multiplet is the infrared triplet (8498, 8542, and 8662 Å) of ionized calcium. At these long wavelengths the ZIMPOL modulation package generates polarized interference fringes, which compromise the quality of the data, but in the observations presented here (Fig. 13), a considerable and careful effort has been invested in removing the fringes in the data analysis. Although this removal cannot be made complete and therefore some remnants show up in the left panel of Fig. 13, we believe that the major features of the displayed spectra (relative amplitudes and polarization line widths) can be trusted.

The upper atomic states of the infrared triplet have $J = \frac{1}{2}$ and $\frac{3}{2}$, while the lower levels have $J = \frac{3}{2}$ and $\frac{5}{2}$. The emission transition $J = \frac{3}{2} \rightarrow \frac{3}{2}$ produces the 8498 Å line, the $J = \frac{3}{2} \rightarrow \frac{5}{2}$ transition the 8542 Å line, the $\frac{1}{2} \rightarrow \frac{3}{2}$ transition the 8662 Å line. There is also fluorescent coupling to the ultraviolet multiplet no. 1 that contains the K and H lines at 3933 and 3968 Å. While their lower state has $J = \frac{1}{2}$, the upper states of $\frac{3}{2}$ and $\frac{1}{2}$, respectively, are common to the upper states of the infrared triplet. Again, calcium has no nuclear spin and therefore no hyperfine structure splitting.

In our list of fluorescent scattering combinations we thus have both the possibility of UV excitation in the K and H lines (with initial state $J = \frac{1}{2}$) and infrared excitation within the same multiplet (with initial state $J = \frac{3}{2}$ or $\frac{5}{2}$). For each of the three triplet lines we have three fluorescent possibilities, except for the 8662 Å line, for which the selection rule (ΔJ cannot exceed unity) allows only two.

For the 8498 Å line:

$$J = \tfrac{1}{2} \rightarrow \tfrac{3}{2} \rightarrow \tfrac{3}{2} : W_2 = -0.40\,,$$
$$J = \tfrac{3}{2} \rightarrow \tfrac{3}{2} \rightarrow \tfrac{3}{2} : W_2 = 0.32\,,$$
$$J = \tfrac{5}{2} \rightarrow \tfrac{3}{2} \rightarrow \tfrac{3}{2} : W_2 = -0.08\,.$$

For the 8542 Å line:

$$J = \tfrac{1}{2} \rightarrow \tfrac{3}{2} \rightarrow \tfrac{5}{2} : W_2 = 0.10\,,$$
$$J = \tfrac{3}{2} \rightarrow \tfrac{3}{2} \rightarrow \tfrac{5}{2} : W_2 = -0.08\,,$$
$$J = \tfrac{5}{2} \rightarrow \tfrac{3}{2} \rightarrow \tfrac{5}{2} : W_2 = 0.02\,.$$

For the 8662 Å line:

$$J = \tfrac{1}{2} \rightarrow \tfrac{1}{2} \rightarrow \tfrac{3}{2} : W_2 = 0.00\,,$$
$$J = \tfrac{3}{2} \rightarrow \tfrac{1}{2} \rightarrow \tfrac{3}{2} : W_2 = 0.00\,.$$

We do not need here any extensive discussion of various cases to immediately see that there is no way in which some combination of fluorescent transitions could come remotely close to qualitatively explain the observations, even if we were given complete freedom to pick and choose whatever fluorescent transition that we want. We see this because the intrinsic polarizability W_2 for the 8662 Å line is exactly zero for both the fluorescent possibilities that can occur, while the observations show a strongly polarized peak for this line. It remains to be seen in future theoretical work whether lower-state atomic polarization could possibly provide an explanation of these observations.

Multiplet no. 2 of barium, with the 5854, 6142, and 6497 Å lines, has the same quantum number structure as the calcium infrared triplet, and it is coupled to the multiplet no. 1 D_2 and D_1 lines at 4554 and 4934 Å in the same way as the infrared triplet is coupled to the K and H lines. Recent (unpublished) observations with ZIMPOL have revealed a polarization structure for the barium triplet that is similar to that in calcium. In particular, the Ba II 6497 Å line, which like the Ca I 8662 Å line should be intrinsically unpolarizable, exhibits a strong and well defined polarization peak. This result further underscores that we are dealing with a fundamental problem, for which we lack a physical explanation.

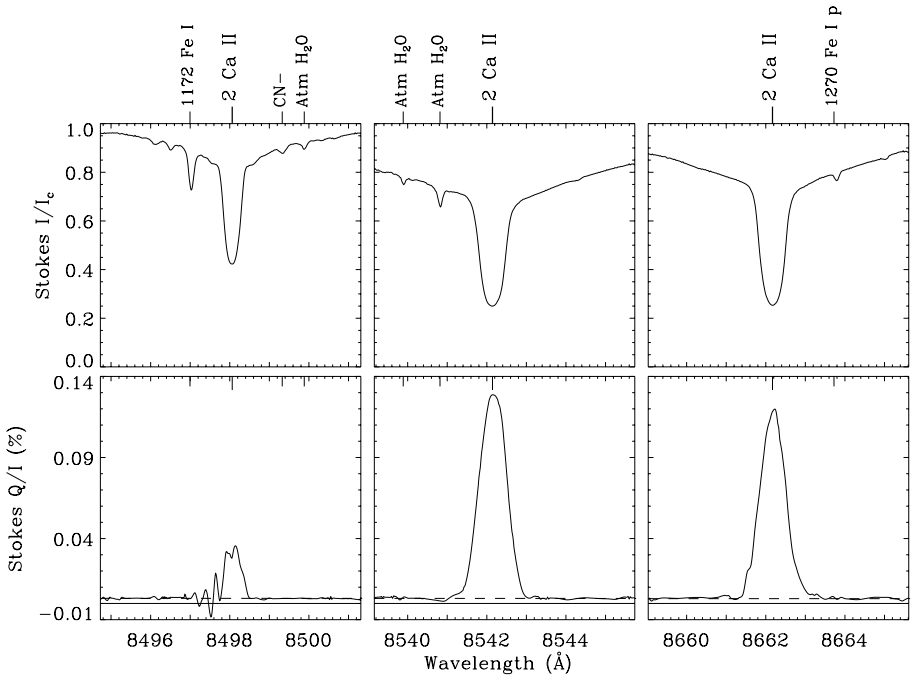

Fig. 13. Recordings of the spectral regions around the three infrared lines of multiplet no. 2 of Ca II made with ZIMPOL at the same place near the solar north pole and on the same day, November 17, 1994. The level of the continuum polarization is represented by the horizontal dashed lines.

8. Conclusions

In the present paper we have assembled a number of observations that have so far defied explanation. The examples focus on spectral lines which, according to standard quantum mechanics, should be intrinsically unpolarizable, even when taking into account possible fluorescence from other line transitions. One type of transition is of the D_1 type, with $J = \frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{1}{2}$, represented most prominently by the Na I D_1 5896 and Ba II 4934 Å lines, both of which exhibit clear and narrow polarization peaks in the line core. The Li I 6708 Å line is a particularly interesting case, because it is formed via a mixed quantum state between the D_2 and D_1 type transitions, which are separated in wavelength by only 0.15 Å. Since Li, Na, and the odd isotopes of Ba have nuclear spin $\frac{3}{2}$, they all have the same hyperfine structure pattern and thus provide three different systems for the exploration of this particular polarization mystery.

One line that should also be intrinsically unpolarizable is the Ca II 8662 Å line, regardless of possible fluorescence from the ultraviolet (via excitation in the 3968 Å H line). However, the observations show a prominent polarization peak for this line. Similarly, the Mg I 5184 and Ca I 6162 Å lines should be nearly unpolarizable, but the observations show them to have larger polarization amplitudes than the other members of the multiplet, which according to their quantum numbers should be much more polarizable.

The procedure of assigning intrinsic polarizabilities to these "anomalous" lines based on the quantum numbers of the respective scattering transitions thus does not seem to work, so a wider theoretical framework is needed. One way to achieve such a generalized framework is to allow for the possibility of lower-state atomic polarization induced by optical depopulation pumping, a process that has been proposed by Trujillo Bueno and Landi Degl'Innocenti (1997) and used by Landi Degl'Innocenti (1998) to explain the observed polarization in the Na I D_2 and D_1 lines. A further generalization would be to allow for coherency transfer from other, excited states in a multi-level atomic system. The effects that this would bring are expected to depend on the details of the atomic system considered.

A simple example of a line that could only become polarizable if there is lower-state polarization is a scattering transition of the type $J = 1 \rightarrow 0 \rightarrow 1$. We have searched for lines in the solar spectrum that are of this type, and explored their polarization properties with ZIMPOL. The result of this exploration is mixed, but it provides at least partial evidence for the existence of this type of polarization. Thus, after a careful analysis aimed at ruling out the possible explanation in terms of a blend line, we conclude that the observed polarization feature at 4932 Å is due to a C I line, which is of the $J = 1 \rightarrow 0 \rightarrow 1$ type. The polarization profile seems to be in the form of a single peak. For the two Ca I 5513 and 5868 Å lines, which are also of this type, the line core seems to be depolarized, while there appear maxima in the line wings, which are likely (but not for certain) due to these lines. Four other transitions of this type, the Mg I 5711, the Si I 5772, the Ti I 4645, and the Sc II 5669 Å lines, however, only seem to depolarize the continuum polarization and do not exhibit intrinsic line polarization.

Although lower-state atomic polarization provides a promising and natural extension of the theoretical framework that could possibly deal with these anomalous cases, there are serious arguments speaking against it (Stenflo 1999). The arguments refer to the circumstance that the lower state, at least when it is a ground state like in the case of the Na I and Ba II D_1 lines, has a life

time that exceeds by about two orders of magnitude that of the excited state. The ground state is therefore vulnerable to depolarization by magnetic fields that are two orders of magnitude weaker than those needed to depolarize (via the Hanle effect) the excited states. The ground state polarization would, according to Landi Degl'Innocenti (1998), only survive, if much of the volume of the solar atmosphere is occupied by magnetic fields weaker than 10 mG, something that seems to be ruled out by other magnetic-field diagnostics.

We are thus facing a new paradox for the Sun: On the one hand the many observed cases of anomalous polarization effects in the second solar spectrum force us to seek explanations within an enlarged theoretical framework, in which lower-state atomic polarization plays a crucial role. On the other hand such polarization should not be able to exist under solar conditions, because it would be destroyed by the ubiquitous magnetic fields that are believed to permeate the solar plasma. The resolution of this paradoxical situation should lead to deepened insight in both atomic and solar physics.

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