Second Solar Spectrum: A Brief Overview

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Abstract. A brief overview of the observed properties of the Second Solar Spectrum is presented, with emphasis on some of the most recent advances. These include clarification of the physical nature and properties of the continuum polarization, diagnostics of chromospheric magnetic fields with the Ca ii K line, progress in elucidating the enigmatic D1 polarization, and molecular scattering in magnetic fields.

1. Introduction

It is now a decade since the full wealth of structures in the Second Solar Spectrum became accessible to exploration (Stenflo & Keller 1996, 1997), through the introduction of the ZIMPOL technology for imaging polarimetry (Povel 1995, 2001). Much of the unfamiliar physics that governs the signatures in this spectrum has since been identified, but a number of still enigmatic anomalies remain. The technology for accessing the particularly rich UV region became available only a few years ago (Stenflo 2003; Gandorfer et al. 2004), and an atlas of the Second Solar Spectrum covering this region down to about 310 nm has recently been completed in three volumes (Gandorfer 2000, 2002, 2005). The Second Solar Spectrum is being applied to diagnose fundamental aspects of solar magnetism, which are not accessible by the Zeeman effect or any other means, for instance the vast amounts of hidden magnetic energy in the solar atmosphere in regions that look empty in solar magnetograms (Trujillo Bueno, Shchukina, & Asensio Ramos 2004; Stenflo 2004b).

2. Polarization of the Continuum

The Second Solar Spectrum, which is due to coherent scattering processes, has in linear polarization \(Q/I\) the appearance of a mixed absorption-emission line spectrum. The lines appear against a polarized continuous background. While many lines exhibit polarization that is much larger than the continuous polarization (and therefore look like emission lines in \(Q/I\)), the majority of lines depolarize the continuum. Since the lines and continuum interact in the radiative-transfer process, a good understanding of the continuum polarization is needed for quantitative analysis of the line polarization.

Direct observational determinations of the continuum polarization requires sufficient control of the \textit{absolute} polarization scale and its true zero point. Since
the absolute polarization level is not determined with the same precision as the relative spectral variations of the polarization (which can be measured with a precision of $10^{-5}$), the zero point of the $Q/I$ scale is not considered as an observable, but is fixed by using theoretical concepts for the continuum polarization and the depolarizing lines.

Using the data set of the three atlas volumes of the Second Solar Spectrum (Gandorfer 2000, 2002, 2005) that cover the spectral range 3160–6995 Å in combination with an improved understanding of the multitude of depolarizing lines (Fluri & Stenflo 2003) and radiative-transfer concepts for the formation of the polarized continuum (Fluri & Stenflo 1999), it has been possible to extract information from which the semi-empirical values of the continuum polarization for any wavelength (within the atlas range) and $\mu$ value (center-to-limb position) can be derived (Stenflo 2005).

The continuum opacity in the visible is almost exclusively due to bound-bound and bound-free transitions in hydrogen, plus Thomson scattering at free electrons (cf. Fig. 1). The dominating opacity source is H$^-$, which is unpolarizing, but, near the Balmer limit, Balmer absorption (which is also unpolarized) begins to compete. Polarization can only be produced by scattering transitions. Balmer scattering is insignificant except in the immediate neighborhood of the Balmer resonances. The only two polarizing sources of any significance are Lyman and Thomson scattering. Lyman scattering, which is the main source of polarized photons, represents Rayleigh scattering in the distant wings of the Lyman series. It therefore actually represents line scattering, although far from the line resonances.

The Balmer jump in the semi-empirically determined curves of Fig. 2 is found to lie about 80 Å above the nominal position of the Balmer series limit. This can be understood in terms of Stark broadening of the Balmer transitions, which causes the oscillating opacities near the Balmer limit to merge and converge to a quasi-continuum well before the formal continuum is encountered.
3. Chromospheric Magnetic Fields

The Second Solar Spectrum is modified by magnetic fields via the Hanle effect. The polarized Hanle signatures are generally easy to distinguish from the Zeeman signatures, since they have a qualitatively different spectral behavior. Since they respond to weaker fields than the usual Zeeman effect, in particular to horizontal fields, and since they are best visible in strong resonance lines, they are particularly useful for exploring the properties of chromospheric fields.

The Ca\textsuperscript{ii} H and K lines are two of the most prominent chromospheric lines in stellar spectra. Their scattering polarization properties have been explored in Stenf\o, Baur, & Elmore (1980), and it could be conclusively clarified that the wing polarization of the H-K spectral system is governed by quantum interference between the $J = 1/2$ and $3/2$ upper levels of the scattering transition (Stenf\o 1980). Since calcium does not have nuclear spin and hyperfine structure splitting, the H-K system does not suffer from the still not understood complications that affect the D\textsubscript{1}-D\textsubscript{2} type systems of sodium, barium, and potassium (see below). The triplet peak structure around the line core of strong resonance lines can be understood in terms of polarized radiative transfer (Holzreuter, Fluri, & Stenf\o 2005), so the underlying quantum and radiative transfer physics for the Ca K line can be considered to be well understood in principle.

Figures 3–5 show examples of ZIMPOL recordings made at NSO/Kitt Peak in March 2005 around the core of the Ca\textsuperscript{ii} K line. The most striking feature is the high degree of spatial structuring of both the $Q/I$ and $U/I$ polarization everywhere on the quiet solar disk, and that well defined polarization signatures are seen for all $\mu$ values, also at the quiet disk center. While the wing polarization is unstructured and vanishes at disk center, the core polarization keeps standing out at all disk locations. This pronounced spatial structuring shows that monochromatic imaging of the Stokes vector with a narrow-band filter would be a very rewarding undertaking, and reveal a new structured face.
Figure 3. Stokes spectra around the core of the Ca II K line for the quiet Sun at disk positions $\mu = 0.1$ (left) and $\mu = 0.3$ (right). Note that the surrounding depolarizing lines are only seen in $Q/I$, not in $U/I$, since the non-magnetic polarized quasi-continuum of the H-K spectral system only appears in $Q/I$.

of the Sun. We are currently implementing a fully tunable, Fabry-Perot based filter system to be used with ZIMPOL for such Stokes imaging of the scattering polarization (cf. Feller, Boller, & Stenflo 2006).

The natural explanation of the spatial variations, and in particular the polarization signals in $U/I$, is in terms of the Hanle effect from spatially varying magnetic fields. In $Q/I$ we have varying depolarization effects (for large-angle scattering, i.e., near the limb), for $U/I$ varying rotation of the plane of polarization. The polarization may however also vary, and the plane of polarization may be rotated, if there are local deviations from axial symmetry of the incident radiation field, like if there are local “hot spots” that illuminate the scattering atoms more from one side than the other. Since the supergranulation network has rather high contrast in the Ca II lines, such fluctuations of the radiation field may well be significant to give rise to observable polarization effects.

The non-magnetic explanation in terms of a fluctuating illuminating radiation field would however be expected to induce spatial variations that are correlated in $Q/I$ and $U/I$. This does not seem to be the case in our observations. Monochromatic mapping of the spatial morphology of the full Stokes vector should allow a definite clarification of this matter. The spatial scale of
Figure 4. Same as Fig. 3, but for $\mu = 0.5$ (left) and $\mu = 1.0$ (right). Note how the depolarizing lines disappear with increasing $\mu$, and how Stokes $V/I$ signals show up more. The K line core exhibits well defined polarization signatures also at the center of the quiet solar disk.

The fluctuations seen in the present recordings is typically the supergranulation scale. If it is confirmed, as seems most likely, that the dominating effect comes from the structured and spatially resolved chromospheric magnetic fields via the Hanle effect, such observations provide a gateway to the determination of chromospheric magnetic fields at the level of formation of the Ca K line core.

While for large-angle scattering (i.e., near the solar limb) the main signatures of the Hanle effect are depolarization and rotation of the plane of polarization, the property of the Hanle effect for small-angle scattering is to create linear polarization under the influence of horizontal magnetic fields (Trujillo Bueno 2001). The linear polarization signatures that we see near disk center are therefore signatures of horizontal chromospheric magnetic fields, assuming that we can rule out the contributions from local fluctuations of the illuminating radiation. It is however outside the scope of the present paper to convert the polarization diagrams to numerical values for the field strength and direction.

When we go to more strongly magnetic regions, the longitudinal Zeeman signatures in $V/I$ show up prominently (and with opposite signs in the absorption and emission features; cf. Fig. 5). In sunspots (cf. the right panel of Fig. 5) the transverse Zeeman effect seems to overtake the scattering polarization.
4. The D$_1$ Enigma: A Problem for Solar or Quantum Physics?

The enigma of the observed solar polarization peaks of the D$_1$ line of Ba II 4934 Å and Na I 5896 Å has eluded all explanation attempts since its discovery in sodium a decade ago (Stenflo & Keller 1996). The detailed observed amplitude, symmetry, shape, and center-to-limb variation for the quiet Sun (Stenflo, Gandorfer, & Keller 2000a; Stenflo, Keller, & Gandorfer 2000b) appear to contradict an explanation in terms of optical pumping of the hyperfine structure components (Landi Degl’Innocenti 1998, 1999), both because the observed amplitude is 1–2 orders of magnitude larger, and the symmetry opposite to the theoretical prediction (Trujillo Bueno et al. 2002; Kerkeni & Bommier 2002; Casini et al. 2002; Klement & Stenflo 2003; Casini & Manso Sainz 2005).

To try to identify if the D$_1$ enigma is a problem of solar physics or of quantum mechanics/atomic physics we have set up a laboratory experiment to explore the Mueller scattering matrix for 90° scattering in the D$_1$ and D$_2$ lines (Thalmann et al. 2006). Since a successful experiment of this type requires the use of a tunable laser, and since the rather inexpensive solid-state tunable laser

Figure 5. Stokes spectra around the core of the Ca II K line for a weakly magnetic region near disk center (left) and across a sunspot at $\mu = 0.61$ (right). Note how the sign of the $V/I$ profile of the K line core is opposite to the sign for the surrounding blend lines, since the K core is an emission line, the blend lines are absorption lines.
systems are not available for the sodium wavelengths, we have chosen to do
the experiment with potassium vapor instead, since the potassium D1 and D2
transitions have the same quantum structure with nuclear spin as the sodium
and barium transitions.

The initial results from the laboratory experiment (Thalmann et al. 2006)
indicate that the answer to our question—whether the problem lies in solar
or quantum physics—is “both”. At least it cannot be a problem of quantum
physics alone, since the laboratory D1/D2 polarization ratio is much smaller
than the corresponding solar ratio (and even has the opposite sign) for the
nearly non-magnetic laboratory case. This suggests that the explanation must
involve magnetic fields.

The K i D1 7699 Å solar polarization is hard to measure, since the photo-
spheric limb darkening in this red portion of the spectrum is very small, which
results in correspondingly small line polarization amplitudes. Still we succeeded
in getting a good and clean recording with ZIMPOL at NSO/Kitt Peak in March
2005, with the slit at $\mu = 0.1$ at the heliographic south pole (cf. Fig. 6). While
this recording shows a positive core polarization peak in $Q/I$ that is similar to
the peaks seen in Ba ii and Na i D1, in particular for the slit section from 20
to 40°, we also see substantial spatial variations with clear signatures of the
transverse Zeeman effect at the other slit portions for both $Q/I$ and $U/I$, and
longitudinal Zeeman $V/I$ signals for all slit portions. This illustrates the ubiq-
utitious presence of magnetic fields on the quiet Sun, and demonstrates that no
solar region can be considered as really “field free”. It is thus possible that the
D1 polarization peak reflects a certain property of the Sun’s magnetic field and
is a sensitive diagnostic of this property, although we still need to identify what
exactly this property is.

The polarization peak in K i D1 might be related to vertical magnetic fields,
since such fields have a transverse component that is oriented along the radius
vector from disk center. The transverse Zeeman effect of such a field produces a
core polarization ($\pi$ component) with linear polarization that is oriented parallel
to the nearest solar limb. This orientation, which is the same as for the observed
positive D1 $Q/I$ peak, is independent of field direction, of whether the field lines
go in or out of the Sun, due to the 180° ambiguity of the transverse Zeeman effect.
Vertical magnetic fields would therefore give qualitatively the same polarization
signature as the observed one.

Although the transverse Zeeman effect may explain the potassium observa-
tions in Fig. 6, it would not be sufficient for the stronger signatures seen in the
broader sodium and barium D1 lines, since the required field strengths would be
too high. The explanation most likely has to involve coherent scattering with
optical pumping in a special magnetic-field environment.

5. Molecular Scattering in Magnetic Fields

One of the great surprises in the early explorations of the Second Solar Spectrum
was the prominence of molecular lines (Stenflo & Keller 1996). While being quite
inconspicuous in the intensity spectrum, they dominate many sections of the
Second Solar Spectrum. Through Gandorfer’s Atlas project it was found that the
molecular polarization appears to exhibit a remarkable immunity to magnetic
fields: while the scattering polarization of atomic lines shows sensitivity to local magnetic fields and variations with the solar cycle, the molecular polarization displays little if any variations. This behavior was given an explanation by Berdyugina, Stenflo, & Gandorfer (2002) in terms of the small Landé factors that most molecular lines have due to their high $J$ quantum numbers. Landi Degl’Innocenti (2003) and Trujillo Bueno (2003) have on the other hand pointed out that the smaller Landé factor is partly compensated for by the smaller Einstein $A$-coefficient, so that some Hanle sensitivity should still be retained for molecular lines. In particular, the differential Hanle effect or molecular line ratio for pairs of molecular lines that are similar but differ in their Hanle sensitivity could provide an important method of determining the magnetic field strength, without needing to depend on radiative-transfer calculations. Such a differential molecular technique has been used by Berdyugina & Fluri (2004) for diagnosing spatially unresolved turbulent magnetic fields, and by Asensio Ramos & Trujillo Bueno (2005) for going a step further to determine the difference in the turbulent field strength between granular and intergranular regions.

Figure 7, recorded with ZIMPOL at NSO/Kitt Peak in March 2005, illustrates the apparent magnetic immunity of the molecular line polarization for the CN lines in the region around 3773 Å. In the right diagram of Fig. 7, obtained
near a small sunspot near the W limb, the atomic lines exhibit (in the central portion of the slit) the well recognizable signatures of the transverse Zeeman effect, both in $Q/I$ and $U/I$, while the molecular polarization appears unchanged and remains zero in $U/I$. Note, however, that this apparent invariance is fully consistent with the possibility that the molecular polarization is modified by a spatially unresolved turbulent field.

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