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Unsolved problems in solar polarization

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Abstract. The Second Solar Spectrum has presented us with a rich and unfamiliar world of polarization phenomena. While the many new spectral structures have great diagnostic potential, they cannot be exploited before we have identified the underlying physical processes and formulated a theory for them. This theoretical challenge has led to considerable advances in our understanding of the interaction between matter and radiation in magnetized media, but a number of observed polarization phenomena remain unexplained. Cases like the enigmatic Na I D_1 line indicate serious gaps in our understanding. A problem has been the lack of benchmarks, against which the quantum theory of polarized scattering can be tested. Polarized light scattering was a hot experimental topic in the early years of quantum physics until about 1935, after which the quantum physicists turned to other topics. A recent laboratory experiment to explore the physics of the enigmatic D_1 scattering transition has exposed the failure of the currently used theory and prompted intense efforts to search for remedies. Besides these issues with scattering polarization we discuss other unsolved problems like the magnetic structuring on spatially unresolved scales. There are also enigmas for the global magnetic field of the Sun. In the final section we expose a case where Hale's polarity law is being violated.

1. Introduction

In principle the topic "unsolved problems" covers everything that we are presently working on in science. It is in the nature of a problem to be unsolved, because if it were solved, then it would not remain a problem any more. For scientists it would be meaningless to devote time to solved problems (except for teaching). Since the topic is thus too broad to be covered in its generality, this presentation will be limited to a personal sample of problems that represent a few different aspects of the subject "solar polarization".

While these aspects range from deep questions in quantum physics to observational techniques, all are ultimately related to issues in magnetic-field diagnostics, which in turn determine the experimental basis for solar and stellar magnetohydrodynamics, dynamo processes, and plasma astrophysics in general. However, when focusing on the central aspects of "solar polarization", the magnetic fields enter the problems mainly through their influence on the spectrum. It is through the recording of the polarized spectral signatures that we can measure cosmic magnetic fields. These polarized signatures are mainly due to the Zeeman and the Hanle effects. While the Zeeman effect has long been a basic tool since Hale's discovery of Zeeman splitting in sunspots (Hale 1908), the Hanle effect has caught the attention more recently, since it is much more challenging for the observations. The Hanle effect represents the magnetic modification of scattering polarization, and the polarization amplitudes of the scattering polarization are tiny and only observable with highly sensitive polarimeters. With the advance of polarimeter technology it has recently been possible to open up this new field.

2. Enigmas of the Second Solar Spectrum

It had long been recognized that non-magnetic scattering processes in resonance lines should produce linear polarization effects in the Sun's spectrum (e.g. Öhman 1929). The first reliable recording of such polarization on the solar disk was done by Brückner (1963) in Locarno (at the observatory that is now operated under the name IRSOL) for the Ca I 4227 Å line. The first survey of linear polarization inside the Sun's limb throughout the solar spectrum, performed at Kitt Peak from 3165 to 9950 Å (Stenflo et al. 1983a,b), gave an indication of the structural richness of the linearly polarized spectrum that is exclusively produced by coherent scattering processes. The discovered structuring was very different from that of the ordinary intensity spectrum, it was as if we were dealing with an entirely new and unfamiliar spectral face of the Sun. This prompted V.V. Ivanov of St. Petersburg to introduce the name "Second Solar Spectrum" for this new polarized spectrum (Ivanov 1991).

Since the polarization amplitudes of the great majority of the structures in the Second Solar Spectrum are very small, of order 0.1 %, it was only with the introduction of the ZIMPOL technology (Povel 1995, 2001; Gandorfer et al. 2004) that the Second Solar Spectrum became accessible to systematic exploration and that the full extent of the structural richness could get exposed (Stenflo & Keller 1996, 1997). As most of the spectral features were completely unexpected, the first task was to begin to identify their origin and the underlying physical processes. Before explanations had been found the features represented "enigmas". In the beginning there were many of them.

One of the first shockingly enigmatic features was the giant polarization structure with sign reversals extending over more than 200 Å around the Ca II K and H lines, but already 30 years ago an explanation was found in terms of quantum interference between the upper $P_{3/2}$ and $P_{1/2}$ levels of the K and H lines, implying that the excited state is not a definite state but a "Schrödinger cat" state, a coherent linear quantum superposition of atomic states (Stenflo 1980). Such quantum interference effects have since been found to play a prominent role in structuring the Second Solar Spectrum.

The first applications (1994-1995) of ZIMPOL revealed a large number of peaked structures that seemed to have no correspondence in the intensity spectrum. After having systematically ruled out all possible instrumental effects and having considered unlikely processes like fluorescence from excitation in the extreme ultraviolet, we could identify the enigmatic structures as being due to various types of molecular lines (Stenflo & Keller 1996, 1997). Later theoretical work provided explanations why the molecular lines are so prominent in the Second Solar Spectrum while being so inconspicuous in the ordinary intensity spectrum (Berdyugina et al. 2002; Landi Degl'Innocenti 2006, 2007).

Similar to the molecular lines, the rare earth elements stand out in the Second Solar Spectrum, although they are inconspicuous in the intensity spectrum (cf. Fig. 3 in Stenflo 2009b). This remains a largely unexplained enigma, although some aspects of it have been clarified (Manso Sainz et al. 2006). Another intriguing rare element exhibiting a significant polarization signature is lithium with its Li I 6708 Å line, which

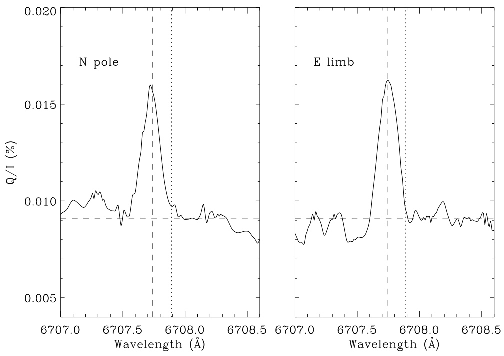

Figure 1. Scattering polarization of the Li I 6708 Å line, observed 5 arcsec inside the limb of the quiet Sun (corresponding to $\mu = 0.1$) with ZIMPOL at THEMIS on June 7, 2008. The left and right panels refer to observations near the heliographic north pole and east limb, respectively. The vertical dashed line marks the central wavelength of the ^{7}Li D_2 line, while the vertical dotted line marks it for both the ^{7}Li D_1 and ^{6}Li D_2 lines. The horizontal dashed line represents the level of the continuum polarization.

is next to invisible in the intensity spectrum of the quiet Sun. Since the first recording of its polarization signature with ZIMPOL at Kitt Peak in 1996 (as reported in Stenflo et al. 2000b), new improved observations were done with ZIMPOL at THEMIS in 2008, as shown in Fig. 1. According to meteoritic abundances, 92.4 % of the lithium abundance is in the form of the isotope ^{7}Li, which has nuclear spin 3/2, while 7.6 % is in the form of ^{6}Li, which has no nuclear spin. The Li I 6708 Å line has the same quantum number structure, including hyperfine structure in the case of ^{7}Li, as the Na I D_2 and D_1 lines at 5890 and 5896 Å (which will be discussed more in the next section), but the D_2 and D_1 lines of lithium are separated by a mere 0.15 Å (cf. the dashed and dotted lines in Fig. 1). The relative isotope shift is such that the ^{6}Li D_2 line happens to coincide with the ^{7}Li D_1 line (marked by the dotted line in Fig. 1).

Recently Belluzzi et al. (2009) have presented theoretical model calculations for the Li I 6708 Å line, which are in excellent agreement with the observed Q/I line shape and polarization amplitude in Fig. 1. The predicted polarization amplitude is very sensitive to the assumed value of the microturbulent magnetic field, but a field strength of order 10 G gives good agreement with the observations. A tiny polarization bump is expected at the location of the ^{6}Li D_2 line, which is not visible in Fig. 1, but the predicted amplitude is so close to the noise level that one cannot speak of a conflict with the observations. Therefore it appears that the observed Q/I profile of the Li I 6708 Å line is no more enigmatic.

Another past enigma was the observed triplet structure of the Ba II 4554 Å line, which had been vaguely noticed already in observations at Sac Peak in 1978 (Stenflo et al. 1980), but which was fully exposed with ZIMPOL (Stenflo & Keller 1997). While the Q/I profile of this barium line consists of three narrow peaks, the intensity profile is a single, broad absorption line. This could be explained and modeled in detail in terms of a combination of hyperfine structure and isotope composition (Stenflo 1997). Thus the central Q/I peak is due to the even isotopes, which make up 82% of the barium abundance, while the wing peaks are due to the shifted hyperfine structure components of the odd isotopes. Recent modeling of this line has clarified how the triplet profile is affected by magnetic fields (Belluzzi et al. 2007). While hyperfine structure effects are nearly invisible in the intensity spectrum and mainly contribute to some line broadening, they are found to play a prominent role in the Second Solar Spectrum.

"Hidden" physical effects can often be revealed through the use of differential effects (line ratios) in the polarized spectrum, by comparing the polarization amplitudes of lines belonging to the same atomic multiplets. This was for instance the technique that revealed the intermittent kG nature of spatially unresolved magnetic fields on the quiet Sun (Stenflo 1973). When applied to the Second Solar Spectrum it was soon noticed that lines that should be intrinsically unpolarizable according to the standard quantum scattering formalism instead showed prominent polarization peaks, which were often larger than the peaks of lines within the same multiplet that were expected to polarize 100 times more. Examples of multiplets where such paradoxical effects were observed are Mg I 5167, 5173, and 5184 Å, Ca I 6103, 6122, and 6162 Å, and the chromospheric infrared triplet Ca II 8498, 8542, and 8662 Å (Stenflo et al. 2000b). This enigma could be explained and modeled by Manso Sainz & Trujillo Bueno (2003) in terms of optical pumping, a concept that had been introduced and explored before by Trujillo Bueno & Landi Degl'Innocenti (1997). The earlier quantum scattering formalism had assumed that the inital, atomic ground state is unpolarized, and that the scattering polarization is exclusively produced by the atomic polarization of the excited state that is induced by the anisotropic excitation process. However, when considering the statistical equilibrium of many scattering processes, the induced polarization in the excited state gets partially mapped into the ground state by spontaneous emission, with the consequence that the subsequent scattering processes start from a ground state that is polarized. This pumping turns out to have a profound effect on the polarization of the scattered radiation.

3. The D_1 enigma

One still enduring enigma is that of the D_1 lines of sodium (5896 Å) and barium (4934 Å). According to quantum mechanics they should be intrinsically unpolarizable, as they represent a $J = \frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{1}{2}$ transition, but observations often reveal a significant polarization peak centered at the resonant frequency of the line (Stenflo et al. 2000a,b). The Ca II H line has the same J quantum number combination, but in contrast to barium and sodium, calcium has no nuclear spin and thus no hyperfine structure. Both barium (its odd isotopes) and sodium have nuclear spin 3/2, which causes a split of the J states into states with total angular momentum quantum numbers $F = 1$ and 2. Interesting and insightful attempts to explain the observed Na D_1 polarization in terms of optical pumping of these hyperfine structure levels seemed to give qualitative results in the right direction (Landi Degl'Innocenti 1998; Casini et al. 2002; Casini & Manso Sainz 2005), but later analysis showed that the predicted effect had the wrong symmetry and was too small by nearly two orders of magnitude (Trujillo Bueno et al. 2002; Kerkeni & Bommier 2002; Klement & Stenflo 2003).

The Sun is in certain respects a "messy" object with complications from fractal-like tangled magnetic fields with poorly known properties. To examine the D_1 enigma under controlled conditions, with the aim of answering the question whether it is a problem of solar physics or of quantum physics, a laboratory experiment was set up to explore the physics of 90° scattering for a D_1 type line (Thalmann et al. 2006, 2009). The goal was not to emulate solar conditions, but to isolate and expose in an optimized way the fundamental physics of the D_1 scattering transition. To reach a sufficiently high S/N ratio to be able to explore the subtle polarization effects one needs a tunable laser as light source. Since inexpensive, solid-state tunable lasers are not available for the sodium 5896 Å wavelength, we have chosen to work with the D_1 line of potassium at 7699 Å, because this resonance line has the same quantum numbers, the same nuclear spin and hyperfine structure, as the corresponding sodium and barium lines.

With the laboratory experiment we can choose 6 different input polarization states ($I \pm Q$, $I \pm U$, $I \pm V$), combined with measurements of the 3 output polarizations Q, U, V. For each of these 18 combinations we can record the full polarized (Q, U, or V) line profiles by tuning the laser through the absorption line frequencies. This can be done for any magnetic field strength (generated with Helmholtz coils) between -30 and $+30$ G for any of the 3 spatial orientations of the field (perpendicular to the scattering plane, or parallel to the scattered or to the incident beam). The results of the experiment reveal a rich polarization structure of D_1 scattering, which appears to be at odds with quantum mechanics as we know it (Stenflo 2009b; Thalmann et al. 2009). For example, when the illuminating beam is linearly polarized along a weak magnetic field perpendicular to the scattering plane, the scattered beam contains linear polarization that is oriented parallel to the scattering plane.

Since standard quantum mechanics, including hyperfine structure and optical pumping, predicts zero scattering polarization, in contradiction with both solar observations and laboratory experiment, there is a need for a solution beyond the standard framework. During the previous Solar Polarization Workshop a fundamental missing ingredient was identified, namely what we may call "final-state interference", or FSI as a short-hand notation (Stenflo 2009b). In standard quantum scattering theory the scattering process starts from a definite initial atomic substate and ends in another definite final substate (with definite m and F quantum numbers). The intermediate, excited state is however in general not a definite substate but a mixed quantum state (coherent superposition, "Schrödinger cat state"). When forming the coherency matrix or the Mueller matrix that describes the polarization properties of the scattering process, one has to sum over all the various possible combinations of paths that can contribute. While the sum over the intermediate substates is a coherent sum, which generates interference terms in the cross products between the scattering amplitudes, the sums over the intial and final substates are incoherent sums, since these states are definite states without level interferences. The new suggestion is that this split between coherent and incoherent summations is incorrect, and that all the sums should instead be coherent sums (for details, cf. Stenflo 2009b).

The conversion of incoherent to coherent summations opens the door to a number of new interference terms that were excluded before, in particular level interferences between the final substates, since the final state is now allowed to be a mixed quantum state. However, there is a condition of phase closure that links the coherences between the final m states with those of the intial m states. This limitation of allowed FSI does not apply to interferences between final F states (between $F = 1$ and 2 in the D_1 case).

Without FSI the D_1 polarization of the laboratory experiment is always expected to be zero, regardless of the atomic polarization of the initial state. In contrast the new contributions from FSI are non-zero and have qualitatively the observed dependence of polarization on field strength. They also have polarization amplitudes of approximately the observed magnitude, depending on the population imbalance of the initial m states, and assuming that this population imbalance is not destroyed by collisions. Therefore the introduction of FSI has appeared to be a promising avenue to resolve the D_1 enigma.

For FSI to give D_1 scattering polarization of the observed sign in the laboratory experiment, one needs to combine it with an overpopulation of the initial $F = 1$ state (relative to the initial $F = 2$ state). My theoretical attempts to generate this type of unbalanced population of the initial state through optical pumping (solution of the standard statistical equilibrium equations) have however failed. In particular the collisional depolarization of the excited state (by a factor of 34 in our laboratory experiment, assuming that it is the same as the observed depolarization of the D_2 upper state, caused by the argon buffer gas in the vapor cell) will destroy any significant substate imbalance of the initial state. Without such an imbalance we would get zero D_1 polarization also with FSI.

The failure of these efforts indicates that some other aspect of scattering physics is not yet understood. In the next section I will present arguments why the presently used optical pumping scenario on which statistical equilibrium calculations are based is incorrect, and indicate in semi-classical terms what the more correct physical picture should look like. Since the new scenario differs fundamentally from the standard pumping scenario, it is likely to have very different consequences for the polarization of the scattered radiation, but a quantitative theory for this is not yet available.

In summary, the question that the laboratory experiment set out to clarify can thus be answered as follows: The D_1 enigma is indeed a problem for quantum physics, which has not found a satisfactory solution yet. Only after the fundamental quantum problem has been solved will it be possible to specify what the D_1 polarization may tell us about solar physics.

4. Do we have a correct formulation of quantum mechanics ?

A common reaction to the conclusion from our laboratory experiment that quantum mechanics as we know it fails to explain the D_1 problem is one of disbelief, with the argument that quantum mechanics cannot be wrong, because it has proven itself to be correct over and over again during more than 8 decades. This reaction is however based on a misunderstanding, since we are in no way suggesting that quantum mechanics per se has been invalidated. What we are saying is that nobody knows yet how to correctly apply quantum mechanics to calculate the scattering polarization for D_1 type atomic transitions, and that this might indicate some deficiency that is not limited only to the D_1 case.

This deficiency of current quantum mechanics has remained hidden for so many decades, because nobody before has cared for carrying out the type of experiment that we have done, it has remained an untested domain of quantum physics. Polarized scattering experiments represented a hot topic during the first decade of quantum mechanics, because such experiments exposed coherency effects that are at the core of quantum physics. For instance, the polarized scattering experiments by Wilhelm Hanle in Göttingen in 1923-1924 (Hanle 1924) not only led to the discovery of what we now call the Hanle effect, but they also demonstrated experimentally concepts such as the linear superposition of atomic states and the partial decoherence caused by external magnetic fields. The theoretical edifice of quantum mechanics was built on these concepts.

The literature on polarized scattering experiments however abruptly ends around 1935, because the atomic physics community apparently came to the belief that this topic had been exhausted, and they therefore turned to other topics. This was a totally justifiable decision, since the polarization effects that we are concerned with in the D_1 case are too subtle for the experimental capabilities of that time. By today's standards the technological means of the 1930s were unbelievably crude, with insensitive photographic plates as polarization detectors. With such equipment they could not have detected any of the effects that we now classify as deep enigmas. Over time, this whole domain of physics got forgotten until it was brought back to the foreground due to the enigmas that got exposed with the discovery of the Second Solar Spectrum.

The edifice of quantum mechanics has always remained a subject of deep controversy, it is in no way a finished theory. Einstein's misgivings are well known, but they are shared by many others. Here a few example of quotes: "I think I can safely say that nobody understands quantum mechanics" (Richard Feynman), "I do not like it, and I am sorry I ever had anything to do with it" (Erwin Schrödinger), "Quantum mechanics is not a theory that describes what is actually happening, it is not describing reality. A perfect theory should describe in an unambiguous way how a system evolves" (Gerardus 't Hooft, Nobel Prize in physics 1999).

In my struggle to try to find the missing ingredient that could help resolve the D_1 enigma I have come upon what I consider to be a conceptual problem in the treatment of optical pumping. There are strong reasons to believe that the solution of the D_1 problem must have to do with optical pumping of the hyperfine levels of the ground state. For instance, the Ca II H scattering transition is not enigmatic, although it is similar to the D_1 type transition, the difference being that it does not have hyperfine structure splitting. Let us therefore next have a conceptual look at the theory of optical pumping.

This theory only exists (so far) for the assumption that the illumination is broad-band in frequency (cf. Landi Degl'Innocenti & Landolfi 2004). From Heisenberg's uncertainty relation $\Delta E \Delta t \approx \hbar$, broad-band in energy (or frequency) implies that $\Delta t \approx 0$, which corresponds to δ function wave packets with zero coherence length. However, such photons do not exist in nature. With these hypothetical (but non-existing) photons the optical pumping scenario is described in terms of a succession of many instantaneous excitation (pumping) events. After each such event there is a waiting time for the next excitation event, which (under solar conditions) is about two orders of magnitude longer than the typical excited-state life time (this large factor being determined by the ratio between the spontaneous and stimulated emission rates). There is little chance for any atomic polarization to avoid destruction (both due to collisions and to weak magnetic fields) during such long waiting times.

This optical pumping scenario is implicitly based on the erroneous quantum mechanical "myth" that quantum "jumps" are instantaneous. In reality transitions between atomic levels take very, very long times, about 10 million times longer than the oscillating period of the electromagnetic radiation that drives the excitation. Photons are not broad-band with vanishing coherence depth. They instead have a typical coherence depth of 3 m, the distance that light travels in 10^{-8} s. This is the typical damping time of spontaneous emission processes, which are the source of the photons.

Figure 2 illustrates the shape of the exponentially damped electromagnetic oscillations of a photon wave packet. However, to make the oscillations visible in this figure the oscillation period has been artificially increased by a factor of 1 million relative to the damping time scale. When keeping the right proportions between the two time

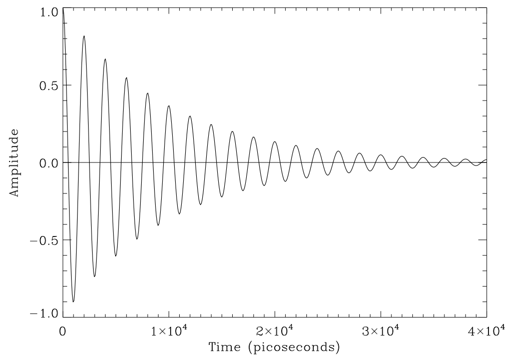

Figure 2. Wave packet illustration of the electromagnetic oscillations of a photon with wavelength 6000 Å, which has been created by a damped dipole oscillator with an e-folding time of 10^{-8} s. To make the oscillations visible in this figure, the oscillation period has been increased by a factor of 1 million.

scales the oscillations become so dense that they cannot be distinguished, as shown in the upper panel of Fig. 3, because there are more than 10 million oscillations within the time window shown. Zooming in by a factor of 1 million, as done in the lower panel of Fig. 3, it becomes obvious that from the perspective of the atom, a single photon represents a radiation bath that is nearly eternal for all practical purposes, due to the enormous separation of time scales.

This long-duration "radiation bath" provided by each photon implies that the statistical equilibrium with coherence transfer to the ground state gets established within the duration of each single interacting photon. In this picture the concept of "waiting time" between excitation events becomes irrelevant for the scattering polarization, in contrast to the standard scenario with a sequence of instantaneous excitation events. This completely changes the way one should treat both the statistical equilibrium problem and the depolarization of the ground state by collisions and magnetic fields.

Unfortunately a mathematical formulation of the "radiation-bath scenario" for the statistical equilibrium does not yet exist. To gain insight into the nature of a problem for which no quantum-mechanical formalism is available, it is useful to start with semi-classical descriptions, as we have done for the photon wave packet. The standard classical description of an atomic system is in terms of a dipole oscillator with a given resonance frequency ω_0. The oscillations of this system get driven by the impinging electromagnetic radiation field of frequency ω. In our case the atomic system contains not only one but a whole cluster of coupled resonant frequencies, corresponding to all allowed transitions between the m states of the lower and upper levels. For the D_1 line with hyperfine structure splitting there are 8 magnetic substates of the lower levels, 8 of the upper. The lower and upper levels are coupled to each other with varying transition probability amplitudes and with the selection rule that $\Delta m = 0, \pm 1$.

The semi-classical scenario is thus the following: The resonating system contains a multitude of coupled resonances, whose frequencies and couplings depend on the strength and orientation of the external magnetic field. During a photon encounter this system gets shaken millions of times by the oscillating electric field of the radiation bath. While the multiple oscillator is being driven (excited), it is also radiating, the excitation and emission processes are not separated in time (an oscillating system al-

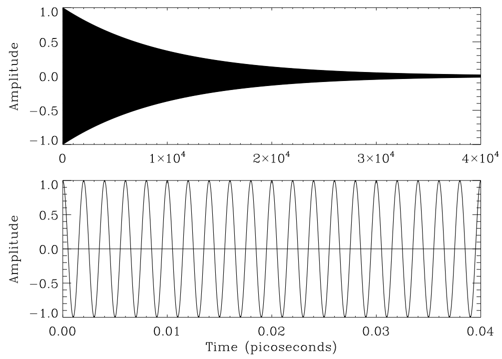

Figure 3. Upper panel: The same photon wave packet as in Fig. 2, but without the artificial increase of the oscillation period. The plot now contains more than 10 million oscillations, which become too dense to be resolved and therefore merge into a black block. Lower panel: Zooming in by a factor of 1 million to illustrate the radiation-bath concept. The exponential decay is not perceived, since it occurs on a vastly separated time scale.

ways radiates, regardless of whether it is being driven or oscillates freely). Both the excitation and emission processes contain millions of oscillation periods, during which the system soon finds a statistical equilibrium between the various couplings or transitions. This equilibrium determines the relative contributions of the various resonances, which collectively define the composition of the emitted (scattered) radiation and its polarization state.

The formulation of this type of statistical equilibrium is fundamentally different from the standard quantum mechanical formulation for the density matrix in terms of discrete, separated excitation and emission events. In my opinion the new formulation is needed to properly deal with the D_1 scattering problem, but since we do not have it yet, the D_1 polarization as observed both on the Sun and in the laboratory remains enigmatic.

To guide the theoretical insights we urgently need a revival of polarized scattering experiments in the laboratory. They should be done for a variety of chemical elements and without the use of buffer gas, to avoid collisional depolarization effects. Such experiments were largely abandoned 75 years ago, but now they are needed more than ever to provide us with benchmarks for the theoretical developments.

5. The hidden world beyond the telescope resolution

There have been two principle types of methods to probe the properties of quiet-sun magnetic fields at spatially unresolved scales: the Stokes *V* line-ratio technique (Stenflo 1973) and the Hanle depolarization effect (Stenflo 1982). While the line-ratio technique revealed an extremely intermittent nature of quiet-sun magnetic fields, with most of the net flux (averaged over the resolution element) residing in kG flux elements with small filling factors, the Hanle effect tells us that most of the photospheric volume is seething with an “ocean” of tangled or turbulent fields with strengths in the range of typically 10 - 100 G (Stenflo 1982; Trujillo Bueno et al. 2004).

While these diagnostic techniques provide no direct information on morphology or spatial scales (except that the scales are smaller than the resolution limit), one expects on theoretical grounds a continuous range of scales that extends orders of magnitude below the presently resolved scales. With the advance in angular resolution of the solar telescopes the boundary between the resolved and unresolved domains has been continually pushed towards ever smaller scales. This has given insights into the scaling behavior of the pattern morphology of the magnetic flux and its evolution. It has been found that the magnetic flux has a fractal-like structure with a high degree of self-similarity or scale invariance as we zoom in on the smaller scales that can still be resolved (Stenflo & Holzreuter 2003; Janßen et al. 2003). The structuring, whether fractal or not, is expected to continue down to the magnetic diffusion limit near the 10 m scale (de Wijn et al. 2009; Stenflo 2010b).

At the 200 km scale we are beginning to resolve some of the larger kG flux tubes on the quiet Sun, whose existence had been ascertained 37 years ago with the line-ratio technique, and there are indications that we are beginning to resolve certain aspects of the large-scale tail of the turbulent magnetic field that was discovered via the Hanle effect 28 years ago. As the angular resolution is improved we will resolve an increasing fraction of these structures.

Pietarila Graham et al. (2009) analysed Hinode quiet-sun data with respect to the scaling behavior of the flux cancellation function. They concluded that at least 80 % of the vertical magnetic flux remains invisible at the Hinode 200 km resolution scale, due to cancellation within the resolution element between the opposite polarities of the tangled field. This conclusion that is based exclusively on Zeeman-effect observations is consistent with the Hanle-based conclusions, like those of Trujillo Bueno et al. (2004), who find that the “hidden”, tangled fields contain so much magnetic energy that they may play a dominant role for the energy balance of the Sun’s atmosphere.

At the Hinode resolution scale the probability density function (PDF) for the vertical magnetic flux densities of the quiet Sun is sharply peaked at zero G, but it has wings that extend out to kG flux densities. The inner core has the shape of a stretched exponential, while the wings decline quadratically (Stenflo 2010c,a). The same PDF behavior is also seen at larger scales and in numerical simulations of magnetoconvection (Stenflo & Holzreuter 2003; Stein & Nordlund 2006). There is however new evidence that the fractal-like scale invariance will get broken when we go to scales smaller than the presently resolved ones. This evidence comes from application of the line-ratio technique to the 6302/6301 line pair in the Hinode data set, which reveals a magnetic dichotomy that occurs in the spatially unresolved domain, with two distinct flux populations, one representing strong-field fluxes in a collapsed, kG state, the other weak-field, uncollapsed flux (Stenflo 2009a, 2010a). This is the first time that a weak flux population, the existence of which has previously been inferred from Hanle diagnostics, is now also revealed by the Zeeman line-ratio technique. One may therefore expect that the PDF for the flux densities, which is now a continuous function with no hint of any disjoint flux populations, will more clearly reveal the two distinct weak and strong field components as we reach scales smaller than the currently resolved ones.

Analysis of Hinode quiet-sun data shows that the flux has a preferentially vertical orientation for the larger flux densities, but that the angular distribution becomes isotropic in the limit of small flux densities (Stenflo 2010a). However, the angular distribution becomes undetermined for flux densities below 5 G due to insufficient S/N ratio, and the distribution may also become different at scales not yet resolved. Additional

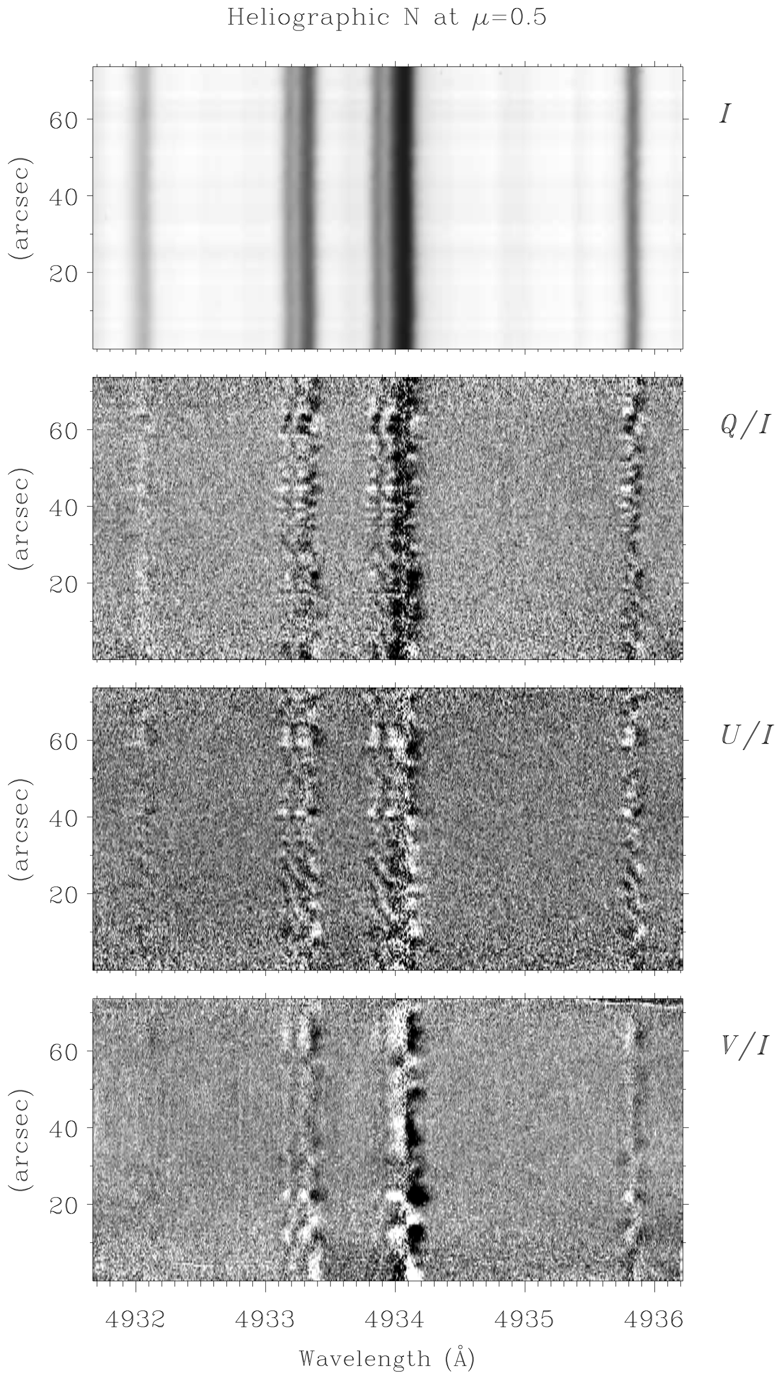

Figure 4. Region around the Ba II D_1 4934 Å line, recorded near the heliographic north pole but at a limb distance corresponding to $\mu = 0.5$. Around this limb distance the polarized spectrum gets extremely structured by the transverse Zeeman effect. Note also the bright line in Q/I near 4932 Å, which is due to scattering polarization in a C I line. The recording was made on June 6, 2008, with ZIMPOL at THEMIS.

Figure 5. MDI magnetogram from February 16, 2010, illustrating how Hale's polarity law is being violated by the bipolar magnetic region in the southern hemisphere to the lower right, which has an orientation opposite to the expected one.

constraints on the angular distribution are provided by the observed center-to-limb variation (CLV) of the polarized line profiles. The ZIMPOL observations have revealed that the linearly polarized profiles (Q/I and U/I) become extremely structured as we move away from the solar limb towards disk center. Practically all lines in the Sun's spectrum have this behavior. As an example we show in Fig. 4 a section of the Second Solar Spectrum around the Ba II D_1 4934 Å line, recorded with ZIMPOL at THEMIS on June 6, 2008, at a limb distance given by the cosine of the heliocentric angle $\mu = 0.5$. A related CLV behavior was noticed in the temporal fluctuations of the circular polarization by Harvey et al. (2007), who coined the term "seething fields". The ZIMPOL observations show however that the spatial fluctuations are rather small near the extreme limb, but increase as we move away from the limb, and reach a maximum near $\mu = 0.5$.

A quantitative determination of angular distributions from these CLV observations has not yet been done, since it is a complex and far from straightforward task. The CLV data have contributions from both the spatially resolved and unresolved structures and depend on the height variation of the distribution functions. Nevertheless this is a rich and as yet unexploited source of information about the magnetic structures.

6. Violation of Hale's polarity law

Much of scientific progress consists of discovering anomalies, misfits that contradict some generally accepted idea or rule. Such anomalies help identify and expose what is wrong with our current understanding or paradigm and indicate what may be missing or may need to be changed. Most of the enigmas that we have discussed here have, when first noticed, appeared to us as anomalies. Only after explanations have been found they are no more seen as anomalies.

Last February when I looked at the SOHO web page with the daily MDI magnetograms, I noticed another unexpected anomaly, namely an unambiguous violation of

Hale's polarity law. This rule states that the east-west polarity orientation of the bipolar magnetic regions is opposite in the two hemispheres, and the orientations in a given 11-year cycle is opposite to the orientations in the previous and following cycles. In contrast the bipolar magnetic region in the southern hemisphere to the lower right in Fig. 5 has the same orientation as the three bipolar regions in the northern hemisphere and the opposite orientation with respect to the region to the left of it in the same hemisphere.

It could be argued that the anomalous region belongs to the previous activity cycle, and that there is statistical overlap between the cycles. However, then another rule must be violated, namely that the bipolar regions of the new cycle appear at high heliographic latitudes, while the last regions of the old cycle emerge at low latitudes. In contrast the two bipolar regions that we see in Fig. 5 are located in the same latitude zone.

Often the orientation of bipolar regions is rotating and adjusting itself after emergence. However, when we follow the evolution of our anomalous region over several days, it does not reveal any significant rotation of this kind, the polarities remain reversed during the whole disk passage.

There probably exist many more violations of Hale's polarity law, but I am not aware of any reported violations of this kind in the literature. The common explanation of the east-west orientation of the bipolar regions is that the subsurface meridional flux is wound up by differential rotation into toroidal flux ropes. When sections of such toroidal "snakes" emerge at the surface, they have an orientation that is governed by the direction of the toroidal field. Figure 5 shows however that there exist bipolar regions in the same latitude zones that cannot be part of the same toroidal flux system but represent opposite-directed toroidal flux at the same latitude location. This puts into question the whole scenario of coherent toroidal flux "snakes" that wind around the Sun. There seems to be no natural way in which the two bipolar regions in the southern hemisphere in Fig. 5 can be topologically connected.

It is not totally excluded that the case presented here represents a statistical fluke. More cases should be searched for. If such are found, this may have profound implications for our understanding of the operation of the Sun's activity cycle. For the time being the presently identified case represents another unexplained enigma with the potential of bringing new insights into the workings of our Sun.

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