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Solving the Paradox of the Solar Sodium D_1 Line Polarization

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Twenty-five years ago, enigmatic linear polarization signals were discovered in the core of the sodium D_1 line. The only explanation that could be found implied that the solar chromosphere is practically unmagnetized, in contradiction with other evidences. This opened a paradox that has challenged physicists for many years. Here we present its solution, demonstrating that these polarization signals can be properly explained in the presence of magnetic fields in the gauss range. This result opens a novel diagnostic window for exploring the elusive magnetism of the solar chromosphere.

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Observations of quiet regions of the solar disk (i.e., outside areas of strong magnetic activity) with high-sensitivity spectropolarimeters reveal that the entire solar spectrum is linearly polarized, especially close to the edge of the Sun's visible disk [1–3]. The physical mechanism responsible for this linear polarization is the scattering of anisotropic radiation within the solar atmosphere. In spectral lines, this so-called scattering polarization is due to the presence of atomic level polarization (i.e., population imbalances and quantum interference between the magnetic sublevels of the atomic energy levels), produced when the atom is illuminated by anisotropic radiation (i.e., anisotropic optical pumping) [4,5]. Atomic level polarization is sensitive to collisions with neutral hydrogen atoms [6] and to the presence of magnetic fields through the Hanle effect [7,8]. These mechanisms are especially efficient in relaxing the polarization of long-lived atomic levels, such as the ground states.

Twenty-five years ago, unexpected scattering polarization signals were discovered in the core of the Na I D_1 line [1,2,9–12], a line transition that was thought to be intrinsically unpolarizable [1,2]. These enigmatic signals could only be explained by taking the hyperfine structure (HFS) of sodium into account and assuming that the lower level of D_1 (the ground state of sodium) has a substantial amount of atomic polarization [13]. Because long-lived atomic levels are particularly vulnerable to the Hanle effect, the required amount of ground-level polarization is incompatible with the presence of inclined magnetic fields stronger than about 0.01 G in the lower solar chromosphere [13], where the core of the D_1 line originates [14]. The requirement that the lower solar chromosphere must be practically unmagnetized conflicts with the results from observations in other spectral lines as well as with plasma physics arguments, which instead indicate the presence of magnetic fields in the gauss range in this key interface region of the solar atmosphere [15].

The proposed explanation for the unexpected scattering polarization signal observed in the core of the Na I D_1 line gave rise to a serious and intriguing paradox in solar physics, which has remained unresolved since its introduction in 1998 [13]. In that original investigation, the anisotropic radiation field that pumps the atoms of the solar atmosphere was assumed constant with wavelength over the very small spectral interval spanned by the nearby hyperfine structure components of both the sodium D_1 and D_2 lines. When this apparently reasonable assumption is made (see Fig. 1), the four HFS transitions of the D_1 line are all pumped by the same D_1 line radiation field. Under this hypothesis, it is found that it is impossible to induce atomic polarization in the upper HFS F levels of the D_1 line, unless atomic polarization is also present in the F levels of the ground state of sodium [13]. In this scenario, the upper F levels of the D_1 line are consequently depolarized by the same very weak magnetic fields that depolarize the F levels of the ground state [16].

Solving the paradox of the solar sodium D_1 line is thus a very important step forward in our understanding of the physical processes that produce polarization in spectral lines. This is essential for deciphering the magnetism of the

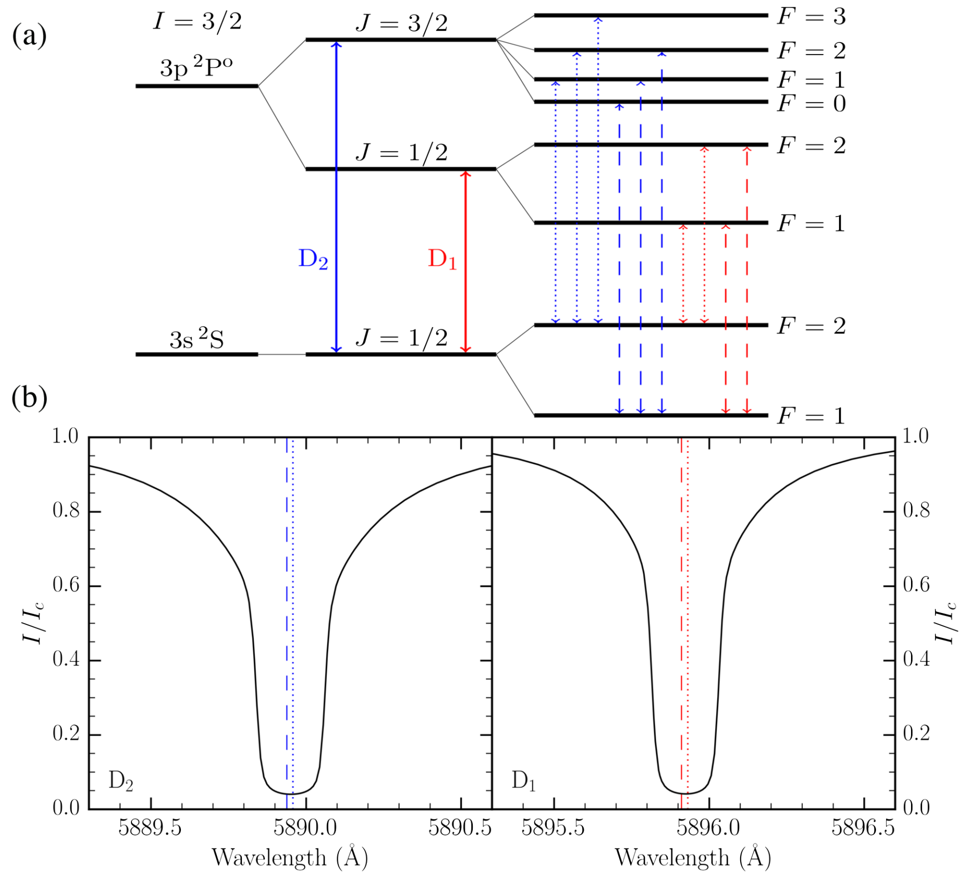

FIG. 1. (a) Grotrian diagram of the considered atomic model of sodium. The diagram shows the upper and lower terms of the sodium doublet, as well as the fine structure and hyperfine structure (HFS) levels (energy splittings not to scale). The fine structure transitions corresponding to the D_1 and D_2 lines are also indicated, as well as the allowed transitions between HFS F levels. The quantum number I indicates the nuclear spin. (b) Theoretical intensity profiles (normalized to the continuum) of the D_2 and D_1 lines. Calculations were carried out in a one-dimensional semiempirical model of the solar atmosphere [17] for a line of sight with $\mu = \cos\theta = 0.1$ (with θ the heliocentric angle). The dashed and dotted vertical lines show the wavelength positions of the various HFS components of the D_1 and D_2 lines, indicated in the Grotrian diagram (a).

quiet solar chromosphere through the modeling of the unprecedented spectropolarimetric observations that the new generation of solar telescopes, such as the upcoming National Science Foundation's Daniel K. Inouye Solar Telescope [18], will soon provide. As a matter of fact, over the last two decades the solar physics community has witnessed an intense research activity motivated by the enigmatic scattering polarization of the solar Na I D_1 line. This paradox even led to questioning the quantum theory of scattering, and motivated optical pumping laboratory experiments using monochromatic (laser [19]) or spectrally flat (halogen bulb [20]) incident light, as well as theoretical investigations in which the atomic system is assumed to be excited by monochromatic [21,22] or broadband [16] radiation.

In the quest to resolve this challenging problem, it was of particular interest to theoretically identify a mechanism capable of introducing linear polarization in the Na I D_1 line without the need of ground-level polarization [23]. This mechanism was identified by taking into account the small variations of the pumping radiation field, and in particular of its anisotropy, across the very narrow spectral interval spanned by the various HFS components of the D_1 line (i.e, by relaxing the apparently reasonable assumption that the radiation field is constant with wavelength across this narrow interval). However, the employed theoretical formulation was only applicable in a very idealized situation, namely in the absence of elastic collisions and magnetic fields, which could potentially depolarize the D_1 line signal [23,24].

Here we model the polarization of the solar sodium doublet radiation through a rigorous theoretical framework for the generation and transfer of polarized radiation, suitable for taking into account the detailed spectral structure of the radiation field pumping the atoms. This quantum theory of atom-photon interactions [25] allows considering correlations between the incoming and outgoing photons in the scattering events (i.e., partial frequency redistribution phenomena), in the presence of collisions and magnetic fields. By applying this theory, for the first time we could take into account the detailed spectral structure of the radiation, together with the effects of magnetic fields of arbitrary strength and elastic collisions in a realistic atomic model including HFS. We have calculated the intensity and polarization profiles of the radiation emerging from semiempirical models of the solar atmosphere by numerically solving this complex non-equilibrium radiative transfer problem. Details of such calculations can be found in the Supplemental Material [26]. Our results show that linear polarization is produced in the D_1 line in the absence of any ground-state polarization, even in the presence of inclined magnetic fields in the gauss range, and that the calculated spectral line polarization is similar to that found in recent high-precision spectropolarimetric observations [12].

Figure 2 shows a comparison between the calculated fractional linear polarization and observations taken with the Zurich Imaging Polarimeter (ZIMPOL-3) [27] in a quiet region close to the edge of the solar disk. The Q/I pattern calculated with (blue solid curve) and without (red dotted curve) magnetic fields in a semiempirical model [17] of the quiet Sun is compared with two different measurements (black curves), one covering a spectral range that includes both lines of the sodium doublet (upper panel) and another with a significantly better spectral resolution but for a range containing only the D_1 line (lower panel). In both cases, a very good agreement between observations and synthetic profiles is found when including a volume-filling tangled magnetic field of 15 G. For more details on the considered magnetic field, see the Supplemental Material [26].

The physical mechanisms considered in the present Letter produce a conspicuous linear polarization signal in the core region of the sodium D_1 line, which survives in the presence of inclined magnetic fields with strengths in the gauss range, in contrast to the linear polarization signals produced by ground-level polarization [13,16]. Indeed, the agreement with the observations improves when including such magnetic fields in the atmospheric model. In the presence of such magnetic fields, we have verified that not only is a clear line-core polarization signal found for lines of sight close to the limb, but it also remains appreciable close to the solar disk, in agreement with observational results [9]. For more details, see the Supplemental Material [26]. Through calculations carried out in the absence of magnetic fields, we have also verified that the depolarizing effect of elastic collisions that induce transitions between magnetic sublevels of the same F level does not have an appreciable impact on the linear polarization pattern in either line of the doublet, even when purposely overestimating the collisional depolarization rates. This is discussed in further detail in the Supplemental Material [26].

As shown in Fig. 2, when magnetic fields with strengths on the order of gauss are present at chromospheric heights,

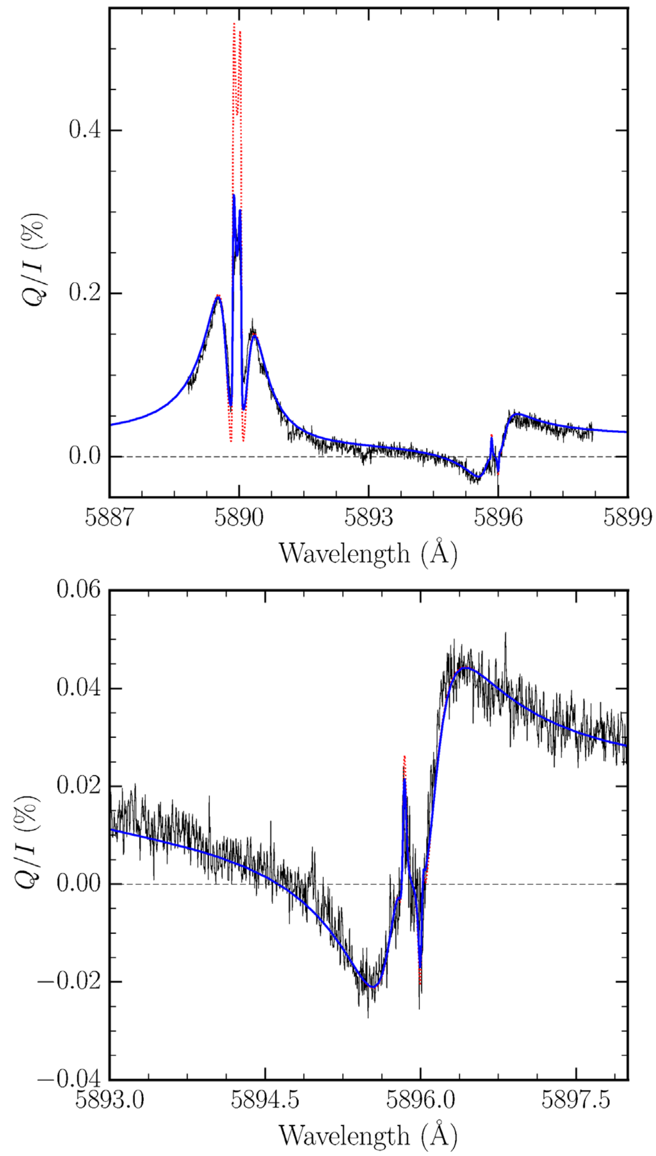

FIG. 2. Fractional linear polarization (Q/I) pattern of the Na I doublet. The black solid curves represent spectropolarimetric observations performed using ZIMPOL-3 [27] in quiet regions close to the solar limb. The measurement shown in the upper panel was taken for a spectral interval containing both D_1 and D_2, and had a spectral sampling of 8.38 mÅ/pixel. The one shown in the lower panel included only D_1, but had a better spectral sampling, of 4.60 mÅ/pixel. In both panels, the red dotted curves and the blue solid curves show the results of radiative transfer calculations in a semiempirical one-dimensional atmospheric model of the quiet solar atmosphere [17]. The red colored profiles were obtained in the absence of a magnetic field, whereas the blue colored ones were obtained including a volume-filling tangled magnetic field of 15 G throughout the entire atmosphere (see the Supplemental Material [26]). The theoretical Stokes profiles were calculated for a line of sight with $\mu = 0.1$ for the top panel, and $\mu = 0.125$ for the bottom one, in accordance with the observation to which they are compared. The reference direction for positive Stokes Q is taken parallel to the nearest solar limb.

the Stokes Q/I amplitudes in the core of both the D_1 and D_2 lines decrease appreciably through the action of the Hanle effect, whose impact is significantly greater in the D_2 line. Moreover, the scattering polarization signals in the wings of both lines, and especially the local minima found just outside the Doppler core of the D_2 line, are sensitive to the presence of magnetic fields in the underlying photosphere through the same magneto-optical effects that introduce a magnetic sensitivity in the scattering polarization wings of stronger resonance lines [28–30]. Interestingly, such magneto-optical effects operate in the wings of the sodium D lines at field strengths similar to those that produce the Hanle effect in the line core.

We point out that our radiative transfer modeling has been carried out for a one-dimensional semiempirical static model of the solar atmosphere, in which only an inclined magnetic field can break the axial symmetry of the pumping radiation field. In the real solar atmosphere, the spatial gradients of the macroscopic velocity and the horizontal thermal and density inhomogeneities of the plasma can break the axial symmetry without the need of an inclined magnetic field [31], and a larger variety of Q/I shapes is to be expected. Moreover, it is important to note that in dynamical models of the solar chromosphere [32] the anisotropy of the D-line radiation shows a wide range of variation, which may result in Q/I signals of much larger amplitudes [33].

Despite the idealization that a one-dimensional static atmospheric model represents, observed antisymmetric linear polarization signals in the core of the D_1 line can be reproduced remarkably well when accounting for the HFS of sodium and for the spectral structure of the pumping radiation field in the presence of magnetic fields. A good agreement with recent observations of high polarimetric accuracy is found when considering isotropic or canopylike magnetic fields with strengths in the gauss range, as inferred from other chromospheric diagnostics [15]. This provides a satisfactory resolution to the two-decades-long solar sodium paradox and opens up a new window for probing the elusive magnetic fields of the solar chromosphere in the present new era of large-aperture solar telescopes.

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