Concerning the existence of a 'turbulent' magnetic field in the quiet Sun

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ABSTRACT

We report on the $a\,^5F$-$y\,^5F^\circ$ multiplet of Ti I and its interest for the study of "turbulent" magnetic fields in the quiet solar photosphere. In particular, we argue that the sizable scattering polarization signal of the 4536 Å line (whose lower and upper levels have Landé factors equal to zero), relative to the rest of the lines in the multiplet, gives *direct* evidence for the existence of a ubiquitous, unresolved magnetic field. We cannot determine precisely the strength of the magnetic field, but its very existence is evidenced by the differential Hanle effect technique that this Ti I multiplet provides.

Subject headings: Polarization — Scattering — Line: formation — Sun: magnetic fields — Sun: atmosphere

Magnetic fields in the solar atmosphere may be detected most clearly by the circular polarization pattern they induce in spectral lines. However, this Zeeman effect technique is not very suitable for investigating magnetic fields that have complex unresolved geometries because the contributions of opposite magnetic polarities within the spatio-temporal resolution element of the observation tend to cancel out. Consequently, extremely weak magnetic fields or even strong fields with a rather convoluted topology may remain virtually undetectable.

This is unfortunate since, according to our general picture of solar magnetism, most regions of the solar atmosphere are expected to be filled by magnetic fields whose geometries

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are complex and far from being spatially resolved. In particular, 'turbulent' magnetic fields driven by highly chaotic fluid motions are supposed to pervade the 'quiet' regions of the solar photosphere, with mixed magnetic polarities even below the photon mean-free-path (e.g., Cattaneo 1999). At higher chromospheric and coronal levels the medium rarefies exponentially, the magnetic fields weaken and the picture becomes still more problematic.

The presence of relatively weak magnetic fields may be revealed by the modification they produce in the linear polarization pattern generated by scattering processes in spectral lines (Hanle effect). Typically (but not always), the change consists in a net depolarization and a rotation of the polarization plane. If the azimuth of the magnetic field has a random variation within the observed resolution element, rotations of polarization planes cancel out, but the reduction of the scattering polarization amplitude remains. Therefore, the Hanle effect has the potential for detecting the presence of tangled magnetic fields on subresolution scales in the solar atmosphere (Stenflo 1982).

It seems then natural to rely on this technique to probe the kind of 'microturbulent' photospheric magnetic fields discussed above. This has been tried out by some authors in the past, concluding that depolarization by a 'turbulent' field is required to be able to explain the available observations of scattering polarization on the sun (Stenflo 1982; Faurobert-Scholl et al. 1995, 2001; Stenflo et al. 1998). The main problem of these analyses is that they require a reference zero-field polarization amplitude which, in turn, heavily relies on theoretical calculations. Only very recently such radiative transfer calculations have started to be sufficiently realistic, taking into account the three-dimensional and dynamic nature of the solar atmosphere (Trujillo Bueno, Shchukina & Asensio Ramos 2004). In any case, the question may always be raised of whether all the other relevant physical mechanisms that can produce depolarization have been accounted for and whether the observed depolarization can then be safely ascribed to the presence of a magnetic field. In order to achieve model independence it is useful to consider various spectral lines with different sensitivities to the Hanle effect (Stenflo et al. 1998). Unfortunately, the particular combination of atomic lines used by Stenflo et al. (1998) is far from optimum, because they have different line formation properties and none of them is insensitive to magnetic fieldsHere we present an analysis of the polarization pattern of the multiplet 42 of Ti I. We argue that the available observations of scattering polarization in this multiplet provide direct evidence that magnetic depolarization due to a 'turbulent' field is really at work in the quiet solar photosphere.

Recently, Manso Sainz & Landi Degl'Innocenti (2003a,b; hereafter Papers I and II, respectively) have investigated the physical origin of the observed linearly-polarized, solar limb spectrum of Ti I. To this end, these authors used a very realistic multilevel model for the Ti I atom, which includes a very interesting multiplet that may be of great relevance

for the study of solar magnetism via the Hanle effect. This multiplet is formed by the transitions between the lowest term of the titanium's quintet system ($a\,^5F$) and the excited $y\,^5F^\circ$ term (see Fig. 1). Interestingly, all the lines in the multiplet lie in the blue part of the visible spectrum and their scattering polarization signals have, in fact, been recently observed in quiet regions near the solar limb (Gandorfer 2002). The important thing about this multiplet is that the transition at 4536 Å shows a large polarization peak relative to the other lines of the multiplet and that the Landé factor of both its lower and upper level ($a\,^5F_1$ and $y\,^5F_1^\circ$, respectively) is zero. In other words, the line at 4536 Å is, unlike the others of the same multiplet, essentially insensitive to magnetic fields. We show here that the most natural explanation of the reported linear polarization observations invokes the existence of a tangled magnetic field permeating the solar atmosphere within the resolution element.

Panel (a) of Fig. 2 shows the observed fractional linear polarization in the $a\,^5F$-$y\,^5F^\circ$ multiplet as reported by Gandorfer (2002). The transition at 4527.3 Å will not be considered further in our analysis for its being blended with two other transitions of Ce II and Cr I, two species seemingly quite 'active' in scattering line polarization. The first thing to note is that all these lines are strong in the sense of Paper II, i.e., they have residual intensities $(I - I_c)/I_c$ larger than 0.5, and all of them, with the notable exception of λ4536, have Q/I signals below the continuum polarization level. In the presence of a significantly polarized continuum the contribution of the strongest spectral lines to the linearly polarized spectrum cannot be simply added up and the depolarization of the continuum by the presence of the spectral line cannot be neglected. Nevertheless, we can always assume a similar effect for all the lines in the multiplet and compare the Q/I signals between them, in particular, with the 4536 Å line.

A theoretical estimate for the Q/I structure of the multiplet is shown in panel (b) of Fig. 2. It has been calculated for a 90° observation of a layer of atomic titanium gas which is illuminated from below by a photospheric-like radiation field. Details on the atomic model and radiation field are given in Paper I. Firstly, we have calculated the atomic polarization that optical pumping processes induce in all the levels of the atomic model in the absence of any depolarizing mechanism. Secondly, we have calculated the Q/I signal in each transition taking into account the emissivity as well as dichroism effects (see Eq. (14) of Paper I). As demonstrated in Paper I, this method is able to reproduce (at least qualitatively) the structure of the whole second solar spectrum of Ti I.

In order to model the depolarization due to a weak microturbulent magnetic field we assume one and the same depolarizing rate for all the atomic levels, except for the levels

$a\,^5F_1$ and $y\,^5F^\circ_1$ which have zero Landé factor (Sugar & Corliss 1985)[6]. We point out that all the ^5F terms of titanium are well described by the LS-coupling. Therefore, according to the well known formula for the Landé factor we can assume that all the $^5F_1$ and $^5F^\circ_1$ levels are completely insensitive to the magnetic field. Panels (c) and (d) show the Q/I structure of the $a\,^5F$-$y\,^5F^\circ$ multiplet assuming depolarizing rates D of 10^8 s^{-1} and 5×10^8 s^{-1}, respectively, for all except the $^5F_1$ and $^5F^\circ_1$ levels (thick lines). If we roughly estimate an 'equivalent' magnetic field intensity through the equation $2\pi\nu_L g = 8.79\times10^6\, B\, g \approx D$ (ν_L and g being the Larmor frequency and Landé factor, respectively), then, taking $g\approx1$, a depolarizing rate $D = 10^8$ s^{-1} corresponds to a magnetic field of the order of 12 gauss, while $D = 5\times10^8$ s^{-1} implies 60 gauss. For comparison, dotted lines show the Q/I values when all the levels are depolarized without exception. Only the transitions involving at least one level with zero Landé factor ($\lambda\lambda$4527, 4536 and 4544) change their behavior, as expected.

It is of interest to note that this $D = 5\times10^8$ s^{-1} case produces a relatively good agreement with the Q/I observations of Gandorfer (2002), and that Trujillo Bueno et al. (2004) concluded that when one assumes a volume-filling and single-valued microturbulent field then the best theoretical fit to the observed scattering polarization in the Sr I 4607 Å line is obtained for $B_{\rm microturbulent}\approx60$ gauss.

Since we are considering transitions belonging to the same multiplet, we can assume that they 'form' in the same atmospheric region and hence, under similar environmental conditions. If this formation region were essentially devoid of magnetic fields (say, a significant volume filled with magnetic fields below one gauss), then we would expect relative Q/I signals qualitatively resembling the solid line in Fig. 2b or the dotted lines in Figs. 2c, d. In particular, the $\Delta J = 0$ transitions $\lambda\lambda$4533, 4534 and 4535 would show Q/I signals similar or even larger than the λ4536 transition. However, the observed large polarization peak in the 4536 Å line relative to the others, can only be explained if the depolarization is of magnetic origin and therefore does not affect the $^5F_1$ levels.

Finally, we would like to point out that the main deficiency of our analysis is our neglecting of the continuum polarization. At such blue wavelengths the continuum polarization due to Rayleigh and/or Thomson scattering is already significant, and lines as strong as the ones in this multiplet show an important interaction with it that cannot be neglected (see discussion in Paper II). For this reason we have presented our theoretical calculations in Fig. 2 without superimposing the continuum. These considerations should be taken into account in further, more quantitative analyses. Yet, they do not change our conclusions.

Summarizing: among the several observed solar lines of the $a\,^5F$-$y\,^5F^\circ$ multiplet of ti-

[6]See `http://physics.nist.gov/`

tanium, only the line λ4536 shows a polarization peak, all others showing just a continuum depolarization. Since the only apparent peculiarity of the 4536Å line lies in its lower and upper levels having zero Landé factor (i.e., its insensitivity to magnetic fields), the observed polarization pattern may be considered as direct evidence for the presence of a tangled magnetic field in the solar atmosphere, which is depolarizing the scattering polarization signals of all the lines in the multiplet except, obviously, for λ4536.

The arguments above rely on a direct interpretation of observations and on a relative independence of theoretical modeling (actually, this is where their strength lies). However, since we are not solving the radiative transfer problem we cannot account for the details of the polarization patterns arising from the different illumination and depolarizing conditions at the height of formation of the individual lines. This prevents, in general, our comparing polarization signals between spectral lines belonging to different multiplets to obtain quantitative estimates of the magnetic field. Notwithstanding, we can compare lines belonging to the same multiplet assuming that they form under similar thermodynamical, radiative and magnetic conditions. We can then make qualitative interpretations of the most conspicuous polarization patterns. That has been precisely the case here.

In this respect, it must be noticed the interesting multiplet a^3H-x^3H, whose line at 4742.8 Å shows a very conspicuous polarization signal (actually one of the strongest of the whole second solar spectrum of Ti I), which is twice as large as the signal observed in the $\lambda\lambda$4758.1 and 4759.3 lines of the multiplet. This cannot be easily explained in terms of the simple modeling of Paper I (all three would show large, but similar amplitudes), nor by some kind of 'differential' action of the magnetic field, since all upper levels of the three transitions have similar critical fields (the field at which the Zeeman splitting is of the order of the natural width of the level): $\approx$ 11, 9 and 8 gauss, respectively. This anomalous behavior is probably related to an interesting spectroscopic feature of the lower level of λ4742.8. Contrary to the other levels involved in the multiplet, this level (with total angular momentum $J = 4$) is not well described as a purely LS-coupling level. Actually, it is a 52% – 44% mixing of the two configurations $3d^3(^2H)4s\,^3H$ and $3d^3(^2G)4s\,^1G$, respectively (see Sugar & Corliss 1985). (It is interesting to note that the lower level (b^1G) of the transition showing the largest observed Q/I signal of the titanium's second solar spectrum (λ5644.1) is a 48% – 48% mixing of the very same configurations $3d^3(^2H)4s\,^3H$ and $3d^3(^2G)4s\,^1G$, respectively.) Due to this accidental coincidence the lower and upper levels of λ4742.8 are spectroscopically similar to an equivalent LS-coupling level (Landé factor, total deexcitation probability, and critical field), but the line itself has a smaller transition probability relative to $\lambda\lambda$4758.1 and 4759.3. Consequently, the line λ4742.8 probably forms at a different height in the photosphere than the other two, where the radiation field may be dissimilar.

We think that, all in all, the interpretation of the polarization pattern in the $a\,^5F$-$y\,^5F^\circ$ multiplet of neutral titanium given in this letter is direct evidence for the existence of an unresolved magnetic field permeating large volumes of the quiet solar atmosphere. In any case, further study of the formation of the second solar spectrum of Ti I is necessary in order to arrive to more definite conclusions. By combining the Hanle-effect line ratio technique proposed here for the relatively strong 13 lines of this Ti I multiplet with that reported by Trujillo Bueno (2003) for the weak C_2 lines of the Swan system, we can now aim at further exploring the full complexity of the small-scale magnetic activity of the 'quiet' Sun. To this end, we have already initiated systematic observations of both atomic and molecular lines as well as more detailed theoretical investigations.

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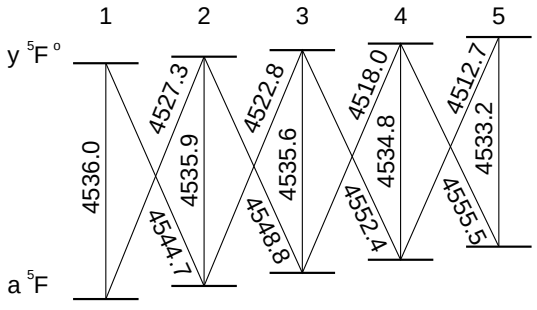


Fig. 1.— Transitions (wavelengths in Å) between the $a\,^5F$ and $y\,^5F^\circ$ terms of Ti I. Upper labels indicate the total angular momentum of the levels.

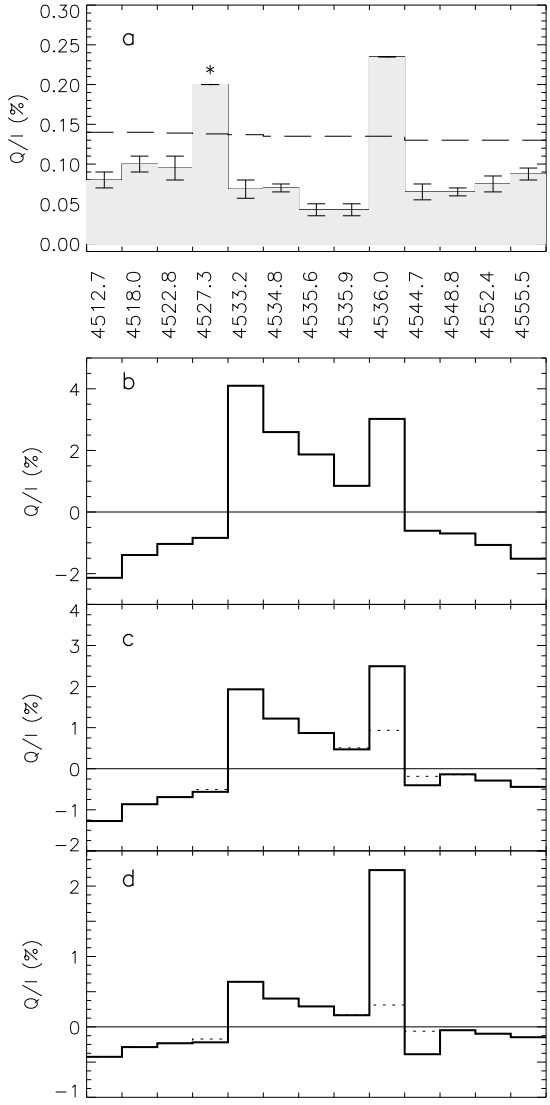


Fig. 2.— Fractional polarization Q/I in the thirteen spectral lines allowed between the $a\,^5F$ and $y\,^5F^\circ$ terms of Ti I. **a)** observations near the solar limb as reported in Gandorfer (2002). **b)** theoretical Q/I calculated as explained in the text. **c)-d)** as panel **b)** assuming depolarizing rates 10^8 s^{-1} and 5×10^8 s^{-1}, respectively, for all Ti I levels except the $a\,^5F_1$ and $y\,^5F_1^\circ$ones. Note the change of the Q/I scale between panels. The meaning of the dotted lines is explained in the text, while the symbol * indicates a Ti I line that we do not consider in our analysis because heavily blended.