IL NUOVO CIMENTO Vol. 25 C, N. 5-6 Settembre-Dicembre 2002

Remote sensing of chromospheric magnetic fields via the Hanle and Zeeman effects(*)

J. Trujillo Bueno(1)(2)(**) and R. Manso Sainz(1)(3)(***)

(1) *Instituto de Astrofísica de Canarias - E-38200, La Laguna (Tenerife), Spain*
(2) *Consejo Superior de Investigaciones Científicas - Spain*
(3) *Dipartimento di Astronomia e Scienza dello Spazio, Università degli Studi di Firenze I-50125, Florence, Italy*

(ricevuto il 10 Giugno 2002; approvato il 7 Agosto 2002)

Summary. — The only way to obtain reliable empirical information on the intensity and topology of the weak magnetic fields of the "quiet" solar chromosphere is via the measurement and rigorous physical interpretation of weak polarization signals in chromospheric spectral lines. The observed Stokes profiles reported here are due to the Hanle and Zeeman effects operating in a weakly magnetized plasma that is in a state far from local thermodynamic equilibrium. The physical origin of their "enigmatic" linear polarization Q and U components is the existence of atomic polarization in their metastable lower levels, which permits the action of a dichroism mechanism that has nothing to do with the transverse Zeeman effect. It is also pointed out that the population imbalances and coherences among the Zeeman sublevels of such long-lived atomic levels cannot only survive in the presence of horizontal magnetic fields having intensities in the gauss range, but also produce very significant polarization signals. Finally, it is shown how the most recent developments in the observation and theoretical modelling of weak polarization signals are facilitating fundamental new advances in our ability to investigate the magnetism of the outer solar atmosphere via spectropolarimetry.

PACS 96.60.-j – Solar physics.
PACS 95.30.Gv – Radiation mechanisms; polarization.
PACS 95.30.Jx – Radiative transfer; scattering.
PACS 32.80.Bx – Level crossing and optical pumping.
PACS 01.30.Cc – Conference proceedings.

(*) Paper presented at the International Meeting on THEMIS and the New Frontiers of Solar Atmosphere Dynamics, Rome, Italy, March 19-21, 2001.
(**) E-mail:jtb@iac.es
(***) E-mail:rsainz@arcetri.astro.it

1. – Introduction

The physical processes that underlie solar magnetic activity are of fundamental importance to astrophysics as well as in controlling the heliosphere including near-earth space weather. However, with the possible exception of the solar photosphere—the thin surface layer where almost all of the radiative energy flux is emitted—, our empirical knowledge concerning the magnetism of the outer solar atmosphere (chromosphere, transition region, corona) is still very primitive. This is very regrettable because many of the physical challenges of solar and stellar physics arise precisely from magnetic processes taking place in such outer layers.

In particular, the "quiet" solar chromosphere is a crucial region whose magnetism we need to understand for unlocking new discoveries. It is in this highly inhomogeneous and dynamic region of low-density plasma overlying the thin solar photosphere where the magnetic field becomes the globally dominating factor. If we aim at understanding the complex and time-dependent structure of the outer solar atmosphere we must first decipher how is the intensity and topology of the magnetic fields of the solar chromosphere.

According to the "standard picture" of chromospheric magnetism described in the recently-published *Encyclopedia of Astronomy and Astrophysics* there is "a layer of magnetic field which is directed parallel to the solar surface and located in the low chromosphere, overlying a field-free region of the solar photosphere". This so-called *magnetic canopy* "has a field strength of the order of 100 gauss and covers a large fraction of the solar surface" [1].

This picture of chromospheric magnetism seems to be in the minds of most solar physicists since the beginning of the 1980s, when R. G. Giovanelli and H. P. Jones interpreted solar magnetograms in chromospheric lines (like the IR triplet of ionized calcium or the Mg I b_2 line) taken in network unipolar regions near the solar limb, as well as in sunspots and related active regions. Such chromospheric magnetograms seem to show a polarity inversion and are considerably more diffused in appearance than photospheric magnetograms, which is interpreted as the result of the expansion of the magnetic-field lines with height in the solar atmosphere [2-6].

The magnetic canopy model was later reinforced in the 1990s via magnetohydrostatic extrapolations of photospheric magnetic flux tube models [7]. However, it was found that only magnetic-field extrapolations that allow for substantial differences between the temperatures of the atmospheres within and outside the assumed magnetic flux tubes are capable of producing a low-lying canopy field. If the internal and external atmospheres are assumed to be similar, the canopy extrapolated field forms in the upper chromosphere and the corona. It was argued that the assumption of much lower temperatures in the external atmosphere fits nicely with the observational finding of strong CO absorption lines near the extreme solar limb [8].

Magnetograms and extrapolations thus led to the idea that the "quiet" solar chromosphere is pervaded by magnetic canopies with predominantly horizontal fields overlying "field-free" regions whose temperatures remain relatively cool up to the canopy bases. As a matter of fact, some researchers investigated the impact of "the magnetic canopy" on the frequencies of solar p- and f-modes (see, *e.g.* [9]), while others found of interest to consider its influence on the linear polarization of some resonance lines [10]. It is however very important to emphasize that, as pressed with great force by a working group on chromospheric fields (see [11]), chromospheric magnetograms have never "detected" magnetic canopies in the truly quiet Sun where the network is fragmentary and photospheric magnetograms show the well-known "salt and pepper" patterns of mixed polarity. In fact, the Ca II IR triplet and other chromospheric lines are relatively broad, which implies that the magnetic fields of the "quiet" chromospheric regions are difficult to diagnose via the only consideration of the longitudinal Zeeman effect on which magnetograms are based on. Obviously, the above-mentioned chromospheric magnetograms (of network and active regions) and magnetohydrostatic extrapolations (of photospheric magnetic flux tube models) are not suitable for drawing conclusions on the magnetism of the most quiet regions of the solar chromosphere.

Over the last few years, observational investigations of scattering polarization on the Sun have pointed out the existence of "enigmatic" linear polarization signals in several spectral lines (observed in the "quiet" solar chromosphere close to the limb as well as in solar filaments), which cannot be understood in terms of the classical theory of scattering polarization [12-16]. In particular, the "enigmatic" features of the linearly-polarized solar-limb spectrum have motivated some novel theoretical investigations of scattering polarization in spectral lines [17-23, 16]. Such investigations have been carried out within the framework of polarization transfer theories that allowed us to formulate scattering polarization problems taking into account a physical ingredient that had been previously neglected: ground-level atomic polarization (*i.e.* the existence of population imbalances and/or coherences among the Zeeman sublevels of the lower level of the spectral line under considerartion).

Of particular interest in this respect is the letter published in *Nature* by Landi Degl'Innocenti with the title "Evidence against turbulent and canopy-like magnetic fields in the solar chromosphere" [18]. He concludes that the explanation in terms of ground-level atomic polarization of the "enigmatic" linear polarization peaks of the sodium D-lines observed by Stenflo and Keller in quiet regions close to the solar limb [12], implies that the magnetic field of the "quiet" solar chromosphere has to be either isotropically distributed but extremely low (with $B \lesssim 10$ milligauss) or, alternatively, practically vertically orientated. More recently, the personal conviction that magnetic fields of milligauss or weaker strength cannot exist in the highly conductive solar atmospheric plasma has led Stenflo *et al.* to the conclusion that the magnetic field in the most quiet regions of the solar chromosphere has then to be preferentially vertical [24].

The only way to obtain reliable empirical information on the intensity and topology of the weak magnetic fields of the "quiet" solar chromosphere is via the measurement and rigorous physical interpretation of weak polarization signals in chromospheric spectral lines. The aim of this keynote article is to show in some detail how the most recent advances in the observation and physical interpretation of weak polarization signals in terms of the Hanle and Zeeman effects is giving us decisive new clues about the topology and intensity of the magnetic fields of the "quiet" solar chromosphere.

2. – The Zeeman and Hanle effects

In order to understand why the observed polarization signals reported in sect. **3** are weak, first we need to advance something concerning their physical origin. The *circular* polarization signals are mainly due to the longitudinal Zeeman effect. As is well known, Zeeman-induced circular polarization signals are sensitive to the net magnetic flux density over the spatio-temporal resolution element of the observations. Although it is true that a complex magnetic field topology within the line formation region may conspire to make the observed circular polarization signals weak, we have some good reasons to believe that the Stokes V signals are weak mainly because the magnetic fields of the "non-magnetic" solar chromosphere are intrinsically weak (*i.e.* below 100 gauss).

The physical origin of the observed *linear* polarization signals is completely different and has nothing to do with the transverse Zeeman effect. The observed Stokes Q and U signals are due to *atomic polarization*, *i.e.* to the existence of population imbalances and quantum interferences (or coherences) among the sublevels pertaining to the upper and/or lower atomic levels involved in the line transition under consideration. This atomic polarization is the result of a transfer process of "order" from the radiation field to the atomic system (see [21]). The most obvious manifestation of "order" in the solar radiation field is its degree of anisotropy arising from its centre-to-limb variation. In fact, the main source of atomic polarization is the anisotropic illumination of the atoms of the solar atmospheric plasma, which produces a *selective* radiative pumping. This pumping is "selective", in the sense that it produces population imbalances among the Zeeman sublevels of each atomic level. This implies sources and sinks of linear (and even circular) polarization at each point within the medium. These locally generated polarization signals are then modified via transfer processes in the stellar plasma. The emergent polarization signals are weak because the degree of anisotropy of the solar radiation field is weak (which leads to population imbalances and coherences that are small compared with the overall population of the atomic level under consideration), but also because we have collisions and magnetic fields which tend to modify the atomic polarization.

The Hanle effect is the modification of the atomic polarization (and of the ensuing *linear* polarization profiles $Q(\lambda)$ and $U(\lambda)$) due to the action of a weak magnetic field (see the review [21]). As the Zeeman sublevels of degenerate atomic levels are split by the magnetic field, the degeneracy is lifted and, as long as the sublevels still overlap, the coherences (and, in general, also the population imbalances among the sublevels) are modified. Therefore, the Hanle effect is sensitive to magnetic fields such that the corresponding Zeeman splitting is comparable to the inverse lifetime (or natural width) of the lower or the upper atomic levels of the line transition under consideration. On the contrary, the Zeeman effect is most sensitive in *circular* polarization (quantified by the Stokes V parameter), with a magnitude that scales with the ratio between the Zeeman splitting and the width of the spectral line (which is very much larger than the natural width of the atomic levels).

The basic approximate formula to estimate the *maximum* magnetic-field intensity B (measured in gauss) to which the Hanle effect can be sensitive is

$$10^6 \; B \; g_J \;\approx\; 1/t_{\rm life} \,, \tag{1}$$

where g_J and $t_{\rm life}$ are, respectively, the Landé factor and the lifetime in seconds of the atomic level under consideration (which can be either the upper or the lower level of the chosen spectral line transition). This formula shows that the measurement and physical interpretation of weak polarization signals in suitably chosen spectral lines may allow us to diagnose magnetic fields having intensities between 10^{-3} and 100 gauss approximately, *i.e.* in a parameter domain that is very hard to study via the Zeeman effect alone.

While the Hanle effect modifies the atomic polarization, elastic collisions always produce atomic-level *depolarization*. The depolarization is complete only if $D\,t_{\rm life} \rightarrow \infty$, where D (given in s^{-1}) is the depolarizing rate of the given atomic level and $t_{\rm life}$ its lifetime. Therefore, at first sight, one would be tempted to conclude that *ground* and *metastable* levels are more vulnerable to elastic collisions than atomic levels of shorter lifetimes. This is however only true if D is assumed to be of the same order-of-magnitude for both, the long-lived and short-lived atomic levels under consideration. Unfortunately, our current knowledge on depolarizing rates due to elastic collisions is very poor, but we may hope to use the Sun itself as an atomic physics laboratory for improving the situation.

3. – Observations of weak polarization signals in chromospheric lines

Stenflo and Keller [12] have adopted the term "the second solar spectrum" to refer to the linearly polarized solar limb spectrum which can be observed with spectropolarimeters that allow the detection of very low amplitude polarization signals (with Q/I of the order of 10^{-3} or smaller). Such observations with the polarimeter ZIMPOL (see also the atlas [25]) have been confirmed (and extended to the full Stokes vector) by Dittmann *et al.* [26], Martínez Pillet *et al.* [27] and Trujillo Bueno *et al.* [15] using the Canary Islands telescopes. One of these telescopes is THÉMIS, which has allowed us to carry out observations of the full Stokes vector in several spectral lines simultaneously [15]. Given the increasing interest of this research field, THÉMIS is being used also by many other colleagues (see, *e.g.*, Bommier's report in this issue, p. 803). Thanks to a modified version of their polarimeter, Stenflo *et al.* have also started to investigate the four Stokes parameters of optical spectral lines in solar regions near the limb with varying degrees of magnetic activity [24]. It is also of interest to point out the enormous diagnostic potential offered by the near-UV spectral region where the degree of anisotropy of the solar radiation field is relatively high. Fortunately, there is at least one solar polarimeter that has been developed recently thinking seriously in the scientific interest of this near-UV region: ZIMPOL-UV.

In the remaining part of this section we show some particularly interesting examples of our own spectropolarimetric observations in optical and near-IR chromospheric lines, which have been obtained using different polarimeters attached to the Tenerife solar telescopes (VTT, GCT and THÉMIS). As we shall see below, the physical interpretation of these observations in terms of the quantum theory of polarization highlights the key role played by some subtle physical mechanisms in producing the emergent polarization.

Figure 1 shows an example of our VTT+TIP observations using the He I 10830 Å multiplet [16]. TIP is the Tenerife Infrared Polarimeter, which is based on ferroelectric-liquid-crystals [28]. The figure shows the case of a solar filament that was located *exactly* at the very center of the solar disk during the observing day. The open circles indicate the spectropolarimetric observation, while the solid line shows the theoretical modelling based on the density matrix polarization transfer theory (see sect. **5**). Like prominences, solar filaments are magnetized plasma ribbons embedded in the 10^6 K solar corona, and confined by the action of highly inclined magnetic fields (with respect to the stellar radius) and having intensities in the gauss range. (The only difference is that prominences are observed off-the-limb, *i.e.* against the dark background of the sky, while filaments are observed against the bright background of the solar disk. Therefore, we see emission lines in prominences, but absorption lines in filaments.)

The observational results of fig. 1 are very interesting. First of all, we have sizable Stokes Q signals in both the "blue" and "red" components of the He I 10830 Å multiplet. This demonstrates that the Hanle effect can give rise to significant linear polarization even at the very center of the solar disk where we meet the case of forward scattering (see [21]). Moreover, the fact itself that the "blue" component is linearly polarized is particularly interesting because it is the result of $J_\text{l} = 1 \rightarrow J_\text{u} = 0 \rightarrow J_\text{l} = 1$ scattering processes (with J_l and J_u the total angular momentum of the lower and upper levels, respectively). According to scattering polarization transfer theories neglecting the role of

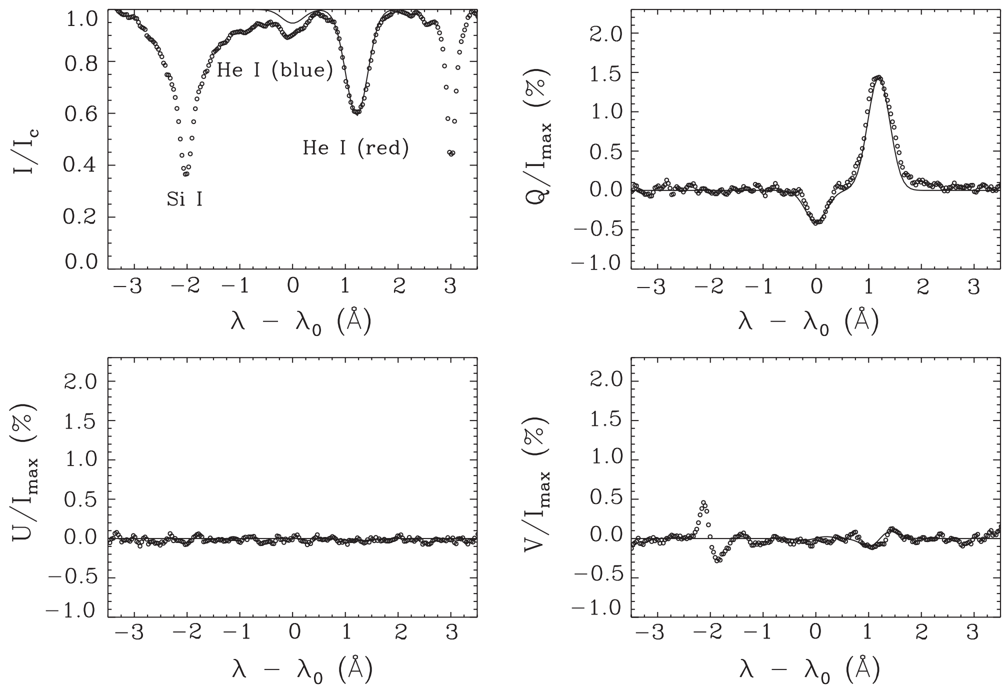

Fig. 1. – He I 10830 Å spectropolarimetric observation of a solar filament located at the solar disk center (open circles) *vs.* theoretical modelling (solid line). The fit to the observations has been achieved assuming a magnetic-field vector of 20 gauss inclined by 105° with respect to the radial direction and that the observed filament region was located at a height of 40″ above the solar photosphere. The positive reference direction for Stokes Q is parallel to the projection of the magnetic-field vector on the solar disk. It turns out that this direction made an angle of about 10° in the clockwise direction with respect to the axis of the solar filament. The Stokes parameters are normalized to the maximum line-core depression (from the continuum level) of the Stokes I profile of the "red" absorption line. This observation has been obtained with the TIP polarimeter attached to the Vacuum Tower Telescope (VTT). From [16].

lower-level atomic polarization, such a line transition should be intrinsically unpolarizable because the upper level, having $J_{\rm u} = 0$, cannot carry any atomic polarization. We will see below that the physical origin of this "enigmatic" linear polarization signal is the existence of a sizable amount of atomic polarization in the lower level, whose $J_{\rm l} = 1$.

Another interesting feature of our solar filament observation is that the "blue" and "red" lines of the He I 10830 Å multiplet show up with amplitudes of opposite sign, which cannot be modeled via the assumption of independent two-level atomic models for the three line components of the helium multiplet. At least a two-term atom taking into account the fine structure of the upper $2^3P_{2,1,0}$ term is needed in order to be able to obtain qualitative agreement with the observed linear polarization amplitudes.

Figure 2 shows the full Stokes vector of the Ca II 8662 Å line observed on the disk at 5″ from the solar limb. This observation is the result of a collaboration between Dittmann, Semel and Trujillo Bueno. They have used Semel's stellar polarimeter attached to the Tenerife Gregory Coudé Telescope and carried out during September 2000 spectropolarimetric observations of the Ca II IR triplet in regions near the limb with

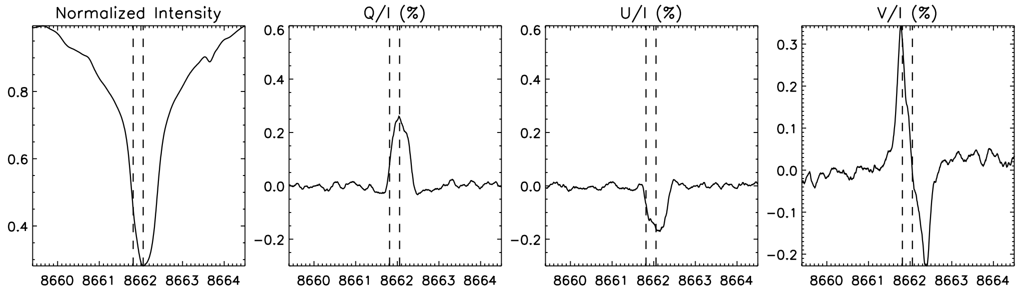

Fig. 2. – The full Stokes vector of the Ca II 8662 Å line observed on the solar disk at about 5″ from the limb during the equinox period of September 2000. The positive reference direction for Stokes Q is along the line perpendicular to the radial direction through the observed point. The vertical dashed line to the r.h.s. of each panel indicates the central wavelength of the 8662 Å line, while the l.h.s. dashed line gives the position of a nearby photospheric iron line. This spectropolarimetric observation with the Tenerife Gregory Coudé Telescope (GCT) is the result of a collaboration between Dittmann, Semel and Trujillo Bueno.

varying degrees of magnetic activity. The Ca II 8662 Å line is of particular interest because its upper level, having $J_{\rm u} = 1/2$, cannot harbour any atomic alignment. This has led to consider the reported detection of a significant Stokes Q/I amplitude in this spectral line as "enigmatic", because of the belief that the polarization effects come only from the population imbalances and coherences in the *excited* states of the scattering process [14]. The full Stokes vector observation of fig. 2 shows the existence of sizable linear polarization signals in the Ca II 8662 Å line, both in Q/I and U/I.

Finally, fig. 3 shows an example of THÉMIS observations of the second solar spectrum (see [15]). It shows the full Stokes vector of the oxygen IR triplet at 777 nm, as observed on-the-disk at 4″ from the North solar limb. It is of great scientific interest to point out that the two lines at 7772 Å and 7774 Å have *positive* Q/I fractional linear polarization amplitudes, while the 7776 Å line shows *negative* polarization (*i.e.* along the solar radius through the observed point!) all over its full spectral range. A forthcoming publication will show in detail that this is due to the existence of atomic polarization in the *metastable* lower level of the oxygen triplet([1]). Finally, note that in these oxygen lines we find significant circular polarization signals, which can only be produced by magnetic fields substantially larger than 0.01 gauss, as is the case also with the Stokes V profiles of the Ca II 8662 Å line shown in fig. 2.

4. – The physical origin of the enigmatic polarization signals: atomic polarization of metastable levels and dichroism

The "enigmatic" signals of the "second solar spectrum" are detected in spectral lines whose lower level is the ground state or a metastable level. These levels have a lifetime

([1]) This oxygen triplet is a beautiful example of the case of three lines with a common *lower* level. The case of three lines with a common *upper* level (*e.g.*, the Mg I *b* lines) has been investigated by Trujillo Bueno, concluding that the physical origin of the "enigmatic" Q/I amplitudes observed by Stenflo *et al.* [29,14] is, again, the atomic polarization of their metastable lower levels [20,21].

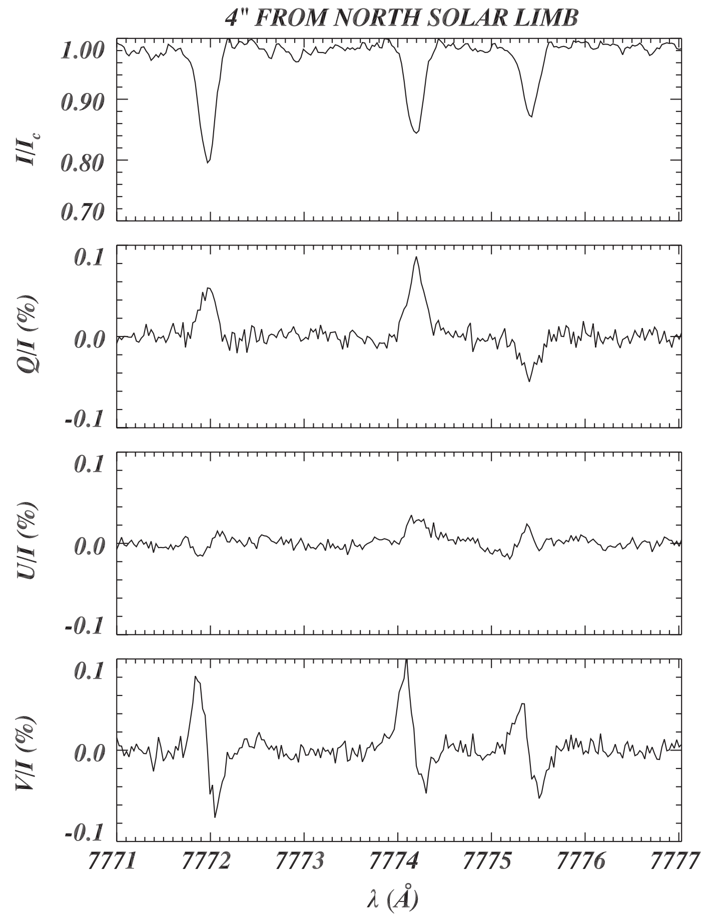

Fig. 3. – The fractional polarization of the oxygen IR triplet at 777 nm observed with THÉMIS on the solar disk at about 4″ from the North solar limb. From [15].

$t^{\rm l}_{\rm life}{\approx}1/B_{\rm lu}\bar{J}^0_0$, which is much larger than the upper level lifetime $t^{\rm u}_{\rm life}{\approx}1/A_{\rm ul}$ (with $B_{\rm lu}$ and $A_{\rm ul}$ are the Einstein coefficients for absorption and stimulated emission, respectively, and $\bar{J}^0_0$ is the line integrated mean intensity of the radiation field). Therefore, the atomic polarization of such *long-lived* lower levels is very sensitive to depolarizing mechanisms. However, it is very important to emphasize that only collisions can depolarize completely a given atomic level. Except for a few very particular cases, the depolarization of the atomic levels due to magnetic fields (the Hanle effect) is never complete. For instance, elastic collisions and a microturbulent and isotropic magnetic field modify the degree of population imbalance of the upper level of a two-level atom (with $J_{\rm l}=0$ and $J_{\rm u}=1$) as dictated by the following approximate expression (cf. [30]):

$$\sigma^2_0 = \frac{\rho^2_0}{\rho^0_0} \approx \frac{\mathcal{H}}{1+\delta}\,\mathcal{A}, \tag{2}$$

where $\mathcal{A} = \bar{J}^2_0/\bar{J}^0_0$ is the anisotropy factor(^{2}) of the pumping radiation field, δ is the collisional depolarizing rate in units of the Einstein $A_{\rm ul}$ coefficient, and $\mathcal{H}$ is the Hanle depolarization factor which varies between 1 (for the zero magnetic field case) and 1/5 (for a Zeeman splitting very much larger than the natural width of the upper level). We point out that $\sqrt{3}\rho^0_0$ is the *overall* population of the upper level, while its atomic alignment (or degree of population imbalance) is quantified by $\rho^2_0 = [N_1 - 2N_0 + N_{-1}]/\sqrt{6}$ (where N_i are the individual populations of the three Zeeman sublevels of the upper level).

A key question is the following(^{3}): to which extent can the atomic polarization of long-lived atomic levels survive the partial Hanle-effect destruction produced by highly inclined magnetic fields having intensities in the range of gauss? The answer to this question is of greatest importance for a correct diagnostics of the magnetic fields of the outer solar atmosphere (chromosphere, transition region and corona). This is because, as clarified below, the physical origin of the above-mentioned "enigmatic" polarization signals is the existence of a significant amount of population imbalances and coherences in the *metastable* lower levels of their respective spectral lines.

Interestingly, the upper level of some of the "enigmatic" spectral lines cannot carry any atomic alignment (because it has $J_{\rm u} = 0$ or $J_{\rm u} = 1/2$, as is the case with the "blue" line of the He I 10830 Å multiplet of fig. 2 or with the Ca II 8662 Å line of fig. 2, respectively). For this type of lines there is no contribution of upper-level atomic polarization to the Q and U components of the *emission* vector (*i.e.* to ϵ_Q and ϵ_U), simply because such upper levels cannot carry any atomic alignment. Moreover, the contributions to ϵ_Q and ϵ_U arising from the Zeeman splitting of the lower level (*i.e.* due to the transverse Zeeman effect) are negligible for the "weak" magnetic fields of prominences, filaments and of the "quiet" solar chromosphere and corona. This type of lines (with $J_{\rm u} = 0$ or $J_{\rm u} = 1/2$) may thus be called "null" lines, because the spontaneously emitted radiation that follows the anisotropic radiative excitation is vitually *unpolarized*.

However, η_Q and η_U can have sizable values, if a significant amount of lower-level atomic polarization is present. In principle, this is possible for the aforementioned helium and calcium lines because their lower levels can be polarized (because they have J_l=1 and $J_l = 3/2$, respectively). When a sizable amount of atomic polarization is present in such lower levels, as it happens in the outer solar atmosphere, then the role of the emissivity in Stokes Q and U comes exclusively from the terms $-\eta_Q\, I$ and $-\eta_U\, I$ that arise in their respective radiative transfer equations. If the Stokes-I intensity along the line of sight is important enough (as it occurs for the on-the-disk observations of figs. 1, 2 and 3, then we can have an important contribution of the absorption process itself to the emergent linear polarization. We call this mechanism *dichroism* in a weakly magnetized medium which, we would like to stress, has nothing to do with the transverse Zeeman effect (see [17]). This *dichroism* mechanism, which requires the presence of a sizable amount of lower-level polarization, plays a crucial role in producing the observed "enigmatic" linear polarization signals in a variety of chromospheric lines [20-23, 16].

The conclusion that some of the "enigmatic" linear polarization signals are due to *dichroism* demonstrates that a sizable amount of atomic polarization is present in the

(^{2}) Its possible values are such that $-1/2 \lesssim \sqrt{2}\mathcal{A} \lesssim 1$. (Note that there is a typing error in eq. (11) of [21], since the inequalities given there are correct for $2\mathcal{A}$, *not* for $\mathcal{A}$.)
(^{3}) In this article, the atomic polarization of a given atomic level is quantified by means of the spherical tensor components of its atomic density matrix and the quantization-axis (the z-axis) is taken along the stellar radius (see [21]).

lower levels of such spectral lines. As mentioned above, such lower levels are metastable (*i.e.* they are long-lived atomic levels). According to the basic Hanle-effect eq. (1) their atomic polarization is vulnerable to magnetic fields of very low intensity (*i.e.* to fields $B \gtrsim 10^{-3}$ gauss!). This magnetic depolarization takes place for sufficiently inclined fields with respect to the radial direction of the star (*i.e.* for $\theta_B \gtrsim 10°$). Unfortunately, the particular conclusion of Landi Degl'Innocenti that the atomic polarization of the hyperfine components of the ground level of sodium does not survive sufficiently in the presence of turbulent or canopy-like horizontal fields stronger than about 10 milligauss [18] has led to unjustifiable reinforcements of the belief that the atomic polarization of *any* long-lived atomic level has to be insignificant in the presence of highly inclined solar magnetic fields having intensities in gauss range [31-33]. If this belief were correct in general, then it would be justified to conclude that the magnetic field throughout much of the "quiet" solar chromosphere has to be either extremely low (with $B \lesssim 0.01$ gauss) or, alternatively, oriented fairly close to the stellar radial direction (but having intensities in the gauss range), in contradiction with the observational results [34, 35] obtained from spectral lines whose lower level is intrinsically unpolarizable.

5. – Multilevel modelling of the Hanle and Zeeman effects: diagnostics of chromospheric magnetic fields

The physical interpretation of weak polarization signals requires to calculate the polarization of the atomic or molecular levels within the framework of a rigorous theory for the generation and transfer of polarized radiation. A suitable theory for many spectral lines of diagnostic interest is the density matrix polarization transfer theory of Landi Degl'Innocenti, which is based on the Markovian assumption of complete frequency redistribution [36, 37]. This theory provides a physically consistent description of scattering phenomena if the spectrum of the pumping radiation is flat across a sufficiently large frequency range $\Delta\nu$ [38](4).

The theoretical modelling of the He I 10830 Å multiplet in solar prominences and filaments (see the solid line of fig. 1) is based on the density matrix theory [36, 37, 16]. Trujillo Bueno *et al.* [16] have assumed a slab of He I atoms lying at about $40''$ above the solar photosphere, from where it is illuminated by unpolarized and spectrally flat radiation. They have adopted a realistic multiterm model atom for He I described in the incomplete Paschen-Back effect regime. They also take into account coherences among magnetic sublevels of each J-level, and between magnetic sublevels of the different J-levels of each term (because they are important for some terms of the model atom like, *e.g.*, for the upper term of the D_3 multiplet). From the fitting to the spectropolarimetric observation of the disk-center filament (open circles of fig. 1) they infer a magnetic field of 20 gauss and inclined by about 105 degrees with respect to the radial direction through the observed point. The agreement with the spectropolarimetric observation is remarkable. It demonstrates that a very significant amount of the atomic polarization that is induced by optical pumping processes in the metastable 2^3S_1 lower level survives

(4) The required extension of this $\Delta\nu$-interval depends on whether or not coherences among Zeeman sublevels of *different* J-levels can be neglected [38]. If they need to be taken into account (as it occurs, *e.g.*, with the He I D_3 multiplet at 5876 Å), then $\Delta\nu$ has to be of the order of the frequency range of the multiplet. However, if such coherences can be neglected (as it happens, *e.g.*, when modelling the Hanle effect in the Ca II IR triplet), then $\Delta\nu$ needs to be only larger than the inverse lifetime of the atomic levels.

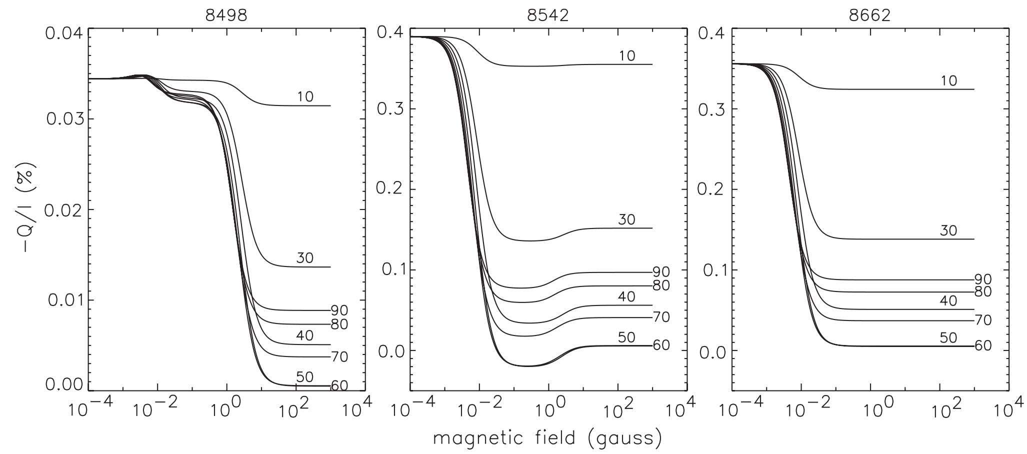

Fig. 4. – The fractional linear polarization of the Ca II IR triplet calculated at $\mu = 0.1$ (about $5''$ from the limb) in an isothermal atmosphere with $T = 6000$ K. Each curve corresponds to the indicated inclination (θ_B) of the assumed random-azimuth magnetic field.

the partial Hanle-effect destruction due to horizontal magnetic fields with intensities in the gauss range, and produces sizable linear polarization signals.

As is well known, prominences and filaments are located tens of thousands of kilometers above the solar photosphere and their confining magnetic field does *not* have a random azimuthal component within the spatio-temporal resolution element of the observation. Therefore, one may ask whether the above-mentioned belief can be safely applied to the solar chromosphere, where the degree of anisotropy of the pumping radiation is significantly lower and the magnetic fields may have a more complex topology. This issue is investigated for the Ca II IR triplet by the authors in [22, 23].

Firstly, we have considered the zero magnetic-field reference case and demonstrated that the "enigmatic" relative Q/I amplitudes (among the three lines) observed by Stenflo *et al.* [14] are the natural consequence of the existence of a sizable amount of atomic polarization in the metastable levels $^2D_{3/2}$ and $^2D_{5/2}$ (which are the lower levels of the Ca II IR triplet). Secondly, we have investigated the Hanle effect in the IR triplet at 8498, 8542 and 8662 Å considering a realistic multilevel atomic model. Figure 4 is one of our most recent and interesting results, which we will describe in full detail in forthcoming publications. It shows the fractional linear polarization calculated at $\mu = 0.1$ (about $5''$ from the limb) assuming magnetic fields of given inclination, but with a random azimuthal component within the spatio-temporal resolution element of the observation.

The results of this figure indicate that, basically, there are two magnetic-field topologies (assuming that the magnetic-field lines have a random azimuthal component over the spatio-temporal resolution element of the observations) for which the limb polarization signals of the 8542 and 8662 Å lines can have amplitudes with $Q/I \gtrsim 0.1\%$ (*i.e.* of the order of the observed ones). As one could have expected, the first topology corresponds to magnetic fields with inclinations $\theta_B \lesssim 30°$. The second corresponds to magnetic fields which are practically parallel to the solar surface, *i.e.* "horizontal" fields with $80° \lesssim \theta_B \lesssim 100°$. This demonstrates that a significant amount of the atomic polarization that is induced by optical pumping processes in the metastable $^2D_{3/2}$ lower level survives the partial Hanle-effect destruction produced by non-resolved canopy-like

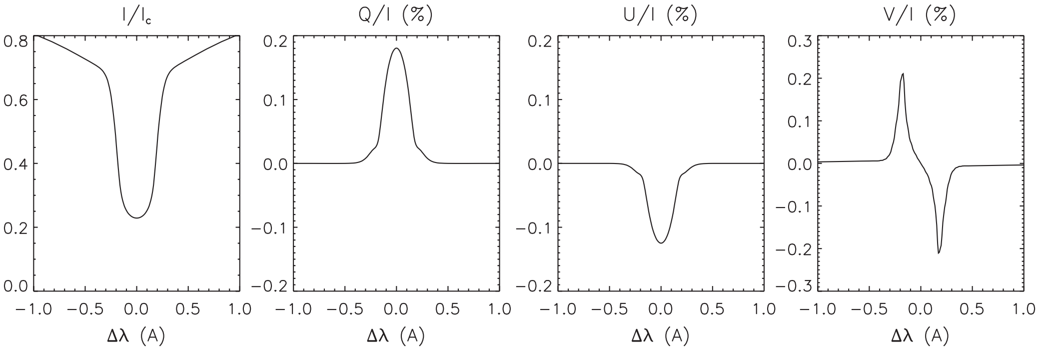

Fig. 5. – The emergent Stokes parameters of the Ca II 8662 Å line calculated at $\mu = 0.1$ in the FAL-C semi-empirical model. We have assumed a deterministic magnetic field of 20 gauss that is inclined by 25° with respect to the radial direction. This figure is to be compared with the observational results of fig. 2.

horizontal fields with intensities in the gauss range, and generates significant linear polarization signals via the dichroism mechanism.

The spectropolarimetric observation of fig. 2 is only one example among many other different cases of our GCT observations. The sizable Stokes V/I signal of fig. 2 indicates that we were observing here a moderately magnetized region close to the solar limb. Within the framework of the CRD theory of line formation (see [37]), this particular observation of fig. 2 cannot be modelled assuming a random azimuth magnetic field, otherwise Stokes U would have been undetectable. It would be of interest to confirm with other telescopes the detection of that significant U/I signal for the 8662 Å Ca II line, because it can only be due to the existence of quantum interferences (coherences!) among the Zeeman sublevels of the metastable $^2D_{3/2}$ lower level (see sect. 7 in [21]). For this particular observation of fig. 2 a good fit can be obtained assuming deterministic magnetic fields with intensities in the gauss range and having inclinations $\theta_B \lesssim 30°$ (see the multilevel Hanle and Zeeman modelling of fig. 5). In any case, observations of more "quiet" and more "active" solar limb regions have been performed. In some regions Q is detected, whereas $U \approx 0$ and/or $V \approx 0$. In other regions V is detected, but $Q \approx U \approx 0$. The physical interpretation of these spectropolarimetric observations in terms of the Hanle and Zeeman effects is giving us valuable clues about the intensities and magnetic-field topologies in different regions close to the solar limb.

6. – Concluding remarks

The physical origin of the "enigmatic" linear polarization signals observed in a variety of chromospheric lines is the existence of atomic polarization in their metastable lower levels, which permits the operation of a *dichroism* mechanism that has nothing to do with the transverse Zeeman effect. Therefore, the absorption process itself plays a key role in producing the linear polarization signals observed in the "quiet" solar chromosphere as well as in solar filaments.

The population imbalances and coherences among the Zeeman sublevels of such *long-lived* atomic levels can be sufficiently significant in the presence of horizontal magnetic fields having intensities in the gauss range (see, however, [39] concerning the very particular case of the "enigmatic" sodium D_1 line). Therefore, in general, one should not feel obliged to conclude that the magnetic fields throughout the "quiet" solar chromosphere have to be either extremely low (*i.e.* with intensities $B \lesssim 10$ mG), or, alternatively, oriented preferentially along the radial direction. The physical interpretation of our spectropolarimetric observations of chromospheric lines in terms of the Hanle and Zeeman effects indicates that the magnetic-field topology may be considerably more complex, having both moderately inclined and practically horizontal field lines with intensities above the milligauss range. A physically plausible scenario that might lead to polarization signals in agreement with the observations is that resulting from the superposition of miriads of different loops of magnetic-field lines connecting opposite polarities. This suggested magnetic-field topology is somehow reminiscent of the magnetic structure model of the "quiet" transition region proposed by Dowdy *et al.* [40], but scaled down to the spatial dimensions of the solar chromosphere.

* * *

We are grateful to the following scientists for their collaboration and for useful discussions: M. Collados, O. Dittmann, E. Landi Degl'Innocenti, V. Martínez Pillet, L. Merenda, F. Paletou and M. Semel. This work is part of the EC-TMR European Solar Magnetometry Network and has been partly funded by the Spanish Ministerio de Ciencia y Tecnología through project AYA2001-1649.

REFERENCES

[1] Steiner O., in *Encyclopedia of Astronomy and Astrophysics*, edited by P. Murdin (Nature Publishing Group, London; and Institute of Physics, Bristol) 2001, pp. 340-343.

[2] Chapman G. A. and Sheeley N. R., in *IAU Symposium 35, Structure and Development of Solar Active Regions*, edited by K. O. Kiepenheuer (Reidel, Dordrecht) 1968, pp. 161-173.

[3] Pope T. and Mosher J., *Solar Phys.*, **44** (1975) 3.

[4] Giovanelli R. G., *Solar. Phys.*, **68** (1980) 49.

[5] Giovanelli R. G. and Jones H. P., *Solar. Phys.*, **79** (1982) 267.

[6] Jones H. P. and Giovanelli R. G., *Solar Phys*, **87** (1983) 37.

[7] Solanki S. K. and Steiner O., *Astron. Astrophys.*, **234** (1990) 519.

[8] Ayres T., in *Encyclopedia of Astronomy and Astrophysics*, edited by P. Murdin (Nature Publishing Group, London; and Institute of Physics, Bristol) 2001, pp. 346-350.

[9] Evans D. J. and Roberts B., *Nature*, **355** (1992) 230.

[10] Faurobert-Scholl M., *Astron. Astrophys.*, **285** (1994) 655.

[11] Jones H. P., in *Chromospheric Diagnostics and Modelling*, edited by B. Lites (National Solar Observatory, Sunspot) 1985, pp. 10-12.

[12] Stenflo J. O. and Keller C., *Astron. Astrophys.*, **321** (1997) 927.

[13] Lin H., Penn M. J. and Kuhn J. R., *Astrophys. J.*, **493** (1998) 978.

[14] Stenflo J. O., Keller C. and Gandorfer A., *Astron. Astrophys.*, **355** (2000) 789.

[15] Trujillo Bueno J., Collados M., Paletou F. and Molodij G., in *Advanced Solar Polarimetry: theory, observations and instrumentation, XX NSO/SP Summer Workshop*, edited by M. Sigwarth, *ASP Conf. Ser.*, **236** (2001) 141.

[16] Trujillo Bueno J., Landi Degl'Innocenti E., Collados M. Merenda L. and Manso Sainz R., *Nature*, **415** (2002) 403.

[17] Trujillo Bueno J. and Landi Degl'Innocenti E., *Astrophys. J. Lett.*, **482** (1997) 183.

[18] Landi Degl'Innocenti E., *Nature*, **392** (1998) 256.

[19] Landi Degl'Innocenti E., in *Solar Polarization*, edited by K. N. Nagendra and J. O. Stenflo (Kluwer Academic Publishers, Dordrecht) 1999, pp. 61-71.

[20] TRUJILLO BUENO J., in *Solar Polarization*, edited by K. N. NAGENDRA and J. O. STENFLO (Kluwer Academic Publishers, Dordrecht) 1999, pp. 73-96.
[21] TRUJILLO BUENO J., in *Advanced Solar Polarimetry: theory, observations and instrumentation, XX NSO/SP Summer Workshop*, edited by M. SIGWARTH, *ASP Conf. Ser.*, **236** (2001) 161.
[22] MANSO SAINZ R. and TRUJILLO BUENO J., in *Advanced Solar Polarimetry: theory, observations and instrumentation, XX NSO/SP Summer Workshop*, edited by M. SIGWARTH, *ASP Conf. Ser.*, **236** (2001) 213.
[23] TRUJILLO BUENO J. and MANSO SAINZ R., in *Magnetic Fields Across the Hertzprung-Russell Diagram*, edited by G. MATHYS, S. K. SOLANKI and D. T. WICKRAMASINGHE, *ASP Conf. Ser.*, **248** (2001) 83.
[24] STENFLO J. O., GANDORFER A., WENZLER T. and KELLER C. U., *Astron. Astrophys.*, **367** (2001) 1033.
[25] GANDORFER A., *The Second Solar Spectrum: a high spectral resolution polarimetric survey of scattering polarization at the solar limb in graphical representation* (vdf Hochschulverlag AG an der ETHZ, Zürich) 2000.
[26] DITTMANN O., TRUJILLO BUENO J., SEMEL M. and LÓPEZ ARISTE A., in *Advanced Solar Polarimetry: theory, observations and instrumentation, XX NSO/SP Summer Workshop*, edited by M. SIGWARTH, *ASP Conf. Ser.*, **236** (2001) 125.
[27] MARTÍNEZ PILLET V., TRUJILLO BUENO J., and COLLADOS M., in *Advanced Solar Polarimetry: theory, observations and instrumentation, XX NSO/SP Summer Workshop*, edited by M. SIGWARTH, *ASP Conf. Ser.*, **236** (2001) 133.
[28] MARTÍNEZ PILLET V., COLLADOS M., SÁNCHEZ ALMEIDA J. *et al.*, in *High resolution solar physics: theory, observations and techniques, XIX NSO/SP Summer Workshop*, edited by T. R. RIMMELE, K. S. BALASUBRAMANIAM and R. R. RADICK, *ASP Conf. Ser.*, **183** (1999) 264.
[29] STENFLO J. O., TWERENBOLD D., HARVEY J. W. and BRAULT J. W., *Astron. Astrophys. Suppl.*, **54** (1983) 505.
[30] TRUJILLO BUENO J. and MANSO SAINZ R., *Astrophys. J.*, **516** (1999) 436.
[31] STENFLO J. O., *Solar Magnetic Fields: Polarized Radiation Diagnostics* (Kluwer Academic Publishers, Dordrecht) 1994.
[32] STENFLO J. O., *Astron. Astrophys.*, **324** (1997) 344.
[33] STENFLO J. O., in *Advanced Solar Polarimetry: theory, observations and instrumentation, XX NSO/SP Summer Workshop*, edited by M. SIGWARTH, *ASP Conf. Ser.*, **236** (2001) 97.
[34] BIANDA M., STENFLO J. O. and SOLANKI S., *Astron. Astrophys.*, **337** (1998) 565.
[35] BIANDA M., STENFLO J. O. and SOLANKI S., *Astron. Astrophys.*, **350** (1999) 1060.
[36] LANDI DEGL'INNOCENTI E., *Solar Phys.*, **79** (1982) 291.
[37] LANDI DEGL'INNOCENTI E., *Solar Phys.*, **85** (1983) 3.
[38] LANDI DEGL'INNOCENTI E., LANDI DEGL'INNOCENTI M. and LANDOLFI M., in *Science with THÉMIS*, edited by N. MEIN and S. SAHAL-BRÉCHOT (Publications of Paris Observatory, Paris) 1997, p.59.
[39] TRUJILLO BUENO J., CASINI R., LANDOLFI M. and LANDI DEGL'INNOCENTI E., *Astrophys. J. Lett.*, **566** (2002) 53.
[40] DOWDY J. F. JR., RABIN D. and MOORE R. L., *Solar. Phys.*, **105** (1986) 35.