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The Last Twenty Years. Optically Polarized Atoms in the Solar Atmosphere

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Abstract. The 8th Solar Polarization Workshop in honor of Prof. Egidio Landi Degl'Innocenti was a unique opportunity to review the last twenty years of research on the generation and transfer of spectral line polarization produced by optically pumped atoms in the solar atmosphere. Many investigations have been carried out since 1997, when Egidio and I published our first joint paper in The Astrophysical Journal Letters, arguing that lower-level depopulation pumping is a key physical mechanism for understanding some of the enigmatic spectral features of the Second Solar Spectrum. Here I provide an overview of the research carried out since then on optically polarized atoms in the solar photosphere, chromosphere and transition region, with emphasis on applications based on the quantum theory of spectral line polarization to which Egidio contributed so many pioneering and fundamental results.

1. Introduction

The 8th Solar Polarization Workshop (SPW-8), which took place in Florence (Italy) in September 2016, was organized in honor of the career and work of Prof. Egidio Landi Degl'Innocenti in the field of solar and stellar spectropolarimetry. In my SPW-8 talk on "The Last Twenty Years" I aimed at giving an overview of the work done since 1997 on optically polarized atoms in the solar atmosphere, with emphasis on the research carried out applying the quantum theories of spectral line polarization to which Egidio made so many fundamental contributions. By choosing that topic for my talk I just wanted to render tribute to an extraordinarily talented physicist, on whose shoulders I stand upon.

I first heard about Egidio in 1983, soon after I started my PhD research work at the Kiepenheuer Institut für Sonnenphysik in Freiburg (Germany). My thesis advisor, Franz Kneer, who two years later became professor at the Universitäts Sternwarte in Göttingen, had encouraged me to read first several papers and only afterwards to decide by myself the topic of my thesis among three possibilities he suggested. One of the papers Franz pointed out to me was "Polarization in Spectral Lines. A Unifying Theoretical Approach," published in May 1983 by someone called E. Landi Degl'Innocenti (see Landi Degl'Innocenti 1983), who was working at the Astrophysical Observatory of Arcetri in the beautiful city of Florence (Italy). Although at that time I was unable to understand Egidio's paper, I was so impressed by its rigor and scientific potential that I told Franz that I wanted to do my thesis on the generation and transfer of polarized

radiation in the solar atmosphere. The advice Franz gave me at that very moment was to do my thesis with him on the generation and transfer of spectral line radiation without accounting for its polarization, and to leave the more complicated topic of polarization in spectral lines for future work, ideally in collaboration with Egidio. I immediately understood that Franz was giving me a wise advice and, accordingly, I decided to work during the four years of my thesis assuming that the world is unpolarized.

The reason why I am choosing 1997 as the starting point for my review is because it was the year in which Egidio and I published our first joint paper on optically pumped atoms in the solar atmosphere (Trujillo Bueno & Landi Degl'Innocenti 1997), arguing that lower-level polarization is a key physical ingredient to understand some of the enigmatic linear polarization signals of the Second Solar Spectrum observed by Stenflo & Keller (1997), which had opened a new diagnostic window on the Sun. As a matter of fact, this field of research has grown enormously since 1997, and this review paper only provides an overview of some of the many results produced since then, with emphasis on the research done through the application of the quantum theories of polarization outlined in the following section.

2. Theories of spectral line polarization

Sir Arthur Eddington said once that "it is also a good rule not to put overmuch confidence in the observational results that are put forward until they are confirmed by theory." Interestingly, the numerical solution of the equations that result from the application of the following quantum theories of spectral line polarization have allowed us to understand many of the enigmatic spectral features of the solar polarized spectrum, and to provide successful theoretical predictions on unexplored spectral windows.

2.1. The density matrix theory for completely uncorrelated scattering

This theory is explained in great detail in the monograph by Landi Degl'Innocenti & Landolfi (2004). Within its framework, the scattering line polarization phenomenon is described as the temporal succession of 1st-order absorption and re-emission processes, considered as statistically independent events. For the particular but important case of a multilevel atom, neglecting quantum interference between the substates pertaining to different levels, this theory is a reliable approach whenever the radiation field that pumps the atomic system is spectrally flat across a frequency interval larger than both the inverse lifetime of the atomic levels and the Larmor frequency of the ambient magnetic field. This approach is suitable for modeling many diagnostically important spectral lines, such as the Mg I *b*-lines (Trujillo Bueno 1999, 2001, 2009), the IR triplet of Ca II (Manso Sainz & Trujillo Bueno 2003a, 2010), or the IR triplet of O I (del Pino Alemán & Trujillo Bueno 2015).

Given an estimate of the radiation field at any given point within the model atmosphere under consideration, the solution of the statistical equilibrium equations for the multipolar components of the atomic density matrix determines the excitation state of the atomic system. Likewise, given an estimate of such multipolar components for each level of the atomic model under consideration, the Stokes profiles of the line transitions can be calculated by solving the radiative transfer equations. Accurate and efficient numerical methods and radiative transfer codes have been developed for solving this so-called "non-LTE problem of the 2nd kind" (Trujillo Bueno 1999, 2003a; Manso

Sainz & Trujillo Bueno 2003b; Štěpán & Trujillo Bueno 2013; del Pino Alemán & Trujillo Bueno 2017).

One of the attractive features of this theory of the generation and transfer of polarized radiation is that it allows us to consider realistic multilevel atoms, taking fully into account the transfer of atomic polarization between the atomic levels and the impact, on the scattering line polarization, of the presence of atomic polarization in the line's upper and lower levels. This is important because, in general, there are two mechanisms that contribute to the "scattering polarization" observed in a spectral line:

- Selective emission of polarization components, due to the atomic polarization of the upper level of the line transition.
- Selective absorption of polarization components, due to the atomic polarization of the lower level of the line transition.

This can be easily understood by considering the case of an unmagnetized and one-dimensional (1D) model atmosphere. The ensuing transfer equations for the Stokes parameter Q reads (s is the linear coordinate along the ray):

$$\frac{d}{ds}\,Q = (\epsilon_Q - \eta_Q I) - \eta_I Q\ , \tag{1}$$

with

$$\epsilon_Q = \epsilon_0 \phi_\nu\, \frac{3}{2\sqrt{2}}\,(1-\mu^2)\, w^{(2)}_{J_u J_l}\, \rho^2_0(u)\ , \tag{2}$$

$$\eta_Q = \eta_0 \phi_\nu\, \frac{3}{2\sqrt{2}}\,(1-\mu^2)\, w^{(2)}_{J_l J_u}\, \rho^2_0(l)\ , \tag{3}$$

where ϵ_0 and η_0 are proportional to the number density of the atoms under consideration, $\rho^2_0(i)$ is the atomic alignment that quantifies the population imbalances between the sublevels of the line's level i (with $i = u$ and $i = l$ for the upper and lower levels, respectively), ϕ_ν is the line's absorption profile, $\mu = \cos\theta$ (with θ the angle between the local vertical and the direction of the considered radiation beam), while $w^{(2)}_{JJ'}$ are coefficients that depend on the angular momentum values of the line's upper and lower levels (e.g., $w^{(2)}_{10} = 1$ and $w^{(2)}_{01} = 0$). Therefore, Stokes Q can be produced either because the emission coefficient $\epsilon_Q \neq 0$ (selective emission of polarization components) and/or because the absorption coefficient $\eta_Q \neq 0$ (selective absorption of polarization components). This second contribution is termed zero-field dichroism, because it has nothing to do with the Zeeman effect (see Trujillo Bueno & Landi Degl'Innocenti 1997; Manso Sainz & Trujillo Bueno 2003a).

Since the transfer equation for Stokes I is[1]

$$\frac{d}{ds}\,I = (\epsilon_I - \eta_Q Q) - \eta_I I \approx \epsilon_I - \eta_I I\ , \tag{4}$$

[1]The approximate expression holds because $\eta_Q Q$ is a second-order term.

with $\epsilon_I \approx \epsilon_0 \phi_\nu \rho^0_0(u)$ and $\eta_I \approx \eta_0 \phi_\nu \rho^0_0(l)$ (where $\rho^0_0(i)$ is proportional to the overall population of the level i), it is easy to show that the emergent Q/I signal at the center of a sufficiently strong spectral line, for a line of sight specified by $\mu = \cos\theta$, is approximately given by (Trujillo Bueno 2001):

$$Q/I \approx \frac{3}{2\sqrt{2}}(1-\mu^2)[w^{(2)}_{J_u J_\ell}\,\sigma^2_0(u) - w^{(2)}_{J_l J_u}\,\sigma^2_0(l)]\,, \tag{5}$$

where $\sigma^2_0 = \rho^2_0/\rho^0_0$ quantifies the *fractional atomic alignment* of the upper or lower level of the line.[2] Note that the σ^2_0 values in this last equation are those corresponding to the atmospheric height where the line center optical depth is unity along the line of sight.

The $\sigma^2_0(i)$ values at each spatial point of the model atmosphere have to be calculated by solving the statistical equilibrium equations for the elements of the atomic density matrix (see Chapter 7 of Landi Degl'Innocenti & Landolfi 2004). For the particular case of a two-level atomic model with $J_l = J_u = 1$, it is easy to show that

$$\sigma^2_0(u) \approx \frac{-1}{2(1+\delta_u)}\left[\frac{\bar{J}^2_0}{\bar{J}^0_0} + \sigma^2_0(l)\right]\,, \tag{6}$$

$$\sigma^2_0(l) \approx \frac{1}{2(1+\delta_l)}\left[\frac{\bar{J}^2_0}{\bar{J}^0_0} - \sigma^2_0(u)\right]\,, \tag{7}$$

where $\bar{J}^2_0/\bar{J}^0_0$ is the fractional anisotropy of the incident spectral line radiation, while $\delta_u = D^{(2)}_u t_{\rm life}(u)$ and $\delta_l = D^{(2)}_l t_{\rm life}(l)$ are, respectively, the depolarization rates of the upper and lower levels due to elastic collisions with neutral hydrogen atoms, multiplied by the levels' radiative lifetimes. For a two-level atomic model, $t_{\rm life}(u) \approx 1/A_{ul}$, where A_{ul} is the Einstein coefficient for spontaneous emission, while $t_{\rm life}(l) \approx 1/B_{lu}\bar{J}^0_0$, where B_{lu} is the Einstein coefficient for absorption and $\bar{J}^0_0$ is the average over frequencies (weighted by the line's absorption profile) and directions of the Stokes I parameter. In the solar atmosphere $A_{ul} \gg B_{lu}\bar{J}^0_0$ and $D^{(2)}_u \sim D^{(2)}_l$; therefore, δ_l can be much larger than δ_u.

2.2. The metalevel density matrix theory for completely correlated scattering

In reality, the phenomenon of scattering polarization in a spectral line is intrinsically a 2nd-order process, where frequency correlations between the incoming and outgoing photons can occur. A convenient theory to treat the limit of completely correlated (or coherent) scattering in the atomic rest frame was proposed by Landi Degl'Innocenti et al. (1997), based on the semi-classical picture of metalevels (i.e., each level is viewed as a continuous distribution of sublevels). In the coherent scattering limit elastic collisions do not cause a transition to a sublevel different to the one the atom was excited, so the atom de-excites from the same sublevel where the previous transition ended. This theory, which initially accounted for radiative processes only, was later extended by including the possibility of excitations and de-excitations caused by inelastic collisions with electrons (see Belluzzi et al. 2013, 2015a).

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[2]For example, $\rho^0_0(J=1) = (N_1 + N_0 + N_{-1})/\sqrt{3}$ and $\rho^2_0(J=1) = (N_1 - 2N_0 + N_{-1})/\sqrt{6}$, where N_1, N_0 and N_{-1} are the populations of the magnetic sublevels of a level with $J = 1$.

There are several diagnostically important resonance lines which result from transitions between the levels of the ground term (e.g., the ground level $^2S_{1/2}$) and the levels of the first excited term (e.g., the excited levels $^2P_{1/2}$ and $^2P_{3/2}$), without any other levels between them. Examples are the Na I D_2 (5890 Å) and D_1 (5896 Å) lines (whose line-core radiation originates in the lower chromosphere) and the Mg II *h* & *k* lines around 2800 Å (whose line-core radiation encodes information on the upper chromosphere, just below the chromosphere-corona transition region). A two-term atomic model with unpolarized and infinitely sharp lower level is suitable for investigating the scattering polarization in these resonance lines.

A convenient way to describe the transfer of resonance line polarization with partial frequency redistribution (PRD) and *J*-state interference (i.e., quantum interference between magnetic sublevels pertaining to different fine structure *J*-levels within the same term) is through the redistribution matrix formalism. The most general form of the redistribution matrix for a two-term atom with infinitely sharp lower levels is given by a linear combination of a $R_{\rm II}$ matrix, which describes the above-mentioned limit of completely correlated (or coherent) scattering in the atomic rest frame, and a $R_{\rm III}$ matrix, which describes the limit of completely uncorrelated scattering (complete frequency redistribution, CRD) in the atomic rest frame. Starting from the expression obtained by Landi Degl'Innocenti et al. (1997) in the atomic rest frame, Belluzzi & Trujillo Bueno (2012) derived the laboratory frame expression of $R_{\rm II}$, which allows to take into account the effect of Doppler redistribution assuming Maxwellian velocity distributions. Belluzzi & Trujillo Bueno (2014) have also proposed an approximate expression for $R_{\rm III}$ for estimating its impact on the wings of the line. Moreover, they have shown that the same approach can be applied to describe the case of a two-level model atom with hyperfine structure (HFS). Belluzzi et al. (2015b) applied the metalevel approach to treat the more complicated case of a two-term atom with HFS, accounting for quantum interference even between the *F*-levels pertaining to the two different upper *J*-levels.

2.3. Other PRD theoretical approaches

A consistent set of PRD equations (master equation for the atomic density matrix and the corresponding radiative transfer coefficients) was derived by Bommier (1997a) for the unmagnetized case, assuming a two-level model atom without lower-level polarization. To this end, she carried out a quantum-electrodynamics perturbative development, extended to orders higher than two, of the atom-photon interaction. In a subsequent paper, Bommier (1997b) extended this theory to the case of arbitrary magnetic fields. Recently, Alsina Ballester et al. (2017) have developed a radiative transfer code based on such density-matrix equations, the application of which has led to some interesting results for the Mg II *k* line (Alsina Ballester et al. 2016), for the Ca I 4227 Å line (Alsina Ballester et al. 2018) and for the hydrogen Ly-α line (Alsina Ballester et al. 2019a).

More recently, the above-mentioned approach has been formulated for the case of a multilevel model atom (see Bommier 2016), including the detailed expressions of the redistribution matrices for the case of a two-term model atom with unpolarized and infinitely sharp lower levels (Bommier 2017, 2018).

Applying a diagrammatic treatment of the atom-photon interaction, Casini et al. (2014) derived the redistribution matrix for the above-mentioned two-term model atom case in the collisionless regime, for arbitrary magnetic fields. This approach was later extended by Casini & Manso Sainz (2016a) for the more general case of a three-term

model atom of the Λ-type in the collisionless regime (see also Casini & Manso Sainz 2016b), while Casini et al. (2017) proposed physically meaningful branching ratios between the CRD and PRD contributions to the emissivity of a polarized multi-term atom in the presence of both inelastic and elastic collisions. Recently, del Pino Alemán et al. (2016) have developed a radiative transfer code based on such equations, the application of which has led to some interesting results for the Mg II *h* & *k* lines.

Finally, the Kramers-Heisenberg formula has been applied to derive redistribution matrix expressions for the case of a two-term model atom with unpolarized and infinitely sharp lower levels (e.g., Smitha et al. 2013a; Sowmya et al. 2014). For the unmagnetized and collisionless case, the ensuing $R_{\rm II}$ matrix agrees with that derived by Belluzzi & Trujillo Bueno (2014) applying the metalevel theory mentioned in Sect. 2.2, which agrees also with those derived by Casini et al. (2014) and Bommier (2018).

3. SPW-1: 1995



Figure 1. Photograph taken during the SPW-1 in St. Petersburg (Russia). From left to right: Javier Trujillo Bueno, Egidio Landi Degl'Innocenti, Nadine Landi Degl'Innocenti (Egidio's wife), Marco Landolfi, Gianna Landolfi (Marco's wife), and José Carlos del Toro Iniesta.

In his SPW-1 talk, Jan Stenflo showed observations of the wavelength variation of the Stokes Q/I pattern across the Na I D_1 and D_2 lines, obtained with the Zurich Imaging Polarimeter (ZIMPOL) in quiet regions close to the solar limb (solid curve of Fig. 2a; see also Stenflo & Keller 1997). In particular, he noted that the signal observed around the D_1 line center was a surprise because the D_1 line levels have total angular momentum $J = 1/2$, and therefore the line should in principle be intrinsically unpolarizable. During his talk Jan asked Egidio if he had any idea about the possible physical origin of the enigmatic linear polarization signal observed in the D_1 line, a question to which Egidio replied negatively.

During the coffee break Egidio and I commented the interesting spectropolarimetric observations that Jan had just shown in his SPW-1 talk. In our conversations, Egidio

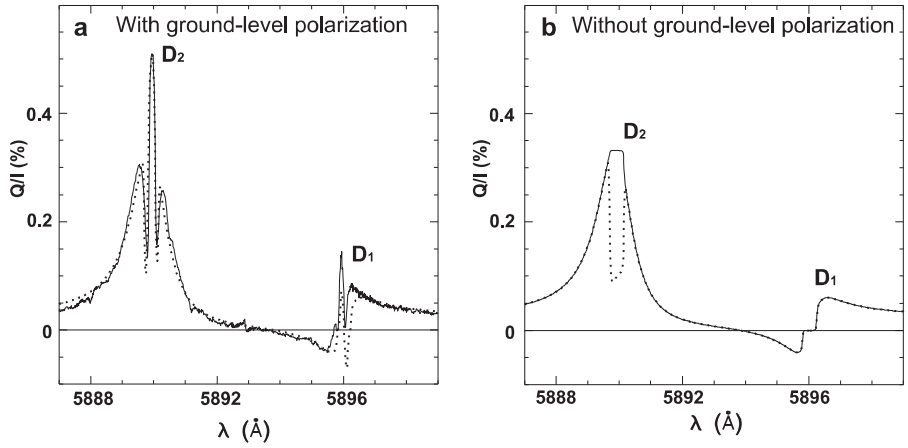


Figure 2. The solid line of panel **(a)** shows the Q/I observed by Stenflo & Keller (1997) at $\mu = 0.05$. The dotted line is the parameterized fit of Landi Degl'Innocenti (1998, 1999) accounting for HFS and assuming $\sigma^2_0(F_l = 1) = 0.0125$ and $\sigma^2_0(F_l = 2) = 0.0238$ at the top of the solar atmosphere. The dotted line of panel **(b)** shows the calculated Q/I when the ground-level is assumed to be unpolarized, while the solid line indicates the emergent Q/I when in addition the HFS of sodium is neglected. From Landi Degl'Innocenti (1998).

remembered me that the theory of spectral line polarization described in the book of Stenflo (1994) is based on the assumption that the lower level of the line transition is unpolarized, while the density matrix theory described in Landi Degl'Innocenti (1983) does not make such assumption. Egidio also told me that nobody had solved yet the non-LTE problem of the generation and transfer of spectral line polarization taking into account the possibility of atomic polarization in the lower level of the line transitions. Both things, the novel observations and the possibility of theoretically investigating previously ignored physical mechanisms within the framework of the density matrix theory of spectral line polarization, immediately attracted my scientific attention. As a result, I decided to investigate the problem of the generation and transfer of spectral line polarization in unmagnetized stellar atmospheres, for an "intrinsically unpolarizable" resonance line having $J_l = 1$ and $J_u = 0$ for the angular momentum of the lower and upper transition levels, respectively. This investigation led to our first paper on optically polarized atoms in stellar atmospheres, the title of which is *Linear Polarization due to Lower-Level Depopulation Pumping in Stellar Atmospheres* (Trujillo Bueno & Landi Degl'Innocenti 1997).

As illustrated in Fig. 3, lower-level depopulation pumping occurs when some lower-state sublevels absorb electromagnetic radiation more strongly than others. As a result, an excess of population tends to build up in the weakly absorbing sublevels. It is also important to note that lower-level atomic polarization can result from repopulation pumping, that is, from the spontaneous decay of a polarized upper level. Obviously, this requires that the angular momentum of the upper level is non-zero.

The high degree of anisotropy of the incident radiation field in the two cases of Fig. 3 is typical of optical pumping experiments in the laboratory. In stellar atmospheres the degree of anisotropy is significantly lower, but more than sufficient to pro-

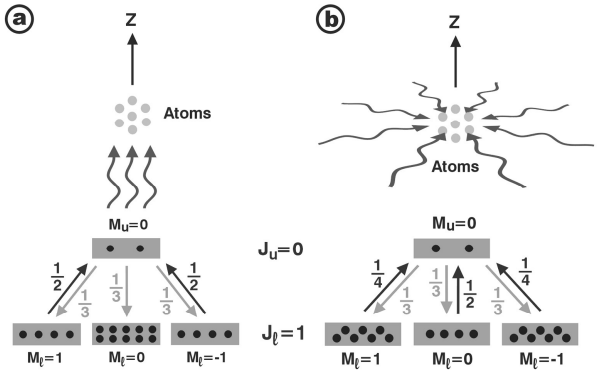


Figure 3. Illustration of the atomic polarization that is induced in the lower level of a two-level atom with $J_l = 1$ and $J_u = 0$ by two types of anisotropic illuminations (**a** and **b**). The incident radiation field is assumed to be unpolarized and with axial symmetry around the vertical direction, which is our choice here for the quantization axis of total angular momentum. In both cases, an excess population tends to build up in the weakly absorbing sublevels. Note that the alignment coefficient of the lower level (i.e., $\rho^2_0 = (N_1 - 2N_0 + N_{-1})/\sqrt{6}$, N_i being the populations of the magnetic sublevels) is *negative* in case (**a**) (where the incident beam is *parallel* to the quantization axis), but *positive* in case (**b**) (where the incident beams are *perpendicular* to the quantization axis).

duce measurable scattering polarization signals all over the solar spectrum (see the atlas of Gandorfer 2000, 2002, 2005).

The upper level of spectral lines with $J_u = 0$ or $J_u = 1/2$ cannot carry atomic alignment. Consequently, when the magnetic field is so weak that the linear polarization caused by the Zeeman effect is negligible, the photons resulting from radiative transitions from the upper to the lower level are unpolarized (i.e., the emissivities in Stokes Q and U are zero). How can we then have linearly polarized radiation in spectral lines like the blue component of the He I 10830 Å triplet ($J_u = 0$) and the Ca II 8662 Å line ($J_u = 1/2$)? The answer to this question is contained in the radiative transfer equation for Stokes Q (see Eq. 1). Clearly, even when $\epsilon_Q = 0$ (because $J_u = 0$ or $J_u = 1/2$), we still have $\eta_Q I$ as a source term for Stokes Q (note that $\eta_Q \neq 0$ if $J_l > 1/2$). Therefore, the linear polarization in such spectral lines is caused by selective absorption of polarization components (see Trujillo Bueno & Landi Degl'Innocenti 1997; Trujillo Bueno 1999; Trujillo Bueno et al. 2002b; Manso Sainz & Trujillo Bueno 2003a).

There are many solar spectral lines whose scattering polarization is dominated by the differential absorption of polarization components (zero-field dichroism), caused by the presence of atomic polarization in their lower level. Remarkable examples are the Mg I *b*-lines (Trujillo Bueno 1999, 2001, 2009), the blue component of the He I 10830 Å triplet (Trujillo Bueno et al. 2002b), the IR triplet of Ca II (Manso Sainz & Trujillo Bueno 2003a, 2010) and the IR triplet of O I around 7774 Å (del Pino Alemán & Trujillo Bueno 2015, 2017). The lower levels of all these spectral lines are metastable (i.e., long lived). Therefore, their atomic polarization is especially vulnerable to elastic collisions with neutral hydrogen atoms. In particular, total depolarization of such lower levels occurs if $\delta_J = D^{(2)}_J t_{\rm life}(J) \approx D^{(2)}_J/(B_{lu}\bar{J}^0_0) >> 1$ (see end of Sect. 2.1).

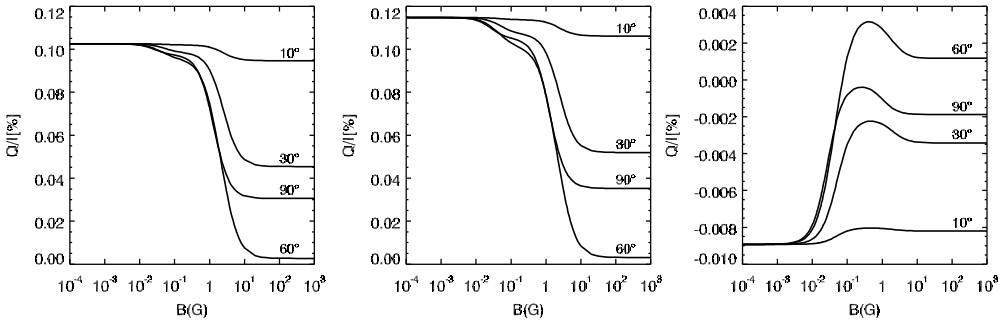


Figure 4. The Q/I line-center amplitudes of the IR triplet of O I around 7774 Å versus the strength of a magnetic field with random azimuth and the indicated fixed inclination with respect to the local vertical, calculated in the FAL-C semi-empirical model of the solar atmosphere for a line of sight with $\mu = 0.1$. Note that there is sensitivity also to sub-gauss magnetic strengths. Line 1 is the shortest wavelength transition of the triplet, while line 3 is the longest wavelength one. The positive reference direction for Stokes Q is the parallel to the nearest limb. From del Pino Alemán & Trujillo Bueno (2017).

Of all the above mentioned spectral lines, perhaps the most remarkable example is the O I IR triplet, because, in the atmospheric region where the line-center optical depth is unity along the LOS (the solar photosphere), its common lower level, with $J_l = 2$, is completely depolarized by elastic collisions with neutral hydrogen atoms. Then, how can it be possible that the on-disk linear polarization observed by Trujillo Bueno et al. (2001) in this triplet is dominated by the atomic polarization of its lower level? The answer is that the observed polarization is due to zero-field dichroism (selective absorption) produced by the lower-level polarization that survives in the solar chromosphere, an atmospheric region where the hydrogen number density is insufficient to have $\delta_{J_l} >> 1$ (del Pino Alemán & Trujillo Bueno 2015). For this reason, the title of the just quoted paper is *Chromospheric Polarization in the Photospheric Oxygen IR Triplet*. Figure 4 illustrates how the magnetic sensitivity to the lower-level and upper level Hanle effects, due to the presence of a random-azimuth magnetic field in the semi-empirical model C of Fontenla et al. (1993) (hereafter, FAL-C model), behaves for various inclinations of the assumed magnetic field.

4. SPW-2: 1995–1998

As mentioned above, the solid curve of Fig. 2a shows the enigmatic scattering polarization pattern observed by Stenflo & Keller (1997) across the Na I D-lines. In his letter in the journal Nature, Landi Degl'Innocenti (1998) pointed out that for modeling the scattering polarization of the Na I D-lines it is necessary to take into account the HFS of sodium. In his investigation, Egidio considered the unmagnetized case and applied the metalevel theory (see Sect. 2.2) assuming that, within the frequency interval spanned by the HFS components of each D-line, the anisotropy of the pumping radiation field is constant (i.e., independent of the frequency of the pumping radiation). Based on this assumption, he showed that it was possible to explain the observed scattering polariza-



Figure 5. Photograph taken in Santiago de Chile in January 2001 during the workhop on Magnetic Fields Across the Hertzsprung-Russell Diagram. From left to right: Javier Trujillo Bueno, Olga del Río (Javier's wife), Egidio Landi Degl'Innocenti and Nadine Landi Degl'Innocenti.

tion *only* if there were a substantial amount of atomic polarization in the HFS sublevels of the ground level of Na I (see the dotted lines in the left panel of Fig. 2a). The ground level of Na I is long-lived and, therefore, very sensitive to depolarizing mechanisms, such as the Hanle effect of very weak fields (see Trujillo Bueno et al. 2002a). Given the substantial amount of ground level polarization needed to fit the Q/I observation, Landi Degl'Innocenti (1998) thus concluded that the observed D_1 signal should imply that inclined magnetic fields stronger than 0.01 G should not exist in the lower solar chromosphere. He also pointed out that this was difficult to understand because there is evidence from other type of observations that the lower chromosphere is significantly more magnetized. This led to the so-called "sodium D_1 line paradox."

In order to resolve this paradox, we need a mechanism capable of introducing atomic polarization in the (short lived) upper F-levels of the D_1 line *without* the need of ground-level polarization. Belluzzi & Trujillo Bueno (2013) have identified such a mechanism by demonstrating that the small variations of the pumping D_1 line radiation across its very close HFS components is actually able to create a significant amount of atomic polarization in the upper F-levels of the D_1 lines of Ba II and Na I. To this end, their first step within the framework of the metalevel theory outlined in Sect. 2.2 consisted in assuming a two-level model atom with HFS, with unpolarized and infinitely sharp lower levels. Recently, Belluzzi et al. (2015b) have extended this work by including the quantum interference between the F-levels pertaining to the two upper J-levels of the sodium doublet. As illustrated in Fig. 6, the resulting Q/I pattern is very similar to new high-sensitivity spectropolarimetric observations of the Na I D_1 line obtained using the Zurich Imaging Polarimeter (ZIMPOL) at the Gregory Coudé Telescope of IRSOL (Locarno; Switzerland). Our next theoretical step is to model the polarization of the sodium doublet in the presence of arbitrary magnetic fields, taking into account the joint action of the Hanle and Zeeman effects while accounting for the effects of PRD and F-state interference.

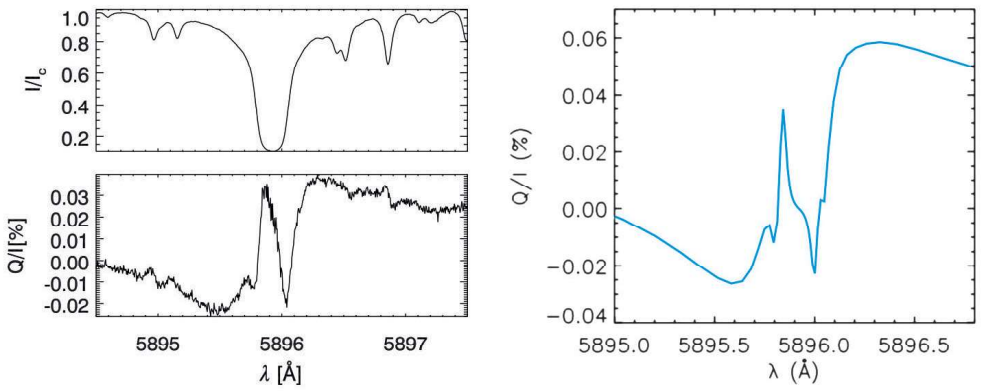


Figure 6. The Q/I scattering polarization pattern around the Na I D_1 line. Left: spectropolarimetric observation taken in close collaboration with M. Bianda et al. using ZIMPOL at IRSOL (more observations in Bianda et al. 2019). Right: the theoretical Q/I profile obtained by Belluzzi et al. (2015b) in the M_{CO} model of Avrett (1995), without the need of any ground-level polarization. The amplitude of the calculated Q/I line-core signal is sensitive to the thermal structure of the solar atmosphere, being larger for cooler chromospheric models. The reference direction for Stokes Q is the parallel to the nearest limb.

5. SPW-3: 1998–2002

One of the interesting features of the Second Solar Spectrum is that diatomic molecules like MgH and C_2 show conspicuous linear polarization signals when observing quiet regions close to the solar limb (Stenflo & Keller 1997; Gandorfer 2000). The fact that their amplitudes appear to be independent of the solar magnetic activity cycle was regarded as an enigma without a clear solution at hand. This observational result seems to be confirmed by more recent measurements (Kleint et al. 2010, 2011).

Berdyugina et al. (2002) claimed that the explanation of such surprising observational result is that the molecular lines that show measurable polarization amplitudes are “immune" to the Hanle effect, because their Landé factors (g) are very small compared to those of atomic lines. However, during the 3rd Solar Polarization Workshop (SPW-3) Landi Degl’Innocenti (2003) pointed out that there is no particular reason, from the point of view of atomic physics, that may substantiate this statement because one must take into account that the radiative lifetimes ($t_{\rm life}$) of molecular levels are generally longer than those of atomic lines (see also Trujillo Bueno 2003b). Therefore, the critical magnetic field for the onset of the Hanle effect turns out to be similar for atomic and molecular lines, and solar spectral lines of C_2, MgH and CN are indeed sensitive to the Hanle effect (see Trujillo Bueno 2003b; Asensio Ramos & Trujillo Bueno 2003; Faurobert & Arnaud 2003; Berdyugina & Fluri 2004; Trujillo Bueno et al. 2004; Asensio Ramos & Trujillo Bueno 2005; Kleint et al. 2010; Shapiro et al. 2011; Kleint et al. 2011). For a very detailed review on investigations of the quiet Sun magnetism based on the Hanle effect in the C_2 lines of the Swan system, see Sect. 6 of Trujillo Bueno et al. (2006).

Some other results that were reported at the SPW-3 are the following:



Figure 7. Photograph taken during the SPW-3, which took place in Tenerife in October 2002. From left to right: Roberto Casini, Egidio Landi Degl'Innocenti, Javier Trujillo Bueno, Stefano Bagnulo, Marco Landolfi and Rafael Manso Sainz.

- Manso Sainz & Landi Degl'Innocenti (2002) presented the first theoretical investigation on scattering polarization in a complex atom, aimed at qualitatively understanding the linear polarization signals observed in Ti I lines. Later, this work led to proposing a novel Hanle effect line-ratio technique for detecting the presence of unresolved magnetic fields in quiet regions of the solar photosphere (Manso Sainz et al. 2004).

- Gandorfer showed observations of the Second Solar Spectrum in the ultraviolet, between 3160 Å and 3915 Å (Gandorfer 2003, 2005).

- Asensio Ramos & Trujillo Bueno (2003) theoretically modelled and explained the regular pattern of the Q/I scattering polarization peaks produced by CN molecular lines in the violet band, which had been observed with ZIMPOL (see Fig. 6 of Gandorfer 2003).

- Another SPW-3 highlight was the application of pattern recognition techniques to the inversion of Stokes profiles produced by scattering processes and the Hanle and Zeeman effects in solar prominences (see Casini & López Ariste 2003; López Ariste & Casini 2002).

- Kerkeni & Bommier (2002) discussed their theoretical investigation about the impact of elastic collisions with neutral hydrogen atoms on the ground-level polarization of Na I, claiming that it is completely depolarized in the region of formation of the core of the D_1 and D_2 lines.

- Manso Sainz & Trujillo Bueno (2003b) presented the first multilevel radiative transfer code for modeling the Second Solar Spectrum through the numerical

solution of the so-called non-LTE problem of the second kind (see Chapter 7 of Landi Degl'Innocenti & Landolfi 2004).

Figure 8 shows an example of the type of investigations that can be carried out with the radiative transfer code of Manso Sainz & Trujillo Bueno (2003b). It shows the forward scattering (LOS with $\mu = 1$) polarization of the K line of Ca II produced by the Hanle effect of horizontal magnetic fields in the FAL-C semi-empirical model. Interestingly, the shape and sign of the emergent Q/I profile corresponding to a calculation with a 5-level model atom that accounts for the H and K lines and the IR triplet (left panel) turns out to be radically different from that corresponding to a calculation with a 2-level atom that includes only the K resonance line. This demonstrates that the atomic polarization of the metastable levels, which must be taken into account to explain the scattering polarization observed in the Ca II IR triplet (Manso Sainz & Trujillo Bueno 2003a), has an important impact on the atomic polarization of the upper level of the K line. Remarkably, because the atomic polarization of the upper level of the K line is sensitive to the atomic polarization of the long-lived metastable levels, the line-center polarization of the Ca II K line is sensitive not only to magnetic fields in the gauss range through the Hanle effect of the upper level, but also to milligauss fields because of the Hanle effect in the metastable levels.

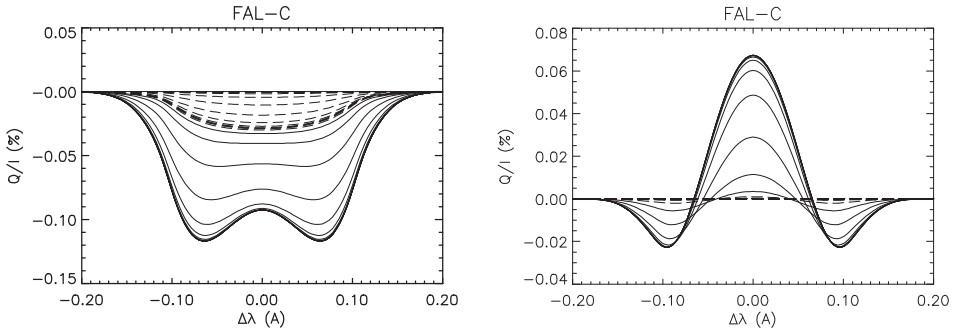


Figure 8. The forward-scattering Q/I profile of the K line of Ca II calculated for increasing values of the strength of a horizontal magnetic field in the FAL-C semi-empirical model, with dashed curves for $B < 0.3$ G and solid curves for $B > 0.3$ G. Left panel: taking into account the atomic polarization of the metastable levels. Right panel: without the metastable levels. This figure results from the radiative transfer calculations described in Manso Sainz & Trujillo Bueno (2010).

6. SPW-4: 2002–2005

Some of the SPW-4 contributions related with optically polarized atoms in the solar atmosphere were the following:

- Stenflo (2006) showed ZIMPOL observations of the linear polarization pattern produced by scattering processes in the K line of Ca II at 3933 Å, including results for quiet-Sun regions at disk center (see the right panel of his Fig. 4). It would be interesting to contrast forward scattering observations with the theoretical profiles resulting from detailed radiative transfer calculations, after rotating



Figure 9. Photograph taken in Florence (Italy) in 2004. From left to right: Javier Trujillo Bueno, Andrés Asensio Ramos, Egidio Landi Degl'Innocenti, Nadine Landi Degl'Innocenti, Gianna Landolfi and Marco Landolfi.

the reference system to minimize the U/I observed signal. For more information on scattering polarization observations of the Ca II K line see Holzreuter & Stenflo (2007).

- The PRD origin of the triplet peak structure of the Q/I profile of strong resonance lines, such as Na I D_2, Ca I 4227 Å and Ca II K, was emphasized by Fluri et al. (2006). Details can be found in Holzreuter et al. (2005, 2006).

- The polarization properties of hydrogen lines in the presence of simultaneous electric and magnetic fields were discussed by Casini & Manso Sainz (2006a). More details can be found in Casini (2005) and Casini & Manso Sainz (2006b, 2008). In particular, these authors pointed out that the presence of electric microfields can significantly enhance the amount of net circular polarization (NCP) of the H_α line for weak magnetic fields, because of the alignment-to-orientation transfer mechanism (see Sect. 10.20 of Landi Degl'Innocenti & Landolfi 2004) between electric-coupled atomic levels, even if the electric microfield distribution is isotropic. They argued that this mechanism could explain the large levels of NCP in Hα found by López Ariste et al. (2005) in solar prominences observed with THÉMIS, a result that could not be confirmed by prominence observations with the ZIMPOL polarimeter (Ramelli et al. 2006b).

- Belluzzi et al. (2006) carried out a careful theoretical investigation of the magnetic sensitivity of the linear and circular polarizations of the Ba II D_2 line at 4554 Å caused by the joint action of scattering processes and the Hanle and Zeeman effects (see details in Belluzzi et al. 2007). They took into account that two of the seven stable isotopes of barium, with a relative abundance of about 18%, have HFS due to their nuclear spin $I = 3/2$. Given the complexity of the problem, the authors assumed CRD and considered an optically thin slab of Ba II ions anisotropically illuminated by the photospheric continuum. The effects of PRD and radiative transfer in semi-empirical models of the solar atmosphere

have been investigated by some authors (see Smitha et al. 2013b, and more references therein). Both effects are key for understanding the peculiar triple-peak structure of the Q/I profile, but they were investigated ignoring the atomic polarization of the (metastable) $5d^2D_{3/2}$ and $5d^2D_{5/2}$ levels. Interestingly, the atomic polarization of such metastable levels has a very significant impact on the scattering polarization amplitude of the Ba II D_2 line, as demonstrated by del Pino Alemán (2015) within the framework of the multilevel CRD theory of spectral line polarization described in Landi Degl'Innocenti & Landolfi (2004). Therefore, a rigorous radiative transfer modeling of the scattering polarization in the Ba II D_2 line requires taking into account the effects of PRD in at least a 5-level atomic model, accounting for the HFS of the odd isotopes of barium and for the atomic polarization of all the atomic levels.

- Novel spectropolarimetric observations of spicules in the He I D_3 multiplet were reported by Ramelli et al. (2006a). Observations of filaments in H_α and in the D_3 multiplet were shown by Bianda et al. (2006), highlighting that with sufficiently long exposures we can measure the Stokes profiles of He I D_3 in filaments seen against the bright solar disk. Ramelli et al. (2006b) showed observations of prominences in the He I D_3 multiplet, as well as in H_α and H_β.

- In a very important paper, Landi Degl'Innocenti (2006) presented the theory of resonance scattering in molecular bands for the general case where both the lower and upper electronic state of the molecule are described in the intermediate coupling scheme between Hund's cases (a) and (b). A more detailed report can be found in Landi Degl'Innocenti (2007), where he provided approximate expressions for the scattering polarization observed at the solar limb in weak molecular lines and its modification due to the Hanle effect.

- The theory and modeling of the Zeeman and Paschen-Back effects in molecular lines was discussed by Asensio Ramos (2006) and by Berdyugina et al. (2006). Methods to calculate the Zeeman splitting effect produced by an external magnetic field on the rotational levels of diatomic molecules can be found in Berdyugina et al. (2005) and Asensio Ramos & Trujillo Bueno (2006).

- Trujillo Bueno et al. (2006) provided a very detailed review on the "Sun's hidden magnetism," that is, the magnetism of quiet regions of the solar photosphere that look "empty" in solar magnetograms. In particular, they showed how a joint analysis of the Hanle effect in atomic and molecular lines indicates that there is a vast amount of hidden magnetic energy and unsigned magnetic flux localized in the intergranular (dowflowing) regions of the quiet photosphere, carried mainly by tangled fields at sub-resolution scales with strengths between the equipartition field values and ~ 1 kG.

Regarding this last topic, it is of interest to mention that recent magneto-convection simulations with small-scale dynamo action have provided three-dimensional (3D) models of the quiet solar photosphere characterized by a high degree of small-scale magnetic activity (see Rempel 2014), similar to that found by Trujillo Bueno et al. (2004) through theoretical interpretation of the scattering polarization observed in the Sr I 4607 Å resonance line. Recently, del Pino Alemán et al. (2018) presented the results of

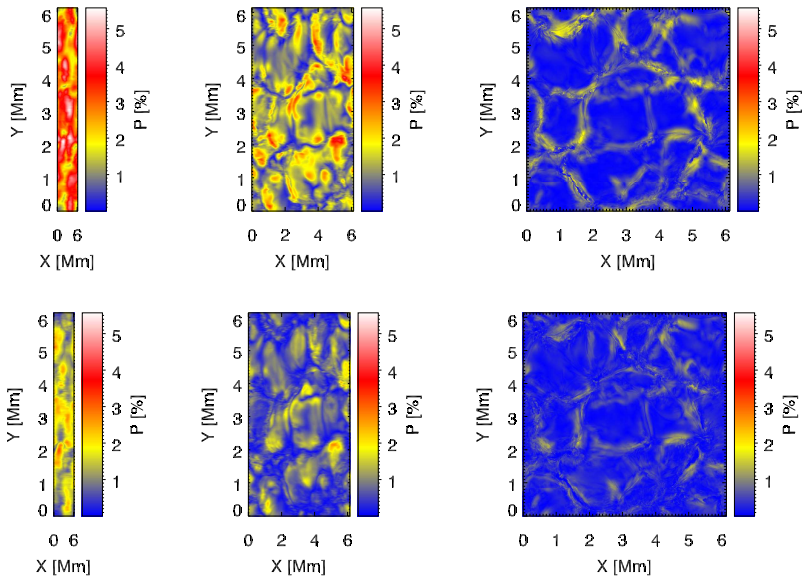


Figure 10. Fractional total linear polarization amplitude (P) for lines of sight with $\mu = 0.1$ (left column), $\mu = 0.5$ (middle column), and $\mu = 1$ (right column), neglecting (top row) or taking into account (bottom row) the Hanle effect due to the small-scale magnetic field of a 3D photospheric model whose surface mean field strength is 170 G. From del Pino Alemán et al. (2018).

a new investigation of the linear polarization produced by anisotropic radiation pumping and the Hanle effect in the Sr I 4607 Å line, based on 3D radiative transfer calculations in a high-resolution (8 km grid spacing) magneto-convection model obtained by Rempel (2014), which has most of the convection zone magnetized close to the equipartition and a surface mean field strength $\langle B \rangle$=170 G. They found that the calculated linear polarization signals are very significant and show small-scale spatial variations (see Fig. 10), even in the forward scattering geometry of a disk center observation, but that their detection would require observing with very high spectral, spatial and temporal resolution (see also Trujillo Bueno & Shchukina 2007; Trujillo Bueno 2011). The small-scale spatial variations are due to the breaking of the axial symmetry of the pumping radiation field at each point within the 3D model photosphere, caused by the horizontal thermal and density inhomogeneities and by the spatial gradients of the *horizontal* components of the macroscopic velocity (see Fig. 11 of del Pino Alemán et al. 2018).[3] Via the Hanle effect the model's magnetic field reduces the amplitude of the linear polarization signals, but the patterns themselves of the Q/I and U/I horizontal spatial variations remain unaltered. As can be seen by comparing the upper and lower panels of the figure, such a Hanle depolarization is very significant, to the extent that the

[3]Via the Doppler effect the spatial gradients of the model's macroscopic velocity can have a significant impact on the scattering polarization profiles. While the *vertical* velocity gradients can enhance the polarization amplitudes and produce asymmetric profiles (Carlin et al. 2012), the *horizontal* velocity gradients break the axial symmetry of the pumping radiation field (Štěpán & Trujillo Bueno 2016).

center-to-limb variation (CLV) of the calculated spatially-averaged $\langle Q\rangle/\langle I\rangle$ line-center amplitudes is compatible with the observed CLV.

7. SPW-5: 2005–2007



Figure 11. Photograph taken in 2007 in Ascona (Switzerland) during the SPW-5.

One of the interesting observational results on scattering polarization highlighted at the SPW-5 was that, in some solar-disk regions close to the solar limb, the Ca I resonance line at 4227 Å shows Q/I profiles with spatially varying signals in their wings and, surprisingly, with sizable U/I wing signals (Bianda et al. 2006, see also Bianda et al. 2003). This came as a surprise because the theory of the Hanle effect predicts that magnetic fields affect the scattering polarization only in the core of the spectral line, while the wings should remain unaffected (e.g., Landi Degl'Innocenti & Landolfi 2004). Other spectropolarimetric investigations confirmed such Q/I and U/I wing signals and discarded the possibility that elastic collisions could allow the Hanle effect to operate outside the core of the Ca I 4227 Å line (Sampoorna et al. 2009).

Recently, Alsina Ballester et al. (2018) have provided a possible explanation of such surprising linear polarization signals observed in the wings of the Ca I 4227 Å line (see also Alsina Ballester et al. 2019b), the lower level of which cannot be polarized. The radiative transfer equations for Stokes Q and U are the following:

$$\frac{\mathrm{d}Q}{\mathrm{d}s} = \epsilon_Q - \eta_Q\, I - \rho_V\, U + \rho_U\, V - \eta_I\, Q \approx (\epsilon_Q - \rho_V\, U) - \eta_I\, Q\,, \tag{8}$$

$$\frac{\mathrm{d}U}{\mathrm{d}s} = \epsilon_U - \eta_U\, I + \rho_V\, Q - \rho_Q\, V - \eta_I\, U \approx (\epsilon_U + \rho_V\, Q) - \eta_I\, U\,. \tag{9}$$

In strong resonance lines the effects of PRD produce sizable amplitudes in the wings of Q/I. On the other hand, while η_Q/η_I, ρ_Q/η_I, and ρ_U/η_I are negligible for magnetic

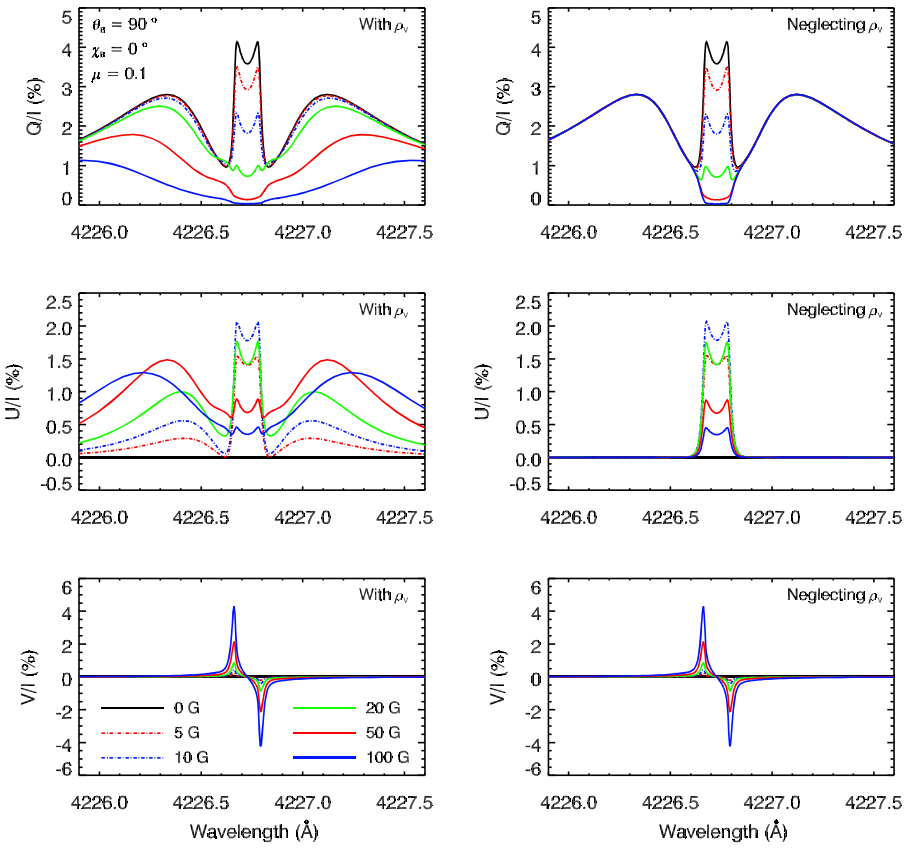


Figure 12. Emergent Q/I (top), U/I (middle) and V/I (bottom) of the Ca I 4227 Å resonance line calculated in the FAL-C semi-empirical atmospheric model for an LOS with $\mu = 0.1$, (left) considering all terms of the propagation matrix and (right) neglecting the ρ_V terms when solving the radiative transfer (RT) equation. The magnetic field is horizontal ($\theta_B = 90°$) and contained in the plane defined by the local vertical and the LOS (i.e., $\chi_B = 0°$), with the field strengths indicated in the bottom left panel. The reference direction for positive Q is taken parallel to the limb. From Alsina Ballester et al. (2018).

strengths of the order of 100 G and weaker, ρ_V/η_I has sizable values outside the line-core frequencies. Therefore, the second-order terms $\rho_V\, U$ and $\rho_V\, Q$ of such transfer equations for Stokes Q and U cannot be neglected (see also Alsina Ballester et al. 2016; Manso Sainz et al. 2019). The $\rho_V\, Q$ term of the transfer equation for Stokes U produces sizable U/I wing signals, already for magnetic fields as weak as 5 G. Likewise, the $\rho_V\, U$ term of the transfer equation for Stokes Q modifies the Q/I wing signals produced by the PRD effects, depending on the strength and orientation of the magnetic field (see Fig. 12). Very likely, these magneto-optical terms of the transfer equations for Stokes Q and U are the physical origin of the enigmatic Q/I and U/I wing signals observed in the Ca I 4227 Å resonance line. Based on this mechanism, the same type of signals along with their magnetic sensitivity have been predicted for the following lines: Mg II k (Alsina Ballester et al. 2016), Mg II h & k (del Pino Alemán et al. 2016; Manso Sainz

et al. 2019), Sr II 4078 Å (Alsina Ballester et al. 2017), and Ly-α (Alsina Ballester et al. 2019a).

There were many other scattering polarizations results discussed during the SPW-5. The following are a few highlights.

- Stenflo (2009) showed observations with ZIMPOL of the scattering polarization in spectral lines of the rare earths, such as yttrium, europium, neodymium, palladium, rutenium, and holmium.

- Ramelli et al. (2009) highlighted very interesting observations of the polarization produced by scattering processes and the Hanle and Zeeman effects in the Ba II D_2 resonance line.

- Belluzzi et al. (2009a) presented their theoretical modeling of the linear polarization produced by scattering processes in the Li I 6708 Å doublet (see also Belluzzi et al. 2009b), pointing out that the three-peak Q/I profile observed by Stenflo & Keller (1997) cannot be explained in terms of quantum-mechanical interference between the F-levels pertaining to the two upper J-levels. Belluzzi et al. (2009b) obtained a two-peak Q/I profile, due to the D_2 lines of ^{7}Li I and ^{6}Li I, which shows an interesting sensitivity to the relative isotopic abundance and to the Hanle effect of unresolved magnetic fields. Interestingly, such theoretical two-peak Q/I profile is obtained only when assuming unrealistically low temperatures in the line formation region. For this reason, Belluzzi et al. (2009b) pointed out that, from the theoretical point of view, the Q/I profile that the Sun is expected to produce is a one peak Q/I profile dominated by the D_2 peak of ^{7}Li I. Much more accurate observations with ZIMPOL at IRSOL (by M. Bianda et al.) and at THÉMIS (by J. Stenflo et al.) showed that this is actually the case.

- Asensio Ramos & Trujillo Bueno (2009) introduced their HAZEL code for the synthesis and inversion of Stokes profiles caused by the joint action of scattering processes and the Hanle and Zeeman effects in the 10830 Å and D_3 multiplets of He I (see full details in Asensio Ramos et al. 2008; see also Trujillo Bueno & Asensio Ramos 2007). The recent paper by Schad (2018) is another example of the interesting science that can be done applying HAZEL.

- Shapiro et al. (2009) discussed how to model the scattering polarization observed in CN lines to infer information on unresolved magnetic fields in the quiet solar photosphere (see also Shapiro et al. 2011).

- A SPW-5 talk that was remembered as "the vision" by several participants was that delivered by R. Manso Sainz, who showed that there exists a hitherto unknown mechanism that introduces scattering polarization in some extreme ultraviolet (EUV) permitted lines of the solar corona, such as that of Fe X at 174.5 Å, in spite of the fact that their upper levels are excited by isotropic inelastic collisions (see Manso Sainz & Trujillo Bueno 2009). The lower level of some EUV lines is also the lower level of a forbidden line at visible or near-IR wavelengths. This lower level can be polarized due to the anisotropic illumination of the coronal ions at the forbidden line wavelength. This lower-level atomic polarization can be partly transferred to the upper level of the permitted EUV line by collisional excitation. Therefore, given that the upper level of the EUV line can

be polarized, we may have scattering polarization signals caused by the spontaneous decay of such polarized upper level. The resulting linear polarization of the EUV line radiation is sensitive to the electron density and to the orientation of the magnetic field in hot coronal loops and arcades.

8. SPW-6: 2007 – 2010



Figure 13. Photograph taken in Maui during the SPW-6. From left to right: Javier Trujillo Bueno, Nadine Landi Degl'Innocenti, Luca Belluzzi and Egidio Landi Degl'Innocenti.

A SPW-6 highlight was that by Kuhn et al. (2011) on observational hints of optical pumping and absorptive linear polarization in embedded stars (see also Harrington & Kuhn 2011). They argued that the anisotropic stellar radiation causes the absorbing material around the obscured star to polarize the transmitted light due to the atomic polarization of the lower level of the observed line transition. This physical mechanism is the selective absorption of polarization components pointed out by Trujillo Bueno & Landi Degl'Innocenti (1997), which explains the linear polarization signals observed in several solar spectral lines, such as the Mg I *b*-lines (Trujillo Bueno 1999, 2001, 2009) and the IR triplet of Ca II (Manso Sainz & Trujillo Bueno 2003a, 2010).

Štěpán & Trujillo Bueno (2010a) investigated the multilevel radiative transfer problem of scattering polarization and the Hanle effect in the solar H_α line, which results from the superposition of 7 transitions between the three fine-structure levels of the $n = 2$ Bohr level and the five fine-structure levels of $n = 3$. It is important to note that, via the Hanle effect, the linear polarization signals at the center of the H_α line are sensitive to the presence of magnetic fields in the upper solar chromosphere (see Fig. 14). Another conclusion was that in semi-empirical models of the solar atmo-

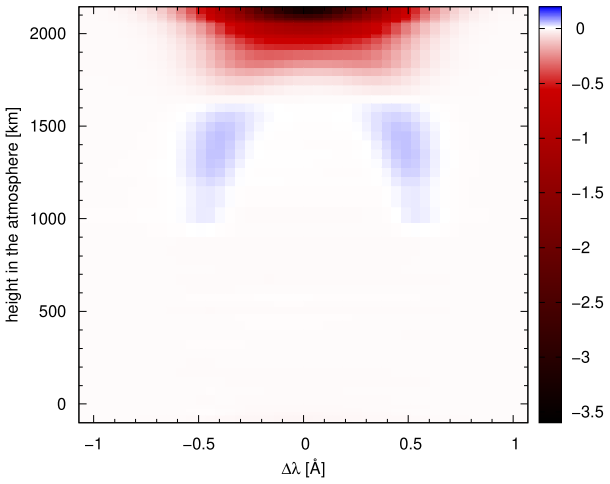


Figure 14. The (non-LTE) response function (RF) of the Q/I profile of the H_α line to small perturbations in the strength of a random-azimuth horizontal magnetic field at each height in the FAL-C model. In this semi-empirical model of the quiet Sun the chromosphere-corona transition region starts at 2200 km. The LOS considered has $\mu = 0.1$. The RF units are 10^{-6} G^{-1} km^{-1}. From Štěpán & Trujillo Bueno (2010b).

sphere the linear polarization of the emergent spectral line radiation is dominated by the atomic polarization of the upper levels, without any significant impact of selective absorption of polarization components. Four of the seven overlapping H_α transitions make a meaningful contribution to the line's scattering polarization. Given that they have significantly different formation heights and critical magnetic strength values for the onset of the Hanle effect, the presence of magnetic field gradients in the upper solar chromosphere can produce a line core asymmetry in the Q/I profile of the emergent radiation (see Štěpán & Trujillo Bueno 2010a). At the SPW-6 Štěpán et al. (2011) presented 1D radiative transfer modeling of new ZIMPOL observations of the H_α scattering polarization, which showed such peculiar line-core asymmetry.

Another set of novel spectropolarimetric observations were shown by Ramelli et al. (2011), concerning the Stokes profiles of the He I D_3 multiplet in prominences and spicules. These authors also reported the strengths and orientations of the magnetic fields that resulted from their application of the HAZEL inversion code.

Manso Sainz (2011) discussed the theory of polarization in complex atoms, which allows to understand the scattering polarization signals observed in lines of Ti I (Manso Sainz & Landi Degl'Innocenti 2002), Ce II (Manso Sainz et al. 2006), and in the 6301.5 Å and 6302.5 Å lines of Fe I (Lites et al. 2010).

Finally, another interesting theoretical work was reported by Landi Degl'Innocenti et al. (2011), who discussed a number of atomic physics phenomena overlooked in laboratory experiments of scattering line polarization, such as the atomic-polarization-induced Faraday pulsation effect and the alignment-to-orientation pulsation effect. The laboratory experiments that have been carried out so far, namely that by Thalmann et al. (2006, 2009) using narrowband excitation of a potassium cell by a tunable laser and the one described in Li et al. (2018) using broadband excitation of a sodium cell by a halogen bulb, were not designed to explore the above-mentioned effects.

9. SPW-7: 2010 – 2013

One of the big challenges of theoretical spectropolarimetry is to formulate a self-consistent set of equations, fully derived from first principles, capable of accounting for the physics of the generation and transfer of spectral line polarization, taking into account the effects of PRD for multilevel systems in the presence of arbitrary magnetic fields. At the SPW-7, Egidio discussed his most recent ideas to solve this problem based on the introduction of the Fourier transform of the density matrix (see Landi Degl'Innocenti & Belluzzi 2014).

Another SPW-7 highlight was the introduction of PORTA, a massively parallel multilevel radiative transfer code for modeling the spectral line polarization caused by scattering processes and the Hanle and Zeeman effects in 3D stellar atmosphere models (see Štěpán & Trujillo Bueno 2013). PORTA solves the 3D multilevel radiative transfer problem of the generation and transfer of polarized radiation assuming that the absorption and emission processes in the scattering events are uncorrelated (CRD limit). For some spectral lines CRD provides a reasonable approximation to estimate the scattering polarization signals at the line center where the Hanle effect operates (e.g., for the Mg II k line see Belluzzi & Trujillo Bueno 2012). The application of PORTA using the MareNostrum supercomputer of the Barcelona Supercomputing Center has allowed us to investigate the Hanle effect in a variety of spectral lines (e.g., Ly-α, Mg II k, Ca I 4227 Å, the IR triplet of Ca II, Sr I 4607 Å) taking fully into account the breaking of the axial symmetry of the pumping radiation field produced by the horizontal inhomogeneities and the non-vertical macroscopic motions present in 3D models of the solar atmosphere resulting from magneto-hydrodynamical simulations (e.g., Štěpán et al. 2015; Štěpán & Trujillo Bueno 2016; del Pino Alemán et al. 2018).

Sampoorna (2014) discussed the radiative transfer problem of angle-dependent PRD in 1D model atmospheres assuming a two-level model atom without ground-level polarization, pointing out that while the angle-averaged approximation may be suitable for investigating the unmagnetized case, the angle-dependent effects become more important in the presence of magnetic fields. More information on the kind of polarization effects that are specific to angle-dependent PRD in 1D model atmospheres can be found in Sampoorna et al. (2017).

Trujillo Bueno (2014) discussed recent investigations of the spectral line polarization signals produced by optical pumping in some infrared, far ultraviolet, and extreme ultraviolet lines, showing that their sensitivity to the Zeeman and/or the Hanle effects is suitable for probing the magnetism of the outer solar atmosphere. Of particular interest were the theoretical predictions for the scattering polarization of the solar disk radiation in the hydrogen Ly-α line (Trujillo Bueno et al. 2011; Belluzzi et al. 2012; Štěpán et al. 2015) and in the Mg II h & k lines (Belluzzi & Trujillo Bueno 2012), which motivated the development of the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP; for Ly-α) and of the Chromospheric LAyer Spectro-Polarimeter (CLASP-2; for Mg II h & k) to probe the upper chromosphere and the transition region.

10. SPW-8: 2013 – 2016

The SPW-8 highlighted many interesting results achieved between 2013 and 2016, some of which can be found in these proceedings.

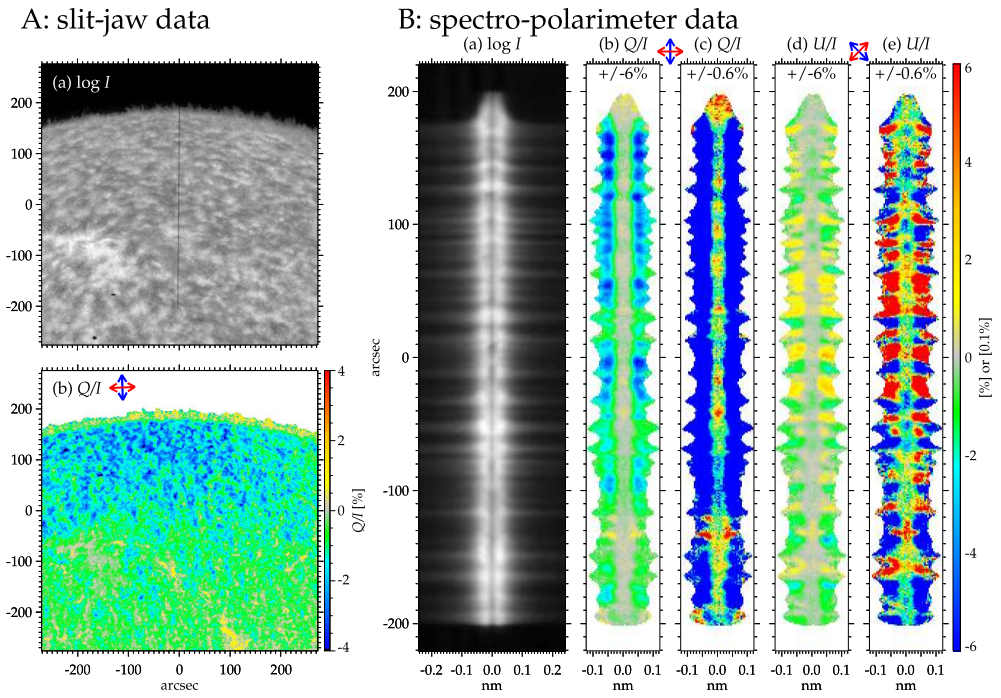


Figure 15. The CLASP experiment. (A) Broadband images of the hydrogen Lyman-α radiation taken by the CLASP slit-jaw camera: (a) intensity and (b) Q/I. The black line in (a) indicates the spectrograph's slit, which covers 400 arcsec. (B) Variation along the slit of the intensity (I) and fractional polarization (Q/I and U/I) profiles of the hydrogen Lyman-α line observed by the CLASP spectropolarimeter. The solar limb is at +175 arcsec. (a) Stokes I in logarithmic scale, (b,c) Stokes Q/I, and (d,e) Stokes U/I. The fractional polarization is clipped between ±6% in (b) and (d) for an optimal visualization of the wings, and between ±0.6% in (c) and (e) for the line core. The reference directions for positive Stokes Q and U are indicated by the red arrows in the corresponding Q/I and U/I panels. From Kano et al. (2017), after correcting a small error in the color table of the lower left panel.

The first flight of CLASP on September 3, 2015, was a true SPW-8 highlight. CLASP provided the first measurement of the linear polarization pattern produced by anisotropic radiation pumping in the hydrogen Ly-α line (see Kano et al. 2017) and in the resonance line of Si III at 1206 Å (see Ishikawa et al. 2017). In particular, the Ly-α Q/I and U/I linear polarization profiles observed by CLASP with a spatial resolution of about 3 arcsec and a temporal resolution of 5 minutes were of order 0.1% at the line center, and up to a few percent in the nearby wings, both showing conspicuous spatial variations with scales of ∼10 arcsec, in agreement with our theoretical predictions (see the spectro-polarimeter data panels of Fig. 15).

The two left panels of Fig. 15 show the Stokes I (top left panel) and Stokes Q/I (bottom left panel) images obtained with the CLASP slit-jaw optical system, which uses a Ly-α broadband filter (FWHM=70 Å). It is noteworthy that the bright plage region and some of the network features that can be distinguished in the Stokes I image show nearly zero linear polarization in the Stokes Q/I image, while the surrounding quiet regions show instead very significant polarization signals. What is the physical

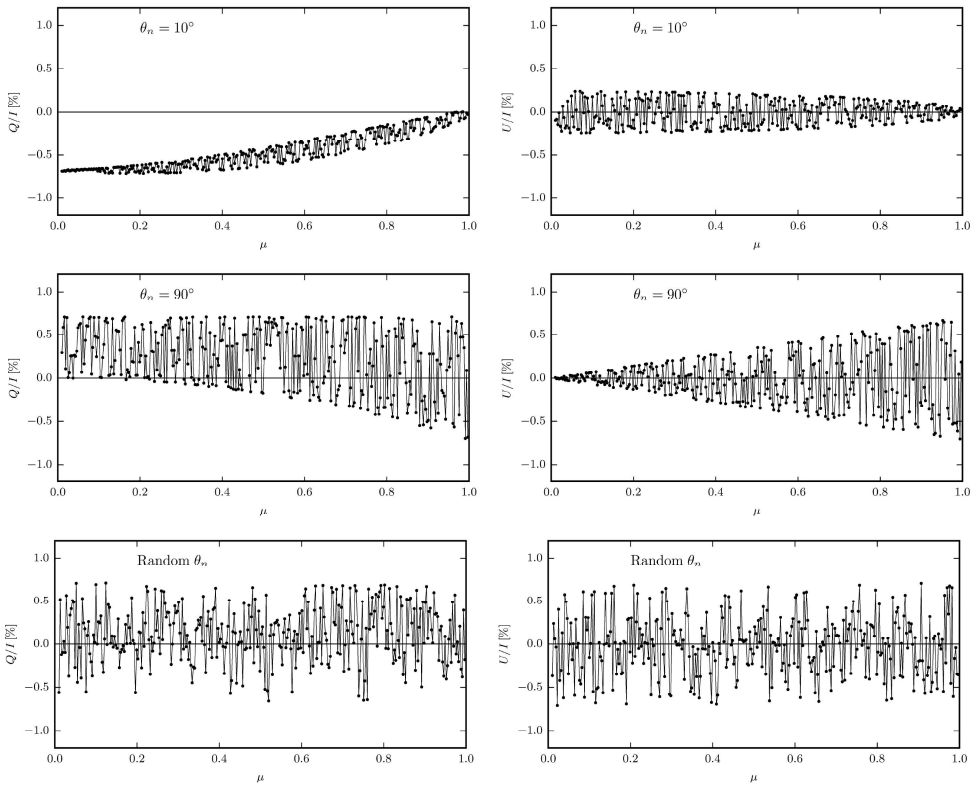


Figure 16. The CLV of the Stokes Q/I (left) and U/I (right) line-center signals of the hydrogen Ly-α line calculated without magnetic fields, assuming three different levels of "corrugation" for the chromosphere-corona transition region. Top panels: assuming that the transition-region normal vector $\boldsymbol{n}$ has a fixed inclination $\theta_{\boldsymbol{n}} = 10°$ and random azimuths $\chi_{\boldsymbol{n}}$. Middle panels: assuming that $\boldsymbol{n}$ has a fixed inclination $\theta_{\boldsymbol{n}} = 90°$ and random azimuth $\chi_{\boldsymbol{n}}$. Bottom panels: assuming that both $\chi_{\boldsymbol{n}}$ and $\theta_{\boldsymbol{n}}$ have random values. Via the Hanle effect, the amplitudes of the spatial fluctuations of the Q/I and U/I line-center signals are sensitive to the magnetization of the transition region. The reference direction for the positive Stokes Q is the parallel to the nearest limb. From Trujillo Bueno et al. (2018).

explanation of this observational fact? The broadband Q/I signals are dominated by the linear polarization in the wings of the hydrogen Ly-α line (see Belluzzi et al. 2012). From radiative transfer calculations of the Ly-α polarization in (unmagnetized) semi-empirical models we know that the wing polarization amplitudes are of the same order of magnitude (a few percent) in plage, network and quiet regions, in as far as they are located at similar distances from the solar limb (see Fig. 4 of Belluzzi et al. 2012). The Hanle effect does not operate in the spectral line wings, but we have learned recently that the magneto-optical $\rho_V\ U$ and $\rho_V\ Q$ terms that couple the Stokes Q and U transfer equations introduce magnetic sensitivity in the wings of the Ly-α linear polarization profiles, producing almost complete depolarization in the Q/I wings for magnetic fields with longitudinal components significantly larger than 100 G (see Alsina Ballester et al. 2019a). This is, in my opinion, the physical explanation of the noteworthy observational fact mentioned above.

Surprisingly, the Ly-α Q/I line-center signals observed by CLASP did not show any clear CLV (see panel (c) of the spectro-polarimetric data shown in Fig. 15), in contrast with the results of our radiative transfer investigations in several models of the solar atmosphere. As illustrated in Fig. 16, the explanation of this unexpected observational result lies in the fact that the CLV of the Q/I line-center signal of the hydrogen Ly-α line is very sensitive to the geometrical complexity of the chromosphere-corona transition region (see Trujillo Bueno et al. 2018). These authors introduced a statistical description of the solar atmosphere based on a 3D model that results from a state-of-the-art radiation magneto-hydrodynamic simulation (see Carlsson et al. 2016). Each realization of the statistical ensemble is a 3D model characterized by a given degree of magnetization and corrugation of the transition region, and for each such realization Trujillo Bueno et al. (2018) solved the full 3D radiative transfer problem taking into account the impact of the CLASP instrument degradation on the calculated polarization signals. They applied the statistical inference method explained in Štěpán et al. (2018) and showed that the transition region of the 3D model that produces the best agreement with the CLASP observations has a relatively high degree of corrugation. Clearly, a suitable way to validate or refute numerical models of the upper solar chromosphere is by confronting calculations and observations of the scattering polarization in ultraviolet lines sensitive to the Hanle effect. For a recent paper on the physics and diagnostic potential of ultraviolet spectropolarimetry see Trujillo Bueno et al. (2017).



Figure 17. Photographs taken in Tenerife during a dinner at home. The "spaghetti alle vongole," prepared by Egidio himself, remains the most exquisite one Olga and I have ever enjoyed.

11. Concluding comments

The SPW-8 was indeed a memorable workshop to honor the career and work of our dear friend Egidio Landi Degl'Innocenti, upon whose shoulders the solar polarization community stands. I will always be grateful to him for his friendship and for the extraordinary scientific and human legacy that he has left with us, and to the benefit of the future generations of scientists.

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