Publ. Astron. Obs. Belgrade No. 91 (2012), 35 - 44 *Invited lecture*

SEARCHING FOR WEAK SOLAR MAGNETIC FIELDS. WHAT CAN WE LEARN FROM THE HANLE EFFECT?

M. FAUROBERT

Lagrange Laboratory. UMR 7293. University of Nice-Sophia Antipolis. CNRS. Observatory of the Côte d'Azur. Campus Valrose. 06108. Nice Cedex 2. France
E–mail: marianne.faurobert@unice.fr

Abstract. Many dynamical phenomena taking place in the solar atmosphere, such as flares and coronal mass ejections, are driven by the interplay between the magnetic field and the turbulent solar plasma. Long standing questions on the physical origin of coronal heating and solar wind acceleration are also probably related to magnetic mechanisms. So the issue of how to measure magnetic fields in the solar atmosphere, from the photosphere up to the corona, is of crucial importance in solar physics. Because of the high value of the Reynolds magnetic number in the solar atmosphere, magnetic structures may develop from large to very small spatial scales, typically ranging from the scale of the solar diameter down to few tens of kilometers. The magnetic field strength also shows a broad dispersion from several thousands of Gauss in active regions like sunspots, down to a few Gauss in the quiet Sun. The amount of magnetic energy stored in magnetic structures is still unkown, and, according to recent numerical simulations, a significant fraction may be stored in weak, small scale fields, which cover a large fraction of the solar surface. However these field are hardly detectable in magnetograms based on the Zeeman effect because of their limited performances both in terms of polarimetric sensitivity and of spatial resolution. The Hanle effect is a valuable alternative for the diagnostics of weak fields with mixed polarity at small scales. It affects the linear polarization of spectral lines formed by scattering of photons in the solar atmosphere. I will present how weak magnetic fields investigations have changed our vision of the solar magnetism and discuss future research directions, in the context of solar polarimetry projects with ground based or space based intruments.

1. INTRODUCTION

The magnetic energy content of the solar atmosphere may be seen as "the dark energy" in solar physics. The reason is that magnetic fields are probably at the origin of many of the very dynamical phenomena that we see on the solar surface, flares and eruptions, coronal mass ejections, spicules and supersonic jets, etc ... But, magnetic fields are difficult to measure by remote sensing. This requires spectro-polarimetric observations and problematic inversion methods of polarized spectra. In the low layers of the atmosphere, at photospheric levels, magnetic maps may be obtained with magnetograms. They are based on the measurement of the Zeeman effect on the polarization profiles of spectral lines formed mostly under LTE conditions. But the zeeman effect is cancelled out if the magnetic field has mixed polarities on the resolution element of the telescope, so that magnetograms are blind to small scale mixed polarity fields. They also have a limited sensitivity to weak magnetic fields which give rise to weak polarization signals, the photometric sensitivity of the instrument then limits the detection of weak fields from their Zeeman effect. Direct measurements of magnetic fields in dilute and hot regions of the chromosphere and corona are even more of a challenge, because spectral lines are formed under non-LTE conditions, they are often broader than photospheric lines and the magnetic field strength is on the average smaller. Most of our knowledge about magnetic structures at higher atmospheric levels are obtained from extrapolation methods relying on magnetic maps derived at the photospheric level, and on the assumption that the magnetic structures are force-free, i.e. that the Lorentz force of the magnetic field on the plasma is negligible (i.e. the current density is parallel to the magnetic field). This assumption is a matter of debate, because in the photosphere the plasma pressure is often larger than the magnetic pressure, and flows are not necessarily parallel to the magnetic field lines (see Eibe et al. 2002; De Rosa et al. 2009). On the other hand, at higher altitudes, the magnetic pressure dominates with respect to the gaz pressure, and the force-free assumption is valid. Then force-free extrapolations would benefit of using magnetic maps obtained at chromospheric levels instead of photospheric levels.

So far, we thus have a very incomplete view of the solar magnetic field 3D-structures from the observations. At the photospheric level, magnetograms are blind to small scale magnetic structures and at higher altitudes the Zeeman effect is almost not detectable either. In that context, the Hanle effect provides us with a very interesting diagnostic tool for investigating solar magnetic fields because it does not cancel out if the magnetic structures are not spatially resolved by the instrument, and it is sensitive to intrinsically weak fields, on the order of a few Gauss to typically one hundred Gauss which are expected in the chromosphere and corona.

In the following I will explain why small scale weak magnetic fields are presently searched for by differents groups and a variety of instruments and techniques. In a third Section I will give some details about diagnotics based on the Hanle effect.

2. WHY DO WE SEARCH FOR WEAK MAGNETIC FIELDS?

Large field of view magnetograms of the photospheric magnetic field, obtained with modern instruments onboard satellites, such as SDO/HMI, show that, outside active regions, the magnetic field has a strong vertical component (1000 G) in structures forming a network of cells on a well defined spatial scale of about 35 000 km (see Fig. 1). The physical origin of this network structure is still not fully understood but it is probably related to the advection of magnetic elements by the supergranulation pattern which is observed in Doppler velocity measurements of photospheric lines. The network cell interior appears as a greyish medium, where no magnetic structures are clearly detected.

2. 1. OBSERVATIONS OF THE QUIET SUN MAGNETIC FIELDS

However, high sensitivity spectro-polarimetric measurements, performed for example with the 50cm-telescope onboard the Hinode satellite, allow to detect the so-called intranetwork magnetic fields, which are intrinsically weaker than the network fields, and seem to have a random direction varying at small scale. Figure 2 shows high

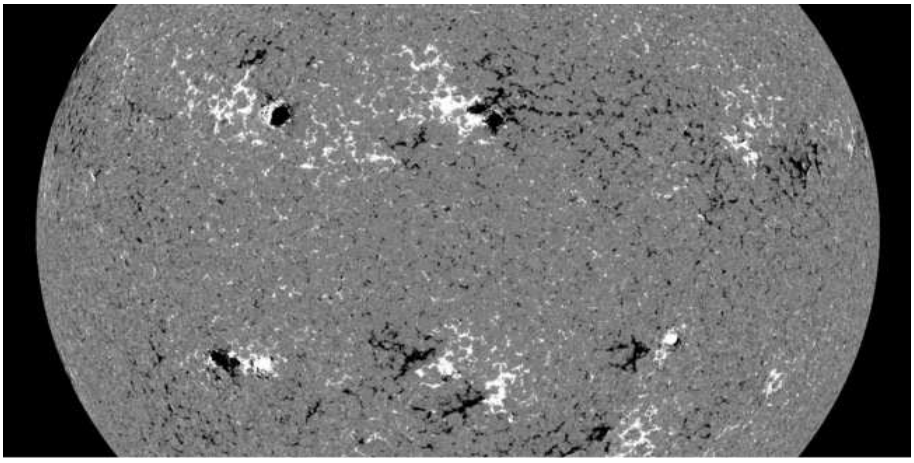

Figure 1: SDO/HMI magnetogram

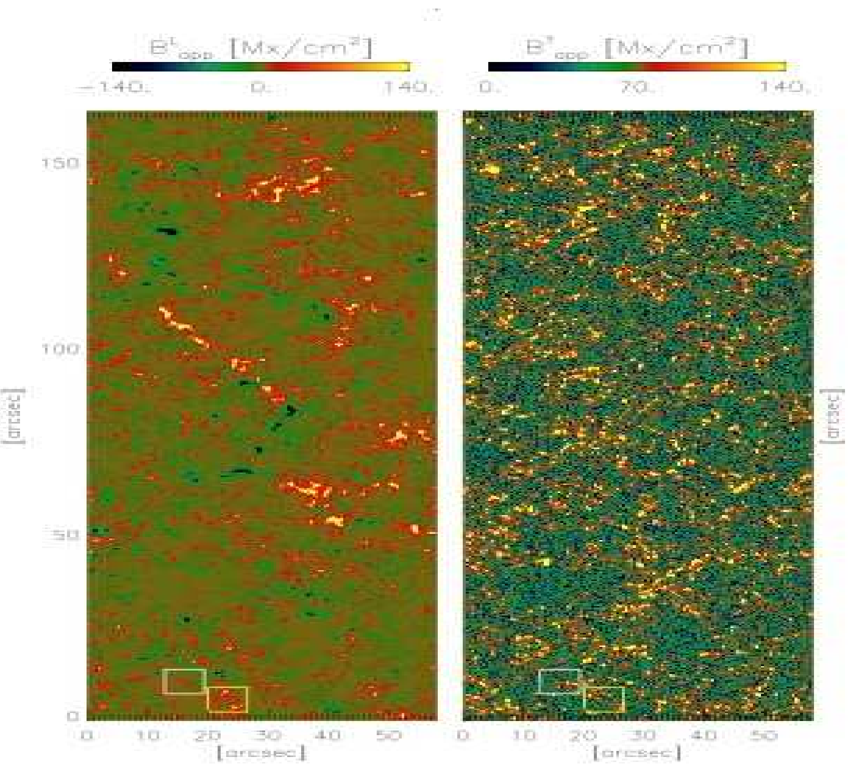

Figure 2: Hinode/SOT high sensitivity magnetic maps of the quiet Sun magnetic field. Left panel: vertical component, Right panel: horizontal component. The boxes at the bottom of the maps show the size of numerical simulation boxes. From Danilovic et al. (2010).

sensitivity maps of the vertical and horizontal components of the quiet Sun magnetic field obtained by Danilović et al. (2010) with Hinode/SOT observations and inversion of the Stokes profiles of the photospheric FeI 630 nm lines. Similar investigations have been carried out with ground based telescopes such as Themis on the Canary Islands (Bommier at al. 2009). They show that the intranetwork magnetic field has mixed polarities at small scale and appears as a turbulent field which should be described through a statistical approach, introducing Probability Distribution Functions (PDF). The PDF for the magnetic strength is derived from the observed histogram of the distribution of magnetic strength over the observed region, i.e. the number of pixels where a given magnetic strength has been measured as a function of the magnetic strength. This kind of analysis has to be carried out with care because the Zeeman effect measured at a given pixel is sensitive to the magnetic flux over the pixel area. If the magnetic field has unresolved structures over this area, inversion methods are in principle unable to recover its actual strength. This is the reason why most inversion codes take into account approximate two-component models where the magnetic field is supposed to cover only a fraction of the pixel area, corresponding to the so-called filling factor. The filling factor is an unkown parameter provided by the inversion together with the strength and direction of the magnetic component inside the pixel. Figure 3 shows the quiet Sun PDF for the magnetic strength and magnetic energy density (proportional to B^2) derived from Hinode observation by Lites (2011). Two observation runs have been used, in the first one the integration time was 80 seconds, the signal-to-noise ratio of the spectro-polarimetric data allowed to achieve the Stokes inversion for 28 % of the total amount of pixels in the image. In the second run, the integration time was shorter, 5 seconds, and only 8% of the pixels had high enough signal-to-noise ratio to allow an inversion of the magnetic field. The PDF's derived in the 2 cases differ significantly, as shown by Fig. 3, as far as the distribution of weak magnetic fields is concerned. Long integration times are needed to have a better statistics on the weak field distribution. This has important consequences on the magnetic energy stored in the weak fields as compared to the strong fields regions. This an important issue, as magnetic energy stored in mixed polarity magnetic fields at small scale could play a role in the still enigmatic chromospheric heating.

2. 2. NUMERICAL SIMULATIONS

In parallel to observational investigations, the magnetic structure of the solar photosphere may be derived from numerical simulations of the MHD equations coupled to the energy and radiative transfer equations. Such simulations are carried our by several groups (Stein and Nordlund 1998, 2006; Cattaneo 1999, Vogler et al. 2005, Steiner et al. 2008, ...). They have shown that a local dynamo takes place in the surface layers of the Sun, driven by turbulent convection, and that it gives rise to small scale mixed polarity magnetic fields inside the network cells. Figure 4 shows the average horizontal and vertical magnetic components as functions of height in the photosphere, computed by Steiner et al. (2008) for two different boundary conditions. It reveals an interesting phenomenon: the convective overshoot flows push the magnetic field in the stable upper layer of the photosphere, so the strength of the horizontal component has a local maximum near the temperature minimum region, about 500 km above the base of the photosphere. This still has to be verified by observations performed in spectral lines formed in the temperature minimum region.

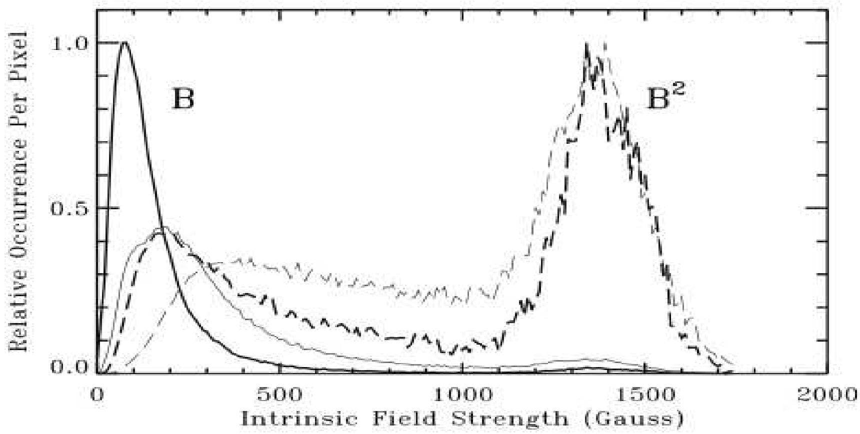

Figure 3: PDF of the magnetic strength and magnetic energy density derived from Hinode observations by Lites (2011). Thick lines: integration time= 80 s, thin lines: integration time= 5s. Dashed lines: B^2 distribution, full lines: field strength B.

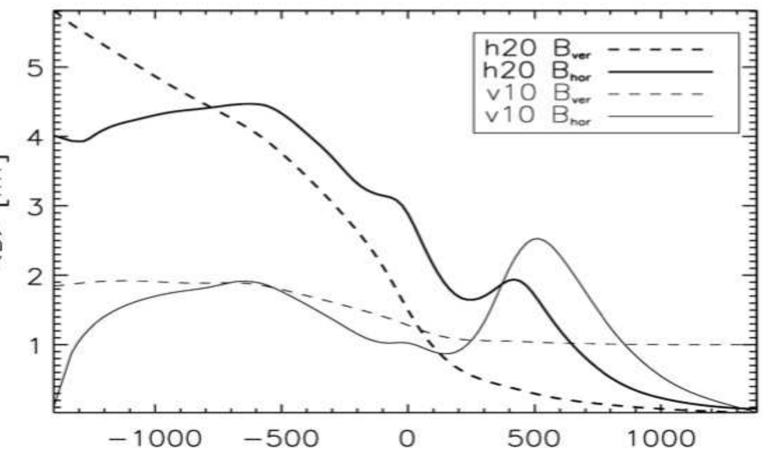

Figure 4: Numerical simulations of the MHD equations in the photosphere by Steiner al. (2008). Height variations of the vertical (dashed lines) and horizontal (full lines) magnetic components for 2 different boundary conditions. The base of the photosphere corresponds to the altitude where continuum images are formed.

Both obervations and numerical simulations demonstrate the need of improving our knowledge about the quiet Sun magnetic field distribution in the weak field regime. We shall now see how diagnostics based on the Hanle effect can bring us valuable information in this domain.

3. WHAT CAN WE LEARN FROM THE HANLE EFFECT?

One of the major limitations of diagnostics based on the Zeeman effect is that Zeeman polarization is cancelled out in the presence of unresolved mixed polarity fields. In other words the Zeeman effect is sensitive to the magnetic flux over the pixel area, it does not allow to infer without ambiguouity the magnetic strength and direction in the case where the magnetic structures are not resolved by the telescope. This is likely to be a common situation because order of magnitude estimates of the magnetic diffusion time and of the advection time under typical photospheric conditions, lead to a magnetic diffusion scale on the order of 15 km. This means that very small magnetic structures, well below the present resolution of our telescopes, may exist in the photosphere. In contrast, the Hanle effect is a non-linear effect which depends on the magnetic strength and which is not cancelled out in the presence of unresolved magnetic fields.

3. 1. HANLE EFFECT MECHANISM

First, spectral lines formed by radiation scattering may be linearly polarized in the absence of a magnetic field, when the illuminating radiation field is anisotropic. The absorption of an anisotropic radiation in a spectral line leads to population imbalences among the zeeman sub-levels of the upper atomic level, together with phase relationships between their wave functions. This is the so-called "atomic polarization". Due to these phase relationships, the radiations re-emitted by the degenerate zeeman sub-levels of the "polarized" atom do interfer and the resulting radiation is linearly polarized (Landi Degl'Innocenti & Landolfi, 2004). This effect is the quantuum counterpart of Rayleigh scattering which takes place when a classical dipole scatters a radiation field. In the presence of a magnetic field, the Zeeman sublevels are shifted but, if the magnetic field is weak enough, the shift remains smaller or on the order of the natural width of the atomic levels and their phase relationships are not totally destroyed. The interaction of the atom with the magnetic field leads to a relaxation of the phase relationship of the Zeeman sub-levels during the absorption or emission process. The resulting linear polarization of the radiation is reduced and its polarization plane rotates with respect to the non-magnetic direction. This is the so-called Hanle effect. The typical magnetic field strength for this effect to occur, is when

$$\nu_L \simeq \Gamma_R, \quad (1)$$

where ν_L is the Larmor frequency of the electron in the magnetic field and Γ_L is the inverse radiative life-time of the atomic level. This gives, for the magnetic field strength,

$$B \simeq 0.88 g_J \Gamma_R, \quad (2)$$

where g_J is the Lande factor of the line upper level, and where B is the magnetic strength in Gauss, and Γ_R is in units of 10^7 s^{-1}. For typical spectral lines in the optical domain, the Hanle effect regime corresponds to magnetic strengths between a

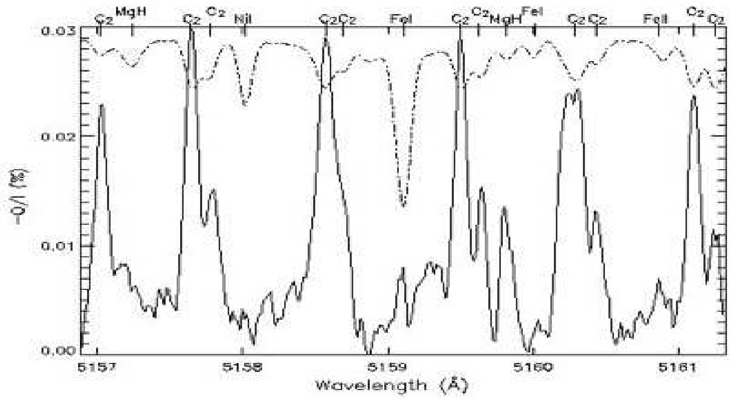

Figure 5: Sample of the Second solar spectrum, observed at THEMIS, showing the linear polarization observed in molecular lines, at 50 arseconds inside the Solar limb. From Faurobert & Arnaud (2003).

few Gauss and one hundred Gauss. The Hanle effect was first applied in solar physics for the determination of magnetic fields in prominences (Sahal-Bréchot et al. 1977).

3. 2. SECOND SOLAR SPECTRUM

When one observes the solar radiation emitted close to the solar limb, some spectral lines formed by radiation scattering outside active regions are linearly polarized. This was first pointed out by Wiehr (1975) who observed strong resonance lines such as the CaI 422.7 nm or BaII 455.4 nm lines, where the linear polarization rates are of the order of 1% or more at 5 arcseconds inside the solar limb. The physical origin of this polarization is the scattering mechanism and quantum interference process described above (Stenflo 1978). Thanks to the improvement of the polarimetric sensitivity of the instruments, Stenflo et al. (1983) have shown that a large number of spectral lines are linearly polarized when observed close to the solar limb, and that the polarization spectrum is quite different from the intensity spectrum. This is why it was called "the second solar spectrum" by Ivanov (1995). An atlas of this linear polarization spectrum has been obtained by Gandorfer (2000) at IRSOL with the ZIMPOL polarimeter. The detailed physical mechanisms giving rise to the wide variety of spectral features encountered in this spectrum have not been completely elucidated yet. Figure 5 shows an illustration of one spectral domain of the second solar spectrum where the linear polarization of molecular lines is observed, whereas the very weak lines, are hardly seen in the intensity spectrum.

3. 3. TURBULENT PHOTOSPHERIC MAGNETIC FIELDS

Following an original idea of Stenflo (1982), the limb polarization observed in photospheric absorption lines was used to search for the presence of weak unresolved magnetic fields which could not be seen in magnetograms in the quiet Sun. One of the most famous, and widely observed, line in the Second solar spectrum is the res-

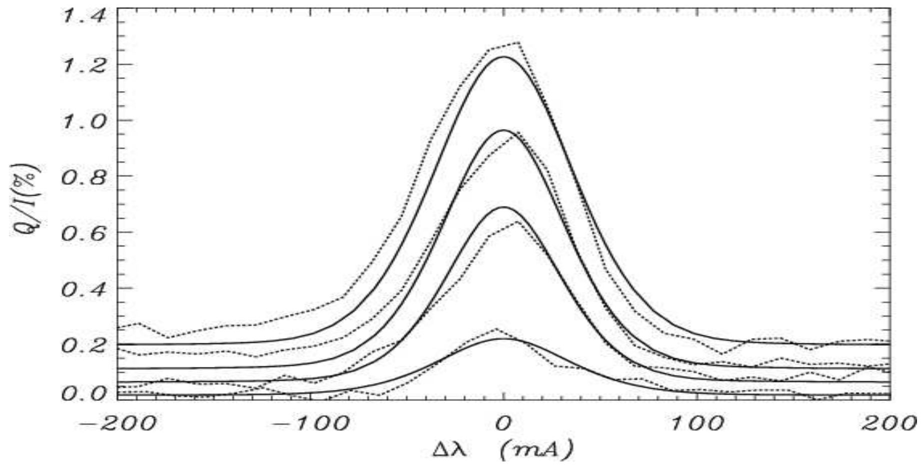

Figure 6: Linear polarization profiles in the SrI 460.7 nm at 4 limb-distances. Full lines: computed profiles with B= 25 Gauss, dashed lines: observed profiles. From top to bottom the curves correspond to increasing limb-distances: 1.3 ", 5", 19.5", 96". From Faurobert et al. 2001.

onance line of SrI at 460.7 nm. It is a normal triplet which exhibits a clear and nice polarization peak on the order of 1% close to the solar limb. As this is an optically thick photospheric line formed by multiple scattering, the interpretation of its polarization requires to solve a polarized non-LTE radiative transfer equation. This was first achieved by Faurobert-Scholl (1993), and Faurobert-Scholl et al. (1995), who showed that the line polarization is affected by the Hanle effect of a weak turbulent magnetic field of the order of 25 Gauss in the line forming region, between 200 km and 400 km above the base of the photosphere. Figure 6 shows the observed linear polarization spectra at various limb distances compared to the results of the polarized transfer modeling, taking into account the Hanle effect of a turbulent, unresolved, magnetic field.

The upper photosphere may also be explored by observing weak molecular lines of C_2 and MgH (see Fig. 5), which have different sensitivities to the Hanle effect, because of they have different Landé factors. If we can assume that the lines have the same optical depth in the photosphere, we can take advantage of the differential Hanle effect in order to determine the magnetic strength independently of the precise knowledge of the atmospheric model (Berdyugina & Fluri 2004, Asensio Ramos & Trujillo Bueno 2005). However, this assumption is not always true, as shown in Faurobert & Arnaud (2003), who proposed a modified diagnostic method based on the differential Hanle effect on blended and unblended lines of the C_2 molecule. The magnetic strength is found to be on the order of 15 Gauss in the upper layers of the photosphere where the molecules are concentrated.

3. 4. CHROMOSPHERIC MAGNETIC FIELDS

As already stressed above, chromospheric magnetic fields are very difficult to measure via their Zeeman effect, both because chromospheric lines are often very broad and formed under non-LTE conditions, and because the magnetic strength is intrinsically weaker, giving rise to weak Zeeman signals. The Hanle effect is a valuable and complementary diagnostic tool. Faurobert-Scholl (1994) has investigated the effect of a magnetic canopy lying in the quiet solar chromosphere, on the linear polarization observed in the resonance line of CaI at 422.7 nm. More recently the BaII resonance line at 455.4 nm has been studied by Faurobert et al. (2009) who observed the center-to-limb variations of its linear polarization close to the solar limb with the Themis telescope. This study also shows that weak unresolved magnetic fields are ubiquitous in the low chromosphere of the Sun, with an average strength on the order of 20 Gauss.

The low chromosphere may also be investigated by observing emission lines seen above the solar limb. We have developped a numerical code which solves the polarized transfer equation in the presence of the Hanle effect, in spherically symmetric media, in order to interpret such observations (Milić & Faurobert 2012). We applied it to molecular lines of C_2 which have been observed in emission above the limb by Faurobert & Arnaud (2002). This shows that these emission lines are sensitive to the Hanle effect of weak fields in the region of the temperature minimum between the photosphere and the chromosphere. More observations are needed to make full use of this new diagnostic tool.

The magnetic fields in even more dilute and hot regions of the chromosphere and transition regions between the chromosphere and the corona may be investigated by measuring the linear polarization in strong absorption lines of the Lyman and Balmer series of hydrogene, as suggested by Trujilllo Bueno et al. (2011). The observations of these lines would require spatial missions with spectro-polarimetric facilities in the Ultraviolet spectral domain.

4. CONCLUSION

The physics of the outer layers of the Sun is mostly driven by magnetic phenomena. This is the reason why high resolution investigations of the magnetic fields in the hot and dilute outer atmosphere of the Sun, from the photosphere to the chromosphere and corona, are the major objectives of the new European Solar Telescope (EST), presently under study.

The so-called "quiet Sun" is probably filled in with magnetic fields distributed in strengths and over a wide range of spatial scales. The magnetic energy content of this distribution of fields is a crucial issue, related to the long standing question of the coronal and chromospheric heating. Zeeman diagnostics of the magnetic fields depend crucially on the spatial resolution of the observations, whereas diagnostics based on the Hanle effect do provide valuable information on the average field strength even if the magnetic structures are not resolved. However, they rely on the precise radiative transfer modeling of polarized lines formed under non-LTE conditions. The use of the differential Hanle effect on lines with different magnetic sensitivities is a method of choice to obtain model-independent diagnostics. Another promissing way explored nowdays is to make use of the complementary diagnostics provided by both the Zeeman and Hanle effects when they can be observed in the same lines (Asensio Ramos et al. 2008, Anusha et al. 2011).

References

Anusha, L. S., Nagendra, K. N., Bianda, M., Stenflo, J. O., Holzreuter, R., Sampoorna, M., Frisch, H., Ramelli, R., Smitha, H. N.: 2011, *Astrophys. J.*, **737**, 95.

Asensio Ramos, A., Trujillo Bueno, J.: 2005, *Astrophys. J.*, **635**, L109.

Asensio Ramos, A., Trujillo Bueno, J., Landi Degl'Innocenti, E.: 2008, *Astrophys. J.*, **683**, 542.

Berdyugina, S. V., Fluri, D. M.: 2004, *Astron. Astrophys.*, **417**, 775.

Bommier, V., Martínez Gonzlez, M., Bianda, M., Frisch, H., Asensio Ramos, A., Gelly, B., Landi Degl'Innocenti, E.: 2009, *Astron. Astrophys.*, **506**, 1415.

Cattaneo, F.: 1999, *Astrophys. J.*, **515**, L39.

Danilovic, S., Schüssler, M., Solanki, S. K.: 2010, *Astron. Astrophys.*, **513**, A1.

DeRosa, Marc L.; Schrijver, Carolus J.; Barnes, Graham; Leka, K. D.; Lites, Bruce W.; Aschwanden, Markus J.; Amari, Tahar; Canou, Aurlien; McTiernan, James M.; Rgnier, Stphane; Thalmann, Julia K.; Valori, Gherardo; Wheatland, Michael S.; Wiegelmann, Thomas; Cheung, Mark C. M.; Conlon, Paul A.; Fuhrmann, Marcel; Inhester, Bernd; Tadesse, Tilaye: 2009, *Astrophys. J.*, **696**, 1780.

Eibe, M. T., Aulanier, G., Faurobert, M., Mein, P., Malherbe, J. M.: 2002, *Astron. Astrophys.*, **381**, 290.

Faurobert, M., Arnaud, J., Vigneau, J., Frisch, H.: 2001, *Astron. Astrophys.*, **378**, 627.

Faurobert, M., Arnaud, J.: 2002, *Astron. Astrophys.*, **382**, L17.

Faurobert, M., Arnaud, J.: 2003, *Astron. Astrophys.*, **412**, 555.

Faurobert, M., Derouich, M., Bommier, V. , Arnaud, J.: 2009, *Astron. Astrophys.*, **493**, 201.

Faurobert-Scholl, M.: 1993, *Astron. Astrophys.*, **268**, 765.

Faurobert-Scholl, M.: 1994, *Astron. Astrophys.*, **285**, 655.

Faurobert-Scholl, M., Feautrier, N., Machefert, F. , Petrovay, K., Spielfiedel, A.: 1995, *Astron. Astrophys.*, **298**, 289.

Gandorfer, A.: 2000, *The Second Solar Spectrum: A high spectral resolution polarimetric survey of scattering polarization at the solar limb in graphical representation. Volume I: 4625 A to 6995 A*, ed. Gandorfer, A.

Landi Degl'Innocenti, E., Landolfi, M.: 2004, *Polarization in spectral lines*, Astrophysics and Space Science Library, (Dordrecht: Kluwer).

Lites, B.: 2011, *Astrophys. J.*, **737**, 52.

Milić, I., Faurobert, M.: 2012, *Astron. Astrophys.*, in press.

Sahal-Bréchot, S., Bommier, V., Leroy, J. L.: 1977, *Astron. Astrophys.*, **59**, 223.

Stein, R. F., Nordlund, A.: 1998, *Astrophys. J.*, **499**, 914.

Stein, R. F., Nordlund, A.: 2006, *Astrophys. J.*, **642**, 1246.

Steiner, O., Rezaei, R., Schaffenberger, W., Wedemeyer-Bhm, S.: 2008, *Astrophys. J.*, **680**, L85.

Stenflo, J. O.: 1978, *Astron. Astrophys.*, **66**, 241.

Stenflo, J. O.: 1982, *Solar Phys.*, **80**, 209.

Stenflo, J. O., Twerenbold, D., Harvey, J. W., Brault, J. W.: 1983, *Astron. Astrophys. Suppl. Series*, **54**, 505.

Trujillo Bueno, J., Stepán, J., Casini, R.: 2011, *Astrophys. J.*, **738**, L11.

Vogler, A., Shelyag, S., Schussler, M., Cattaneo, F., Emonet, T., Linde, T.: 2005, *Astron. Astrophys.*, **429**, 335.

Wiehr, E.: 1975 *Astron. Astrophys.*, **38**, 303.