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QUIET SUN MAGNETIC FIELDS

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. The quiet Sun is a highly turbulent plasma that exhibits a rich and complex magnetic structuring which is still not fully resolved nor understood. It has been shown recently that the magnetic flux of the quiet Sun is at least three orders of magnitude larger than the one of active regions. The amount of magnetic energy stored in quiet Sun magnetic structures is still unknown, but long standing questions on the physical origin of coronal heating and solar wind acceleration are probably related to magnetic mechanisms taking place in the quiet Sun. In the last ten years many studies, both observational and theoretical, have been devoted to the investigation of this essential aspect of the solar magnetism. Thanks to the advent of high-resolution, high-sensitivity spectropolarimetric observations from space and ground our vision of the solar magnetism is changing nowadays but many questions and matters of debate still remain.

1. INTRODUCTION

The quiet Sun (QS) is defined as the region outside sunspots and pores where strong coherent magnetic fields over large scales are observed. But the QS is far from being magnetic free. High spatial resolution and high sensitivity QS magnetograms show magnetic fields in network and internetwork (IN) elements. The network elements have strong fields of the order of 1 kG and are located at the borders of the supergranular cells with typical diameters of 30 000 km, while the internetwork ones, in the cell interior, show much weaker fields (for a review see Sánchez Almeida & Martínez González 2011). It has been estimated that a significant fraction of the total magnetic flux of the solar surface resides in the quiet Sun and a recent study by Gosic et al. (2014) from deep magnetograms at 0.3" spatial resolution, estimates that 14% of the quiet Sun magnetic flux is in the form of internetwork elements.

The origin of both network and internetwork elements is not clear. Numerical simulations by Vögler & Schüssler (2007), or Steiner et al. (2008), have shown that the vigorous convective motions in the solar photosphere, where the dynamic pressure of the flows exceeds the magnetic pressure, can cause an efficient amplification of the magnetic energy at small scales from a magnetic seed. This small-scale dynamo action could be the source of the quiet Sun magnetic fields, but another possible source could be the turbulent dissipation of active regions present at large scale associated to the global solar dynamo.

Quiet Sun magnetic fields are difficult to measure because they are organized on small spatial scales and seem to evolve rapidly. The polarimetric signals they produce are very weak and their interpretation involves ill-posed inversion problems. Developments of theoretical approaches and numerical simulations are in progress but they are presently not realistic enough to be quantitatively compared to observations.

So many issues are still under vigorous debate among the solar physicist community, in consequence the present paper is not intended to give a comprehensive view of the quiet Sun magnetism, but rather to show how our vision on this subject has been evolving and to present some of the debates presently going on.

2. A BRIEF HISTORICAL SURVEY

2. 1. LOW SPATIAL RESOLUTION ERA

In the presence of a magnetic field, spectral lines may be polarized by two different physical mechanisms, namely the Zeeman and Hanle effects. In the presence of Zeeman effect, magnetic sensitive lines show both circular and linear polarization profiles, the profile shapes depend on the strength and direction of the magnetic field with respect to the line-of-sight (see Landi Degl'Innocenti & Landolfi, 2004). In the weak field regime, when the Zeeman splitting is smaller than the line Doppler width, the amplitude of the circular polarization measured in the line wings may be approximated by

$$V(\lambda) = -f \Delta\lambda_B \cos\gamma \frac{dI_0}{d\lambda}, \tag{1}$$

where the Zeeman splitting $\Delta\lambda_B$ is given by

$$\Delta\lambda_B = 4.67\,10^{-13} \lambda_0^2 g_{eff} B. \tag{2}$$

The coefficient g_{eff} denotes the Landé factor of the line, B is the magnetic field strength (in Gauss) and γ is its angle with respect to the line of sight, λ_0 is the line center wavelength, in Å. If the magnetic field is not spatially resolved only the fraction of the pixel surface where the magnetic field is present is producing the signal. So the measured signal is proportional to the filling factor f of the magnetic element over the pixel. A strong field concentrated over a small fraction of the surface would give the same signal as a weak field covering the whole pixel surface.

One method to discriminate between both cases was introduced by Stenflo (1973). He pointed out that the ratio of circular polarization measured in two lines of the same multiplet with different sensitivity to Zeeman effect, but formed in identical conditions, is given by the ratio of their Landé factors if the magnetic field is weak, but saturates to one if the field is intrinsically strong. This allowed him to show that network elements have strong fields concentrated on sizes of the order of one hundred kilometers in diameter. However internetwork fields which have mixed polarities at small scales give very low circular polarization signal which could not be measured reliably. So the predominant view was that QS magnetic fields were formed of kilo-Gauss concentrated magnetic elements in the network and mixed polarity weak field in the internetwork.

Among the more recent studies performed from ground based observations, let us quote Bommier et al. (2009) and Bommier (2011) who used Themis observations to investigate the statistical properties of the QS magnetic fields. The inversion method which was implemented to interpret the observations allows to derive independently the filling factor and the magnetic field strength and direction. The results were quite different from the one recorded above. It was found that the photospheric internetwork field is mainly formed of scattered narrow fluxtubes consisting in a vertical field, which weakens in opening and widening with individual field line bending with height. The weakest fields then have a 2D horizontal structure, instead of the usually admitted 3D turbulent one.

These weak mixed polarity fields were investigated through the measurement of their Hanle effect on spectral lines. The Hanle effect gives rise to a depolarization and a rotation of the linear polarization plane in lines formed by scattering of photons (see Landi Degl'Innocenti & Landolfi 2004). It is a non-linear effect so the depolarization is not averaged out in the presence of mixed polarity fields. The magnetic field strength diagnostics then relies on the comparison of the observed polarization with the zero-field value derived from numerical modeling and polarized radiative transfer calculations (see Faurobert-Scholl et al. 1995, Faurobert et al. 2001). Line ratio methods may also be applied to the Hanle effect observed in several spectral lines with different magnetic sensitivity (see Stenflo et al., 1998, Berdyugina & Fluri, 2004). Typical intrinsic field strength of the order of 20 G were found in the internetwork from spatial averaging over large fields of view and long exposure times. The same observations were then interpreted with more sophisticated radiative transfer codes allowing for 3D structures in the solar granulation and larger mean field strength, of the order of 130 G were obtained (see Trujillo-Bueno et al. 2004). Detailed modeling of the center-to-limb variations of the linear polarization in C2 and MgH molecular lines observed at Themis by Faurobert & Arnaud (2002), together with a more sophisticated inversion method then showed that the mean field strength has a strong depth-gradient in the upper photosphere, where it varies from more than 100 Gauss at 200 km to 10 Gauss at 400 km above the base of the photosphere (Milic & Faurobert, 2012). This result is compatible with the results of Bommier (2011), as the weak fields detected from their Zeeman effect have mixed orientations in an horizontal plane and a depth-decreasing strength in the upper photosphere.

In the last decade significant progress have been made in the sensitivity and spatial resolution of polarization measurements. This progress was due to the implementation of adaptative optic systems on ground-based solar telescopes, and to the launch of space based and balloon instruments (SOHO, Hinode, SDO, Sunrise).

2. 2. HIGH SPATIAL RESOLUTION ERA

One of the important achievements of high spatial resolution polarization measurements is that the Zeeman effect can now be observed in internetwork elements as well as in the network. Figure 1 shows a comparison of quiet Sun magnetograms at low and high spatial resolution, respectively from ground based and space base instruments. At high resolution the internetwork appears filled of magnetic elements that are not detected at lower spatial resolution. The improvement of spatial resolution allowed to explore the distribution of the magnetic flux in the QS. Figure 2 shows that the distribution of flux has a fractal behavior with no characteristic scale, and that the contribution of the QS to the total solar magnetic flux is at least three orders of magnitude larger than the contributions of active regions (see Parnell et al. 2009)!

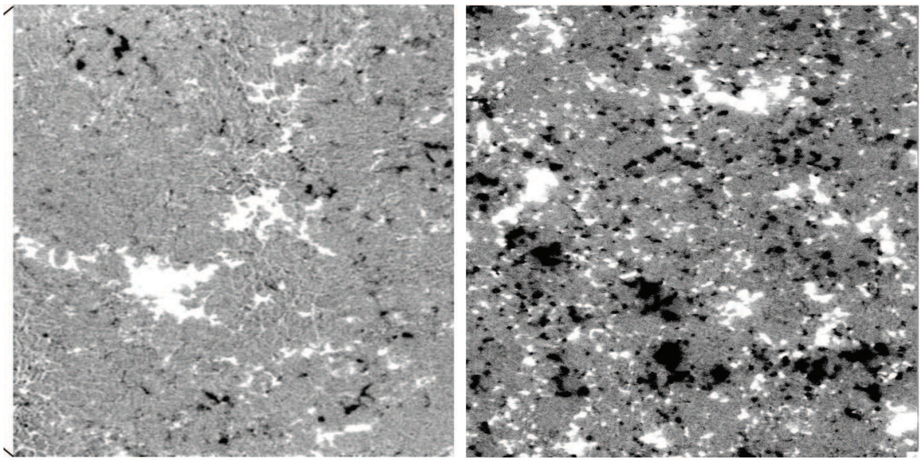

Figure 1: QS magnetograms: the longitudinal magnetic flux is coded in white for outward directions and in black for inward ones. Left panel: from ground-based instrument with 2” resolution, right panel: from Hinode NFI instrument with 0.2” resolution. Network magnetic elements are detected in the left hand figure, whereas IN elements also appear in the right hand figure

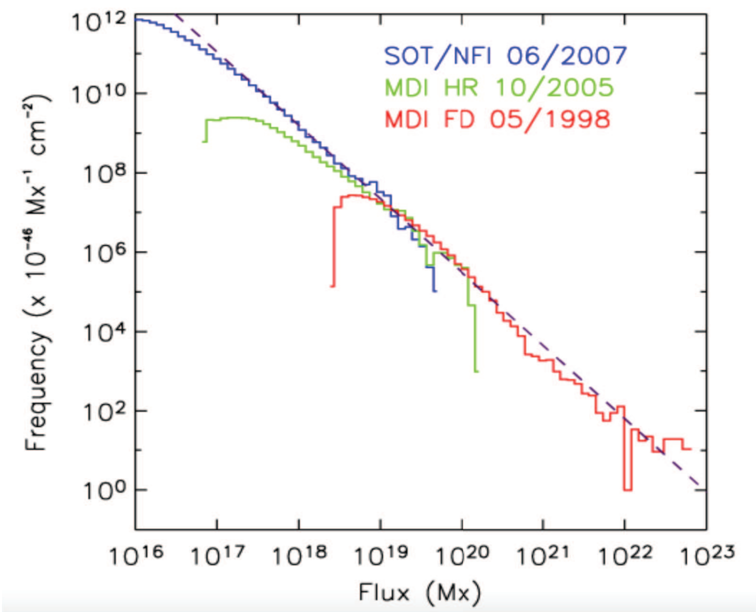

Figure 2: Distribution of longitudinal magnetic fluxes observed in Hinode/NFI magnetograms of the quiet Sun (blue curve) and SOHO/MDI high resolution and full disk magnetograms (green and red lines, respectively), from Parnell et al. 2009.

Many QS studies have been carried out in the last decade based on the high quality polarization measurements from the Hinode satellite (Lites et al. 2013). Its 50-cm SOT telescope with spectro-polarimetric facilities allows Zeeman magnetic field diagnostics using the FeI line pair at 630 nm. Both circular and linear polarization profiles are recorded, and the magnetic field is derived through different inversion methods depending on the authors. However even with the highest available spatial resolution (0.3" with the SOT telescope), it seems clear that we do not yet resolve the smallest magnetic structures (see Stenflo 2010). One of the evidences of this limitation is obtained from the high resolution observations of magnetic flux disappearance events. Magnetic flux is observed to disappear from the solar internetwork through cancellation and in-situ fading. Cancellation of flux arises when two magnetic patches of opposite polarities encounter each other due to their continuous motions, this phenomenon is observed in the Intranetwork (see Gömöry et al. 2010). The submergence of small-scale Ω-loops (see Iida et al. 2010) or the rise of a U-loop are also observed, they do not correspond to real flux removal from the solar surface. The most intriguing phenomenon is in-situ disappearance that has been observed in high resolution magnetogram movies where small magnetic flux elements disappear without interacting with other features. Statistical studies have shown that this is the most frequent mode of flux disappearance in the intranetwork (see Zhou et al. 2010, Lamb et al. 2013)! Some of these events are probably due to the presence of opposite polarity features which are not resolved by the instrument.Various magnetic instabilities taking place in small scale flux tube can also lead to in-situ disappearance, such as the interchange instability (Steiner 2007) or the Kelvin-Helmoltz instability.

Bearing in mind that, even with the best present instruments, the smallest magnetic scales are not yet resolved, various inversion methods have been designed to recover the magnetic field vector from the measured polarization profiles. However, different inversions methods may lead to different results for some of the statistical properties of the QS magnetic fields, as shown in the following.

3. WEAK OR STRONG FIELDS?

Typically, three kinds of inversion methods have been applied to Zeeman polarization data to infer the intrinsic magnetic field strength. The line ratio technique (Stenflo 2010) is based on the analysis of the ratio of circular polarization in the wings of two lines of the same multiplet with different Landé factors, the MISMA model (Sanchéz Almeida et al. 1996) for Micro-Structured Magnetic Atmospheres, assumes that each pixel contains a distribution of magnetic fibrils with different strengths and orientations, temperatures and velocities, whereas Milne-Eddington models assume that a fraction f of the pixel contains a depth-independent magnetic field with given strength and direction and the remaining fraction of the pixel is non-magnetic.

The line ratio technique applied to FeI lines at 524.7 nm and 525.02 nm first showed that in the network the magnetic field is strong, on the order of 1 kG, and with small filling factors on the order of 1%. Applied to internetwork regions, its results are more ambiguous, Keller et al. (1994) used observations at the German Vacuum Telescope with the ZIMPOL polarimeter and found an upper limit of 500 G for the strength of IN magnetic fields, but new observations performed at the Mc Math-Pierce telescope by Grossman-Doerth et al. (1996) led to strong fields of 1 kG. Many different studies were carried out with different pairs of lines in the optical

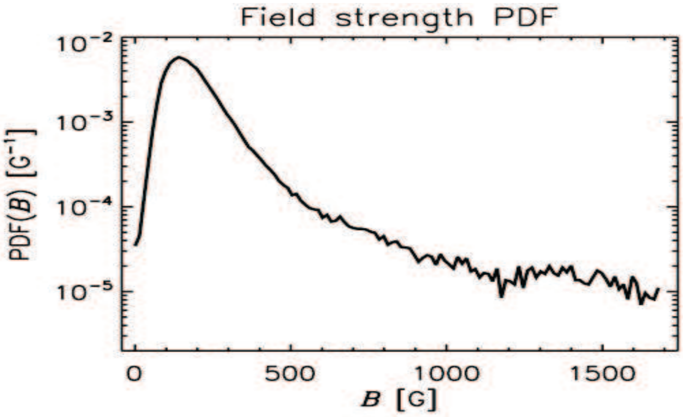

Figure 3: PDF of the magnetic strength in the internetwork derived from Hinode observations by Orozco Suárez & Bellot Rubio (2012).

and in the infrared domain where lines are more sensitive to the Zeeman effect, but the controversy between weak hG or strong kG fields was not solved. Finally Bellot Rubio & Collados (2003) showed that the line ratio technique is very much affected by photon noise in regions where the polarization signals are weak. So only pixels where the signal-to-noise ratio is larger than 10 should be inverted with this technique.

More recently a modified version of the line-ratio technique was applied to high spatial resolution observations performed in the FeI 630.15 an and 630.25 nm lines with the SOT/SP instrument onboard the Hinode satellite (Stenflo, 2010, Stenflo et al., 2013). The Probability Distribution Function (PDF) for the magnetic strength in the QS derived from these analysis shows two populations of magnetic regions, with respectively kG and hG field strengths.

Two populations of magnetic regions were also detected by Faurobert & Ricort (2013) from a cross-correlation analysis of Hinode/SP data. Polarization maps of the QS obtained at various limb-distances in the QS were cross-correlated with granulation images measured simultaneously. One magnetic population is well correlated with the granules whereas a second one is correlated with the intergranular lanes. This could correspond to the collapsed and uncollapsed populations described by Stenflo (2010). The physical origin of these two populations is supposed to be the convective collapse phenomenon (Parker 1975), which predicts that due to convective advection optically thick magnetic regions will get concentrated over small patches of kG strength in the inter granular lanes (downward velocities), whereas optically thin ones will not be sensitive to this instability mechanism.

The MISMA inversions performed by Sanchéz Almeida & Lites (2000) and Socas Navarro & Sanchéz Almeida (2002), considering two-magnetic components and one non-magnetic one inside each pixel, were applied to observations in the FeI 630 nm lines and the results were that a large fraction of the IN fields are in the strong kG field regime, but that weak fields also exist, both were found to occupy a few percents of the solar surface. The authors also concluded that an unknown amount of magnetic flux was still not detected. The MISMA inversion was also applied to observations

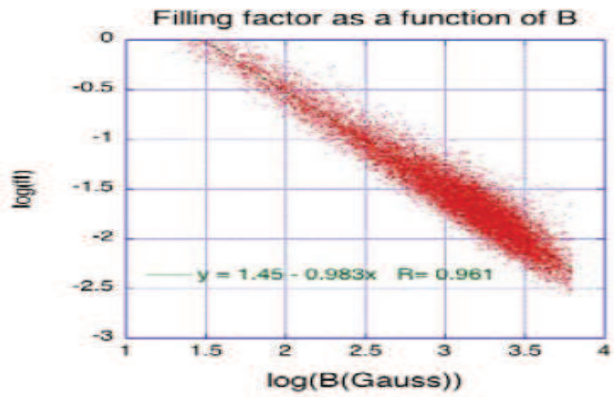

Figure 4: Filling factor of the magnetic fields in the quiet Sun as a function of the magnetic strength, from Bommier (2011).

obtained simultaneously at the German VTT in spectral lines of the visible and of the infrared domains (Domíngez Cerdena et al., 2006). Visible lines are more sensitive to the Zeeman effect of strong fields whereas infrared lines are sensitive to weaker fields. Actually both strong and weak fields were derived in the same pixels from the two spectral domains, and mixed polarity fields were also often detected.

The Milne-Eddington inversion method assuming one magnetic component with a filling factor f over the surface of the pixel was applied to invert both the circular and linear polarization recorded in the FeI 630 nm line pair with SOT/SP (Orozco Suárez et al., 2007, Lites et al. 2008, Ishikawa, R. & Tsuneta, S. 2011, Borrero & Kobel, 2012, Orozco Suárez & Bellot Rubio, 2012). Figure 3 shows the PDF of the magnetic field strength derived by Orozco Suárez & Bellot Rubio (2012). The magnetic strength peak at 100 G, and shows an extended tail to kG values. The high spatial resolution (0.3") and high sensitivity of the observations allowed to measure the linear and circular polarization in both lines. The temperature gradient was taken into account and both lines were inverted with the same atmospheric and magnetic parameters, but only the pixels where the signal-to-noise ratio is larger than 4.5 were considered. They represent a significant fraction, 27 % , of the observed area. Another noticeable result of this study is that the filling factor of weak fields is around 20% at 0.3" resolution, this is consistent with results found previously by Bommier (2011) from the inversion of Themis observations, where she showed that the filling factor of magnetic fields in the QS varies as the inverse of the magnetic strength (see Fig. 4).

The validity of Milne-Eddington inversions in the QS, based on the Zeeman polarizations of the FeI 630 nm line pair has been put into questions by various authors, (e. g. Martinez Gonzales et al. 2006, Lopez Ariste et al. 2007) because the line profiles are sensitive to temperature effects and this results in ambiguity in the inversion procedure between the temperature gradient and the magnetic field strength. As more observables are required, Lopez Ariste et al. (2007) proposed to use simultaneously the MnI line at 553.7 nm which is particularly well suited for magnetic strength diagnostics because of its strong coupling between hyperfine structure and Zeeman

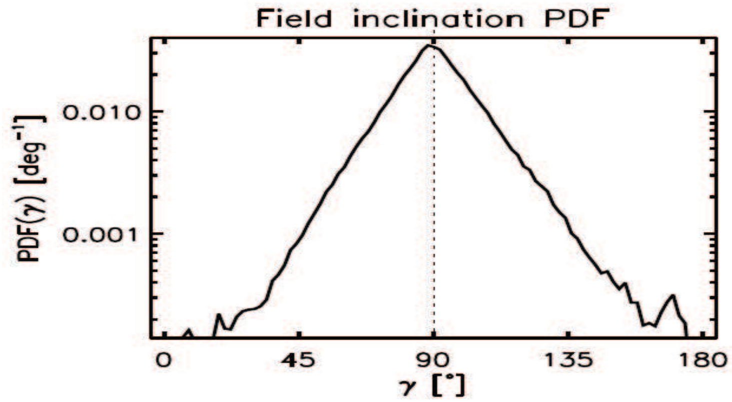

Figure 5: PDF of the magnetic inclination in the internetwork derived from Hinode observations by Orozco Suárez & Bellot Rubio (2012).

effect. In the presence of magnetic fields below 600 G the Stokes V profile shows an anomalous spectral feature between the two main Zeeman lobes. Such a feature disappears when the atom enters into Paschen-Back regime for magnetic strength stronger than 600 G. They applied this method to QS observations performed with the Themis telescope simultaneously in the FeI 630 nm line and in the MnI 553.7 nm line, showing that in some cases Milne-Eddington inversions of the FeI 630 nm data were not be able to distinguish between strong kG fields and hG ones, whereas the behavior of MnI stokes V profiles allows to conclude unambiguously.

4. ISOTROPIC OR HORIZONTAL FIELDS?

Another matter of debate is the orientation of the magnetic vector in IN regions. Here again various methods give different results. First let us recall that in order to retrieve the vector magnetic field from polarization measurements one needs to measure both the circular and linear polarization with good accuracy. At disk center (when the line of sight is perpendicular to the solar surface), the circular polarization is due to the vertical magnetic component whereas the linear polarization is due to the horizontal one. However, in the QS the linear polarization of spectral lines due to the Zeeman effect is intrinsically smaller by at least a factor 10 than the circular polarization, moreover it is more affected by instrumental polarization problems due to oblique reflexion of light inside the instruments. At low spatial resolution the linear polarization of the IN regions was hardly detected. So one of the first surprises which came from high resolution polarization measurements from space was that linear polarization was detected everywhere in the IN. The total amount of apparent horizontal flux was found to be five times larger than the apparent vertical one (Lites et al., 2008).

A PDF of magnetic vector inclination with respect to the vertical in the IN has been obtained from Milne-Eddington inversions of Hinode data by Orozco Suárez & Bellot Rubio (2012), it shows a striking peak at 90 which implies that most of the IN fields are horizontal. However, MISMA inversions and line ratio analysis,

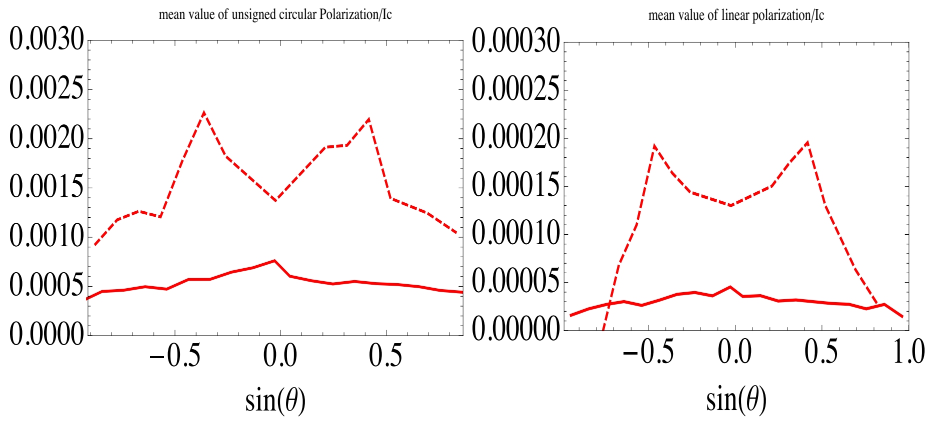

Figure 6: Center-to-limb variations of the mean polarization signals in the QS in December 2007 (full lines) and in December 2013 (dashed lines) measured with SOT/SP onboard the Hinode satellite. Left panel: unsigned circular polarization in the FeI 630.25 nm line, right panel: linear polarization in the FeI 630.25 nm line. One clearly sees the increase of signal in the Quiet Sun at active latitudes at the solar maximum.

on the contrary lead to mostly vertical fields! Bommier (2011) found that strong fields are mostly vertical and weak fields mostly horizontal. Stenflo (2013) used the polarization-free French solar telescope Themis to perform center-to-limb measurements of the linear polarization profiles in the FeI lines at 524.7 nm and 525.0 nm. Without any inversion, the symmetry properties of the linear polarization profiles observed away from the solar disk center, allow to distinguish between horizontal and vertical fields. He found that in the IN the magnetic fields are mostly vertical in the low photosphere, and become more and more horizontal in the upper photosphere. The spatial resolution of the Themis observations was 2" whereas the Hinode data have a better spatial resolution of 0.3", this could be a source of discrepancy between both studies, if the magnetic fields in the weakest IN regions have mixed polarities on scales smaller than 1". Further studies are needed to clarify this issue.

5. EVOLUTION WITH THE SOLAR CYCLE?

One way of testing the origin of IN magnetic fields is to see if they vary with the solar activity cycle. In that case they would be at least partly due to the decay of active regions, whereas if they are created by a local surface dynamo mechanism they would not vary with the solar cycle. Observational studies of this question require to have stable and accurate measurements of the IN polarization over at least one half of a solar cycle. This is now possible thanks to the Hinode satellite that was launched in 2006, at a solar minimum and is still in operation, at the present solar maximum.

Buehler et al. (2013) investigated the long-term evolution of weak IN signals observed at disk center with the Hinode satellite between 2007 and 2012. They detected no variations of polarizations signals or magnetic flux, and concluded that the weak IN polarization signals recorded by Hinode are not driven by the global dynamo but rather by a local surface dynamo. Lites et al. (2014) also studied

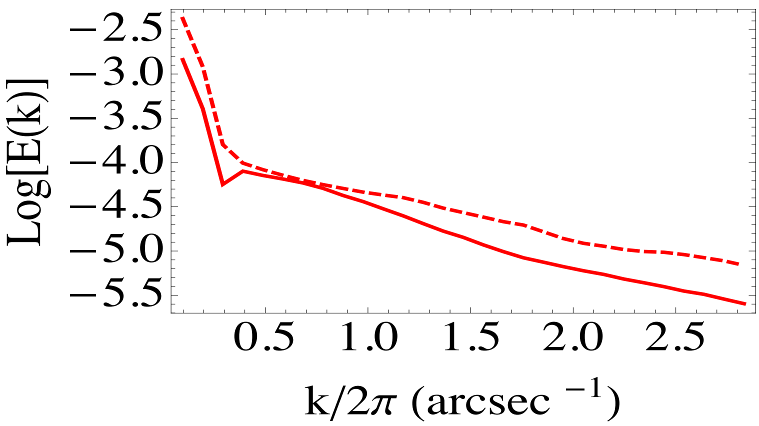

Figure 7: Fourier spectra of the spatial fluctuations of the unsigned circular polarization in the FeI 630.25 nm line in an IN region at $\cos\theta = 0.78$ (θ denotes the heliocentric angle). Full line: from 2007 data, dashed line: from 2013 data.

the same question from the analysis of center-to-limb measurements of the very weak polarization signals during the same period. They also found no solar cycle variations.

Faurobert at al. (2014) have compared the Fourier spectra of the polarization spatial fluctuations recorded with Hinode/SP in the QS at a minimum (December 2007) and at a maximum of the solar cycle (December 2013). They found that the decay of active regions is a source of magnetic fields in the QS (see Fig. 6). But they showed that in the IN regions the polarization spatial spectrum is unchanged at granular scales (spatial scales around 1.3 "), whereas it increases in phase with the solar cycle at mesogranular and sub granular scales (see Fig. 7). This result indicates that a very efficient mechanism of magnetic field removal is operating in the QS at the granular scale so that the source of magnetic fields at large scale due to the decay of active regions is very rapidly dissipated or concentrated on smaller scales. The cycle-independent polarization signal that is measured at the granular scale is thus continuously created by a mechanism which is independent of the global solar dynamo. This mechanism may be identified to a local surface dynamo.

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