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Do the quiet sun magnetic fields vary with the solar cycle?

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Abstract. The quiet Sun observed in polarized light exhibits a rich and complex magnetic structuring which is still not fully resolved nor understood. The present work is intended to contribute to the debate about the origin of the quiet sun magnetic fields, in relation or not to the global solar dynamo. We present analysis of center-to-limb polarization measurements obtained with the SOT/SP spectropolarimeter onboard the Hinode satellite outside active regions, in 2007 and 2013, i.e. at a minimum and a maximum of the solar cycle, respectively. We compare the spatial fluctuation Fourier spectra of unsigned circular and linear polarization images after corrections for polarization bias and focus variations between the two data sets. The decay of active regions is clearly a source of magnetic fields in the quiet Sun. It leads to a global increase of the polarization fluctuation power spectrum in 2013 in the network. In the internetwork, we observe no variation of the polarization fluctuation power at mesogranular and granular scales, whereas it increases at sub-granular scales. We interpret these results in the following way. At the mesogranular and granular scales very efficient mechanisms of magnetic field removal are operating in the internetwork, that leads to a dissipation or a concentration of magnetic fields on smaller scales. So the cycle-invariant magnetic signal that we detect at mesogranular and granular scales must be continuously created by a dynamo mechanism which is independent of the solar cycle.

Keywords. Polarization, magnetic fields, quiet photosphere

1. Introduction

The quiet Sun magnetic fields consist of network and internetwork elements. The network elements show strong fields of the order of kG and are located at the borders of the supergranular cells, while the internetwork ones, in the cell interiors, show much weaker fields of the order of hG with mixed polarities at small scale (for a review see Sánchez Almeida & Martínez González 2011). A recent study by Gosic *et al.* (2014) from Hinode 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) and 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.

An interesting test to distinguish between both mechanisms is to see whether the quiet Sun magnetic fields vary with the solar cycle, in relation with the global solar dynamo. Several studies have been devoted to this issue. Buehler *et al.* (2013) have analyzed linear and circular polarization maps obtained in very quiet regions of the internetwork at disk center from 2007 to 2013 with the Hinode/SP instrument. They found no significant variations of the polarization level nor of the size distribution of the polarization patches with the solar cycle. Lites *et al.* (2014) investigated the center-to-limb variation of the circular and linear polarization signals measured in the very weakly polarized regions of the internetwork between 2008 and 2013 using the Hinode/SP irradiance program. At moderate latitudes they found no evidence for systematic changes as a function of time and solar latitude in either the unsigned line-of-sight flux or in the measures of the transverse flux. Both studies favor a small scale dynamo as the source of weak magnetic fields observed in the internetwork regions.

In this paper we also address the issue of solar cycle variations of the quiet Sun magnetic fields with a different approach. We analyzed center-to-limb observations performed with Hinode/SP in December 2007 and 2013, i.e. at a minimum and a maximum of the solar cycle, respectively. The December 19, 2007 observations are part of the irradiance survey program HOP79, where pole-to-pole scans with full spatial resolution (0.16" per pixel) were performed. The December 7, 2013 data is taken from a different program dedicated to the investigation of the quiet Sun magnetism, where the same strategy was carried out with the full 0.16" per pixel resolution. However, due to the limited data transfer rate the polar regions were not observed in the 2013 campaign. We computed the line integrated unsigned circular and linear polarization in the Fe I 630.25 nm line and the Fourier power spectra of their spatial fluctuations on spatial scales between 0.3" and 20" in both data sets. One advantage of using Fourier spectrum is that it is quite easy to correct them from any bias in the signal and from the effect of possible defocus between the two data sets. The bias is an additive quantity that can be estimated and removed from the spectra and the defocus modifies the Modulation Transfer Function (MTF) of the instrument which affects the Fourier spectrum through a multiplicative function that can be quite easily modeled (it is a phase default on the entrance pupil of the telescope). Moreover, if the noise is not correlated to the signal, the Fourier spectrum of the observed signal is the sum of the "true" signal spectrum and of the noise spectrum. The noise spectrum may be estimated from the polarization at the continuum.

In the second part of the paper, we first examine the center-to-limb variation of the mean polarization values over 130" x 30" images containing both network and internetwork elements, after corrections for the polarization bias introduced by the line integration of the polarization signal. Then we compare the Fourier spectra of the polarization spatial fluctuations observed at the center of the solar disk in 2007 and 2013.

In the third part, to distinguish the network from the internetwork regions, we extract from the initial 130" x 30" images a set of 20" x 20" images, smaller than the typical scale of the supergranular cells and covering a South-North stripe along the polar axis. We examine the center-to-limb variation of the polarization fluctuations averaged over three spatial frequency bands, namely the Low Frequency band (LF) corresponding to spatial scales between 2" and 10", the Mid-Frequency band (MF), corresponding to spatial scales between 0.5" and 2" (typical granular scales), and the High Frequency (HF) band corresponding to scales between 0.5" and 0.3" (sub-granular scales).

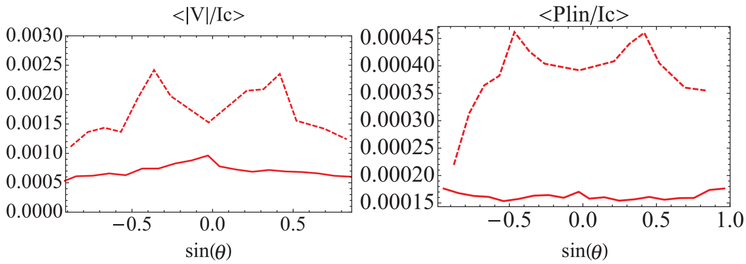

Figure 1. Mean value of the unsigned circular polarization (left panel) and of the linear polarization (right panel) in the FeI 630.25 nm line corrected for the bias, and divided by the mean continuum intensity in the image, as a function of the sinus of heliocentric angle (negative values refer to southern latitudes). Full line: 2007 data, dashed line: 2013 data.

2. Mean polarization values and disk-center spatial fluctuation Fourier spectra

The unsigned circular and linear polarizations are defined as

$$\begin{aligned} \mid V(x,y) \mid &= \frac{1}{2\Delta\lambda} \left| \int_{\lambda_0-\Delta\lambda}^{\lambda_0} V(\lambda,x,y)d\lambda - \int_{\lambda_0}^{\lambda_0+\Delta\lambda} V(\lambda,x,y)d\lambda \right|, \\ P_{lin}(x,y) &= \frac{1}{2\Delta\lambda} \int_{\lambda_0-\Delta\lambda}^{\lambda_0+\Delta\lambda} \sqrt{Q^2(\lambda,x,y)+U^2(\lambda,x,y)}d\lambda, \end{aligned} \tag{2.1}$$

where the wavelength λ_0 is the line-center wavelength and $2\Delta\lambda$ is the spectral range where the line absorption is detected. The polarization signals arise from magnetized regions only. They may thus be used as tracers of the spatial distribution of these regions. However, in the integrations carried out in Eq. 2.1 for the linear polarization we sum over positive quantities, this introduces a bias in the linear polarization signals, due to the accumulation of the noise contribution. In order to estimate the bias we computed polarization-noise images with the same integral as in Eq. 2.1, but in the continuum of the spectral domain which is intrinsically unpolarized. Figure 1 shows the center-to-limb variation of the mean value of the unsigned circular and linear polarizations from the 2007 and 2013 scans, after subtraction of the bias. We notice that the mean values are significantly increased at active latitudes in 2013 data, showing that the decay of active regions is a source of magnetic fields in the quiet Sun. Let's now examine the polarization spatial fluctuations.

We wish to compare the spatial fluctuation Fourier spectra of the polarization for 2007 and 2013 observations, so possible defocus problems between the two observing runs must first be corrected (see Buehler *et al.* 2013). In order to address this problem we computed the Fourier spectrum of the continuum intensity spatial fluctuations. Assuming that the statistical properties of the continuum intensity at 630 nm do not change significantly with the solar cycle, we derive the focus change between the two data sets. This is illustrated on Fig. 2 where we show the ratio of the two intensity spectra as a function of the spatial frequency and compare it with the theoretical values derived for various defocus between the two data sets. A defocus of the telescope modifies the MTF of the instrument which is given by the autocorrelation of the pupil of the telescope. The defocus introduces a phase term over the entrance pupil. The ratio of two identical signals observed with different defocus is simply equal to the ratio of the respective MTFs. We see in Fig. 2 that the ratio of the continuum intensity fluctuations observed in 2013 and in 2007 is quite well reproduced if the 2007 observations were affected by a relative phase

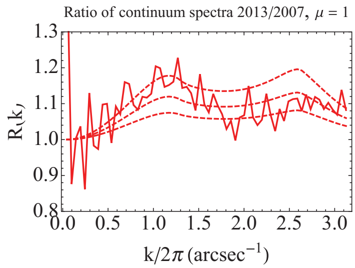

Figure 2. Full line: ratio of the spatial fluctuation Fourier spectra of the continuum intensity at 630 nm at the center of the solar disk in 2013 and 2007 observations. Dashed curves: theoretical ratio of intensity spectra for various defocus of the 2007 observations with respect to 2013 ones. Upper curve: relative phase default of 1.2π, middle curve: relative phase default of π, lower curve: relative phase default of 0.8π.

default of π with respect to the 2013 observations. In the following we shall compensate for this defocus by modifying the MTF for the 2013 data.

Figure 3 shows the comparison of the spatial fluctuation Fourier spectra of the unsigned circular and linear polarization measured at disk-center in 2007 and 2013. At disk center we observe a global increase of the fluctuation power spectrum in 2013 with respect to 2007. We also observe a possible change of slope of the linear polarization spectrum which seems more flat at small spatial frequencies in 2013 than in 2007 observations. At high spatial frequencies the linear polarization spectra seem to saturate, but the signal-to-noise ratio is of the order of unity (we observed that the noise is larger by a factor 2 in 2013 than in 2007).

The images that we have compared here contain both network and internetwork elements. As the network carries an important fraction of the magnetic flux, the changes that we observe in the Fourier spectra are probably mainly due to the contribution of the decay of active regions which tend to increase the number of network elements at the active phase of the solar cycle. Let us now try to disentangle the network and the internetwork.

3. Center-to-limb variation of the lowest polarization fluctuation level

To distinguish the cycle variation of the network from the one of the internetwork we extracted from our data two sets of 20" x 20" images along the South-North polar axis trying to avoid the locations of prominent network patches visible on the unsigned circular

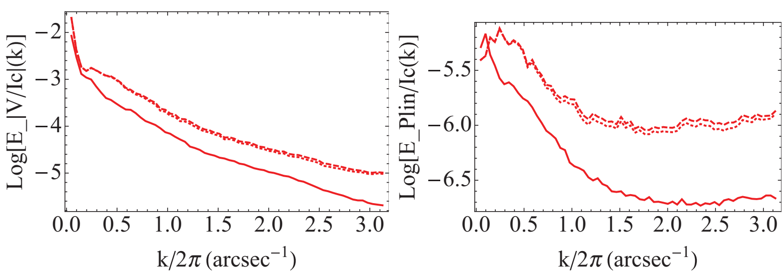

Figure 3. Spatial fluctuation Fourier spectrum of the unsigned circular polarization (left panel) and of the linear polarization (right panel) in the FeI 630.25 nm line at the center of the solar disk. Full line: 2007 data, dashed line: 2013 data; dotted line: 2013 spectrum modified for compensating the defocus of 2007 data.

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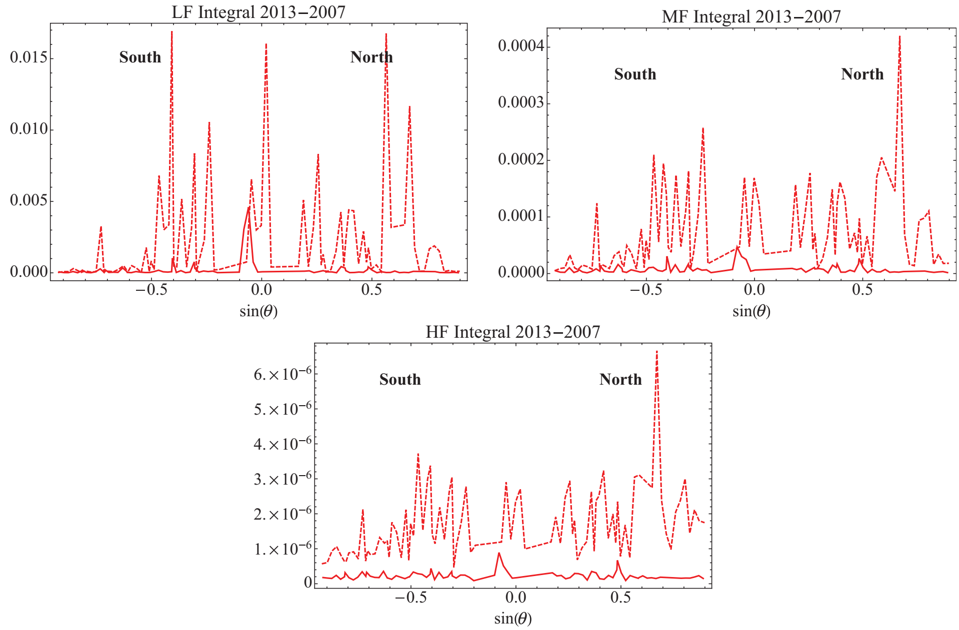

Figure 4. Center-to-limb variation of the unsigned circular polarization average fluctuation level in LF, MF and HF spatial frequency bands. Full lines: 2007 data, dashed lines: 2013 data corrected for the focus variation between the two data sets. Upper left panel: low frequency band, upper right panel: mid-frequency band, lower panel: high frequency band.

polarization maps. As the images are smaller than the typical size of the network cells, we expect that some of them will be free of network elements. The polarization fluctuation level will then reach its lower value in these images. The new data sets contain 84 images for both the 2007 and 2013 observing runs. To compare easily the center-to-limb variation of the polarization spectra in these two sets of images we defined three spatial frequency bands and we computed the average polarization fluctuation level in these bands. We introduced a Low Frequency band (LF) for spatial frequencies smaller than 0.5 arcsec $^{-1}$ (spatial scales larger than 2 arcsec), the Mid-Frequency band (MF) for spatial frequencies between 0.5 and 2 arcsec $^{-1}$ (granular scales), and the High Frequency (HF) band for spatial frequencies between 2 and 3 arcsec $^{-1}$ (sub-granular scales). Figures 4 and 5 show respectively the center-to-limb variation of the unsigned circular polarization and linear polarization levels in these three bands in our 2007 and 2013 data.

The fluctuation levels show large variations from one image to another depending on the number of network patches contained in the image. We remark that many images of the 2013 data set are actually showing quite large polarization signals, however in the three spatial frequency ranges we observe a well defined lower fluctuation level that we attribute to the internetwork quiet Sun. The internetwork fluctuation level shows no center-to-limb variation at mesogranular and granular scales, both for the unsigned circular and linear polarization and their values are identical in 2013 and in 2007 data. However, at sub-granular scales the polarization fluctuation level in the internetwork is larger in 2013 than in 2007, both for the unsigned circular and linear polarization. A center-to-limb increase of the fluctuation level seems to show up for the linear polarization. However, in this spatial range the signal-to-noise ratio is poor for the linear polarization signal in both data sets.

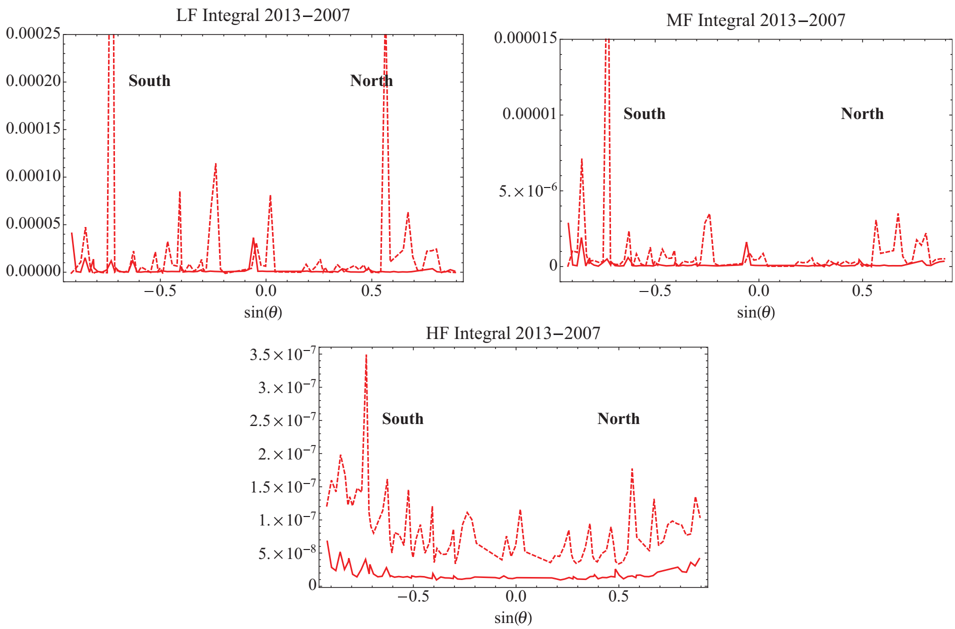

Figure 5. Same as Fig. 4 but for the linear polarization.

4. Interpretation

In the network, larger spatial fluctuations with unchanged spectral slope for the unsigned circular polarization indicates that in our 2013 observations the disk center regions contained a larger number of magnetic patches but with similar small scale structuring of the vertical flux as in 2007. The change of slope of the linear polarization may be due to a change in their magnetic filed horizontal component behavior at granular scales.

In the internetwork, it seems that the magnetic field structure shows variations with the activity cycle at subgranular scales but remains unchanged at the mesogranular and granular scales. The decay of active regions could be a source of magnetic fluctuations at large scales in the internetwork, these magnetic fluctuations would then cascade to smaller scales. The fact that we do not see any change in the internetwork fluctuation level at the mesogranular and granular scales can be understood if in these scale ranges very efficient mechanisms of magnetic field removal are operating. If this is the case, then the magnetic fluctuations measured over these spatial ranges have to be restored by a continuous creation mechanism which is independent of the solar cycle. We believe that this mechanism can be identified as a small scale solar dynamo.

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